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Development of Kinetic Inductance Detectors for KIS

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Millimetre-wave astronomical observations have an enormous discovery potential for the study of the earliest stages of the evolution of the universe, clusters of galaxies, high-redshift objects, and star formation regions. One of the challenges today is to perform observations with the finest angular resolution, in order to accurately investigate the nature of these astrophysical sources. While for spectroscopic investigations of point-like sources ALMA is the obvious solution, for continuum measurements of diffuse sources large single-dish telescopes (e.g. GBT, TML, IRAM, SRT, etc.) equipped with large-format bolometeric cameras provide a much higher mapping speed. Kinetic Inductance Detectors represent an interesting option for the detector array, due to their easiness to multiplex and their capability to efficiently tackle with atmospheric issues. We are developing Aluminum Lumped Element KIDs for the 3 mm atmospheric window (W-band). While interesting performance of KIDs has already been demonstrated for the 1 and 2 mm windows, further technological development is needed for their use at longer wavelengths. In this contribution we will describe a recent proposal for a new KID imager to be installed at the Sardinia Radio Telescope, the largest Italian radio astronomy facility. We will discuss detector requirements and we will show the results of optical tests of the first devices.

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1. Introduction

Which is the role of ionized gas and dust in the formation and evolution of small and large scale structures of the universe? This question is still largely unanswered. The W-band (80-115 GHz) is an interesting transition band between free-free, dust and Cosmic Microwave Background (CMB) emissions and would allow to explore in an original way different astrophysical science cases, as for example:

- the study of distant and nearby galaxy clusters through Sunyaev-Zeldovich effect, a CMB anisotropy;
- the characterization of the nature of dust in star-forming galaxies, proto-stars and planet formation regions;
- the investigation of the Anomalous Microwave Emission in galactic regions.

Thanks to the development of mm-wave detectors, large radio telescopes are gradually attempting to exploit the scientific potential of mm-wave astronomy. Interferometers, like the recently operative ALMA, are fundamental instruments for millimeter-wave astronomy, but are not suitable for large sky surveys in the continuum. The role of single-dish telescopes are therefore essential. The MUSTANG experiment installed at Green Bank Telescope has already well demonstrated the potentiality of observations in the W band with large single-dish telescopes [1].

The Sardinia Radio Telescope (SRT) is the largest Italian radio astronomy facility (primary dish of 64 m). It is currently in the commissioning phase and will be soon a key player in the future of radio and mm-wave astronomy. In order to fully exploit its potential the observatory needs to be equipped with state of the art instruments in all the frequency band. In this paper we will describe KIS, a Kinetic Inductance Detector Imager in W-band, proposed to the Italian Ministry of Reserach to become the resident instrument at SRT.

We will begin with a brief description of the instrument (section 2) and then we will focus on detector requirements (section 3) and their design (section 4), showing also the first results of our R&D activity.

2. KIS: a KID Imager for the Sardinia Radio Telescope

KIS will implement a new promising microwave detectors, based on surface impedance of superconductors, called Kinetic Inductance Detectors (KIDs) [2]. Easy to fabricate and to multiplex, KIDs are ideal for this application. Thanks to the size of the mirror of SRT (64 m), the emission of the atmosphere is a common mode at 3 mm; however the atmospheric background and its noise will represent the main limitations of such an instrument. With respect to traditional bolometric detectors working at the same wavelengths (e.g. high impedance and TES bolometers), KIDs are faster; they have large dynamic working range and the capability to intrinsically measure the incident background power [3, 4]. This will allow KIS to constantly monitor the transmissivity and emissivity of the atmosphere and to decorrelate its noise also at high frequencies.

The instrument will host a cold reimaging optics and an array, built of about 100 diffraction-limited pixels (FOV = 2 arcmin) with angular resolution of 12 arcsec and noise limited by the photon noise

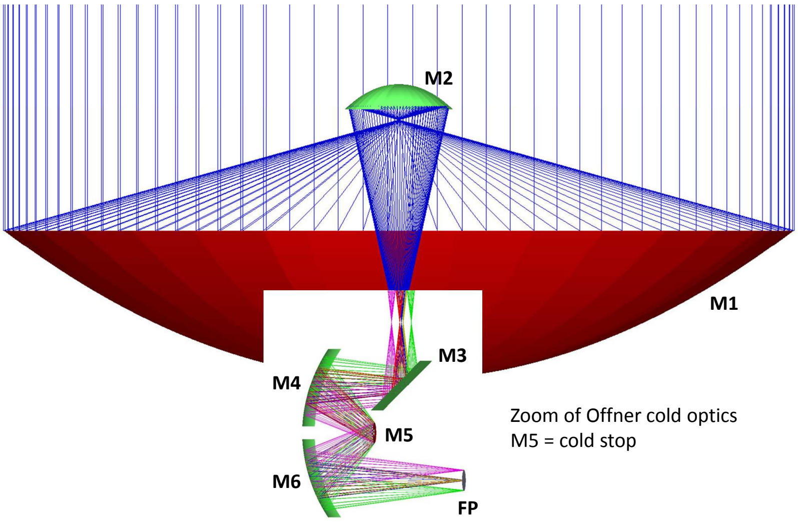

Figure 1: The optics design of the instrument

due to the background (about 0.1 fW $Hz^{-0.5}$). The expected sensitivity of each of the 100 pixels will be 30 μJy in 1 hour of integration (5 sigma). The scientific goals of KIS could be reached with an accurate technological effort on different aspects:

1) Detectors: Aluminum KID can work at a frequency higher than 95 GHz. In order to fully cover the W-band, we need to lower the superconducting critical temperature of the metal, increasing its thickness. Different materials could also be studied (e.g. Aluminum alloys or Titanium Nitride). Detectors will be fabricated by the Institute for photonics and nanotechnologies (IFN) of CNR.

2) Cryostat and optics: Detectors will be cooled to temperatures of 100 mK by a pulse tube equipped with a compact dilution refrigerator. Similar systems are commercially available; however a specific development is needed to allow to tilt the system more than 45° enlarging the fraction of sky observable. This could be achieved by applying specific cryogenic solutions or by using a derotator. Optics will implement a 4K stop to refine the aperture stop of the telescope, minimizing the spillover due to primary mirror sidelobes and will be telecentric (see 1).

3) Electronics: We own already a complete system for the readout of the detectors. The multiplexing electronics, developed for the NIKA experiment and based on a XILINK VIRTEX 5, is able to readout up to 100 channels in a bandwidth of 125 MHz with a sampling rate of 1 KHz [5]. Data Acquisition system will be adapted to the SRT standards.

4) Warm and cold plugins: Instrument design will allow the implementation of warm and cold plugins, e.g. a rotating halfwave plate for polarimetry [7] or a Differential Fourier-Transform spectrometer [6];

3. Detector requirements

The performance of Lumped Element KIDs (LEKIDs) has been demonstrated by NIKA at 1.25 and 2 mm [10]. Our group has already developed KIDs for the 2 mm band [8]. The devel-

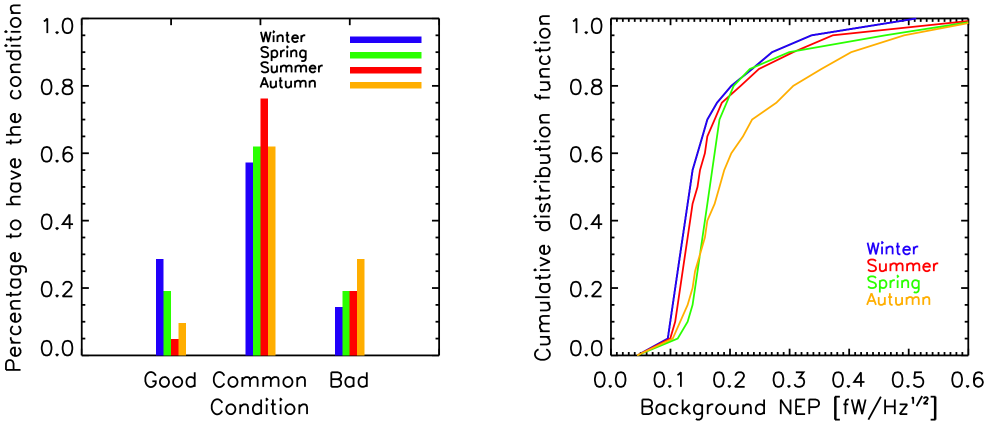

Figure 2: LEFT: Frequency of the different background power values during the year (see the text). RIGHT: Cumulative distribution function for the photon noise due to the background

opment of similar detectors for the W band is scalable under several points of view (pixel size, maximization of the optical absorbance via optimization of the thickness of the substrate and of its distance from the backshort). The expected resonant frequency for a LEKID, working at 3 mm, is between 0.5-1 GHz; this band is fully compatible with the commercial cryogenic SiGe amplifiers, needed for the readout of the low bias signal (about - 70 dBm).

The major criticality is the selection of the superconducting metal since KIDs are not sensitive to photons with energy lower than the superconducting gap. Our baseline solution is represented by Aluminum, which is the standard for mm-wave KIDs, because it is easy to process, producing reliably thin (tens of nanometers) films with high reproducibility and very good merit factors. The critical temperature of bulk Al is 1.18K, corresponding to 86 GHz incident photons, so this solution is nominally suitable for our purpose. However it is well known that in films with thickness comparable to the London penetration depth (20 nm for Al) the critical temperature increases significantly. In our case we do not need extremely thin (10-20 nm) films, since the typical radiative background on a pixel is larger than 25 pW, which is relatively high for these detectors.

In order to define the main requirements of the detectors it is necessary to characterize the background on the devices and the consequent Noise Equivalent Power (NEP). We estimated the background emission in a band between 80 and 100 GHz considering different contributions: the atmosphere [9], the mirrors , the optical window of the experiment and the CMB. Taking into account seasonal and meteorological effects, it is possible to define three typical background conditions: good ($P_{BG} < 25$ pW), common (25 pW $< P_{BG} <$ 75 pW) and bad ($P_{BG} > 75$ pW). The left panel of Fig. 2 shows shown the frequency of the different backgrounds for each season. Good conditions are about 15 % over the whole year. The right panel of fig. 2 shows the photon noise due to the background in terms of NEP. With good weather the Background Limited Infrared Photodetection (BLIP) condition is about 0.1-0.15 fW Hz$^{-0.5}$. It goes up to 0.5-0.6 fW Hz$^{-0.5}$ in bad weather conditions. The consequent requirements - we decide to set in order to fully exploit the potentiality of the observatory - are the following:

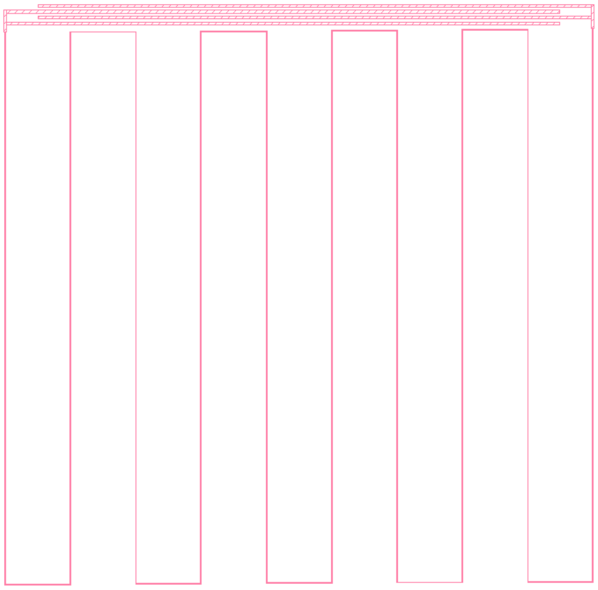

Figure 3: Design of the LEKID resonator (size 3 mm × 3mm). In the upper part the fingers composing the capacitance, in lower part the inductive meander, that acts as absorber of the radiation and sensor.

- **Working frequency**: The minimum working frequency of the detectors should be not higher than 90 GHz;
- **Working dynamic range**: Detectors should be able to operate correctly and with good performances for any background power lower than 75 pW;
- **NEP**: Detector should have a NEP of 0.1 fW Hz$^{-0.5}$.

4. Detector design and test

Our R&D acitivity begun in early 2014. Our starting point for the detector design was the attempt to scale a 2 mm LEKID to a device optimized for the W band, keeping as main free paramater the metal thickness. Considering the background conditions, the optimal thickness of an Al film in order to avoid saturation of the detector is 40-100 nm. This range of thickness implies a volume of the device such so the degradation of the film quality factor due to the background is moderate (i.e. Q > 3 10^4).

At this moment we have tested the first generation of devices. The chip is composed by 2 resonators of 3 mm × 3 mm (see Fig. 3), made with 40 nm thick aluminum deposited by an electron gun. The metal is deposited on 300 μm thick silicon 100 substrate. The litography is performed using an EBL with a lift-off approach. The pixel resonates at 1.0 GHz with a quality factor of 2 x 10^4. Meander spacing is optimized for the absorption of radiation in W-band. On the other hand Si substrate is too thin with a loss of efficiency of a factor 2-3.

We were able to measure the superconducting gap Δ using a Vector Network Analyzer. For a 40 nm film we have obtained Δ=0.2 meV, that implies T_c=1.32 K and ν_c=96.5 GHz. We were also able to perform preliminary optical tests, chopping two blackbodies at 300 K and 77 K. The estimated NEP is about 0.5 fW Hz$^{-0.5}$.

The first optical tests are encouraging: the results are near our goal of 0.1 fW Hz$^{-0.5}$, also considering the poor optical coupling efficiency. On the other hand, the measure of ν_c shows that we need to test higher thickness to verify its dependence with T. The 2nd generation of devices with a thickness of 100 nm is currently in fabrication and will be tested very soon.

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