Contribution aux exercices de prospective nationale IN2P3
"Technologies quantiques pour les deux infinis"

Kinetic Inductance Detectors for millimeter and sub-millimeter cosmology

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Introduction

The goal of this document is to show and argue the effort of the research and development activities on experimental cosmology within the collaboration of IN2P3 laboratory LPSC, INP laboratory Institut Néel, INSU laboratory IPAG and IRAM. This collaboration has strong roots starting from the 1990s thanks to the balloon-borne Archeops and space-borne Planck experiments. During the last 15 years the collaboration has pioneered the utilisation of Kinetic Inductance Detectors (KID) at millimetre frequencies through the NIKA and NIKA2 instruments [Catalano et al. (2014), Adam et al. (2015)] (since September 2015 at 30m-IRAM telescope, dual-band, dual-pol, 3.5 k-pixels), the KISS instrument [Fasano et al. (2021)] (since November 2018 at 2.5m QUIJOTE telescope, spectro-interferometer 0.6 k-pixels) and the CONCERTO instrument [Concerto coll. (2020)] (since April 2021, at 12 m APEX telescope, spectro-interferometer 4 k-pixels). The collaboration is now consolidated through a GIS (*Groupement d'intérêt scientifique*), in its final stage of creation. Today, we participate together in the preparation of the next generation instrument based on KID technology for cosmology and millimetre science [CMB-S4 collab. (2016)]. In order to be a competitive candidate for the next generation of instruments devoted to cosmology, we need to develop and test new focal planes with tens of thousands of pixels, extend the range of frequency, and develop on-chip multicolor and polarization splitting. Indeed, the specific detailed requirements on individual detector arrays will heavily depend on the final reported characteristics of the focal plane instruments such as the optical load, the frequency range, coverage of the focal plane (filled arrays, or horned-coupled detectors) and strategy of polarisation measurements. This will allow us to identify the main challenges in detector technology.

Scientific Context

New Frontiers in Cosmology: During the last decade, CMB (Cosmic Microwave Background) observations from space (most recently by the European Space Agency's Planck satellite [Planck Collaboration et al.(2019)] but also with several balloon-borne and ground-based instrument as for example BOOMERanG, MAXIMA, Archeops, Dasi, QUaD, ACT, POLARBEAR, BICEP to cite some of the most prominent experiments) have significantly increased our understanding of the standard model of cosmology, allowing percent constraints on the cosmological parameters. Nonetheless, the current model remains incomplete. The nature of dark energy and dark matter is still unknown. The current expansion rate (H_0) of the Universe measured using the cosmic distance ladder and time delay of gravitationally lensed quasars is discrepant at the 5 σ level with the one inferred from observations of the early Universe. The amplitude of matter fluctuation (σ_8) measured

from clusters of galaxies and galaxy surveys is in tension with the one predicted from the CMB [Planck Collaboration et al.(2019)]. Cosmology seems to be at the edge of a crisis, and one way to reveal new physics beyond the standard model is through the advent of the new generation spaceborne experiments and of high resolution ground based CMB telescopes.
The next generation of experiments therefore must not only achieve higher precision and make an unambiguous detection of inflationary B-modes, but eventually also precisely measure the distortion of the CMB spectrum which is becoming an important and complementary tool. By distortions we mean those produced from the out-of-equilibrium energy exchange between matter and radiation before the last scattering surface and through the inverse Compton scattering by high-energy electrons in galaxy clusters. In this case, the low-energy CMB photons receive an overall energy boost during collisions with the high-energy cluster electrons (Sunyaev–Zel'dovich effect). Based on these scientific motivations, several ground-based experiments such as ACT [Salatino(2017)], BICEP3/Keck Array [Bischoff(2018)], SPT [Pan(2019)] and Polar Bear [Lee et al. 2008] have been deployed, and future ground-based CMB Stage-4 experiments [Keating(2019)], Simons Observatory [Ade et al. (2019)] and space mission LiteBIRD [Lee et al.(2019)] have been proposed. Current experiments have a focal plane on the order of 10,000 detectors which improves the mapping speed by at least one order of magnitude in comparison to that of the first generation precision cosmology experiments.

New generation cryogenics detectors Kinetic Inductance Detectors (KID) are now mature enough to answer to these challenges in particular thanks to their sensitivity, the assembly simplicity, and the possibility to arrange them in in large arrays.

Kinetic Inductance Detectors: KIDs are a particular type of non-equilibrium superconducting photon detector, where incident radiation is absorbed in a superconducting material which is arranged in a resonant circuit. They were first developed by Peter Day and other scientists at the California Institute of Technology and the Jet Propulsion Laboratory in 2003 [Day et al.(2003)]. The primary attraction of KIDs is that, unlike most of the other low temperature detectors, they present several advantages:

- Easy to fabricate, in most cases, a single layer deposition is sufficient (a week is necessary to make them, two weeks to test them, compared with other technologies where the lifecycle is more like a year).
- Very sensitive, reaching the photon noise limit for most applications.
- They can be used in a very broad band.
- Fast, with a small time constant (from tens of microseconds to hundred of microseconds) for a large range of optical loads.
- Highly multiplexed (which means that making large arrays is simple).
- Relatively insensitive to micro-phonics and Electromagnetic interference (EMI).
- Insensitive to the base temperature fluctuations

In order to absorb incident millimetre and submillimetre radiation, it is necessary to match the impedance of the detector absorber to free space. In the case of KIDs developed by our collaboration we use *Lumped-Element* KID (LEKID) where the inductive meander section is designed to act as a solid absorber for the target frequencies. By accounting for the resonator and substrate impedance and the cavity formed with the sample holder, it is possible to directly impedance match the LEKID to free space [Doyle et al.(2010)].

Our development is driven by the scientific cosmological context as expressed in the previous section. In this direction we have both a fundamental R&D on the detectors-readouts, and an instrumental program in order to develop and optimize photometers, polarimeters and interferometers devoted to observe galactic polarization and CMB B-modes (NIKA2 and ongoing discussions on a participation to the Stage-4 network), distortion of the CMB spectrum via the S-Z effect (NIKA2, KISS and CONCERTO) and intensity line mapping (CONCERTO).

Experimental Context and KID R&D

The goal of our development is directly related to the preparation of the next generation instruments dedicated to sky observations in the (sub)millimetre domain. More in detail:

● ***Short-term goal*** *(2021-2023)*: maintaining activity with existing instruments NIKA2 and CONCERTO. Ensuring upgrades to increase the performance. Design, simulation and first prototype fabrication of on-chip spectrometers.

● ***Mid-term goal*** *(2023-2025):* Begin studying the design for S4-like instruments. Development of first large arrays of on-chip spectrometers.

● ***Long-term goal*** *(2025-2030):* be ready to deploy S4-like experiments. Be a valid candidate for covering the focal plane of the next generation space mission devoted to the CMB B-modes of polarisation or/and CMB spectral distortions.

In order to meet these goals, it is mandatory to have a continuous R&D on KID detectors and the related readout electronics. For the following years our plans, already expressed in several forms (as for example CNES working group on mm and sub-mm LEKID and instrumentation, Labex FOCUS road map, prospectives IN2P3 - GT05), are to consolidate our range of action both in the frequency coverage (60-600 GHz, from the present 120-360 GHz) and in dynamic range (space conditions such as lower background, down to 0.5 pW per pixel compared to 5-10 pW at present) and cosmic rays susceptibility. Up to date these studies have been essentially focused on single pixel optimisation. For the incoming years we need to transfer our knowledge on bigger arrays of detectors (of the order of few 10k-pixels or more). Together with the development directly related to the KID, we also study all the aspects related to the readout and more in general the instrumentation.
In the mid-term/long-term timescale we also develop in parallel on-chip spectrometers using KIDs. The aim is to improve, at least for small patches of the field-of-view and without affecting the overall optics, the sensitivity and spectral resolution of our future instruments. A simple slot microstrip antenna with low loss dielectric will be used to obtain a relatively wide bandwidth. The first prototype, in the range 80 GHz to 110 GHz, i.e. the so-called “3-mm atmospheric window” is already in development for the design and simulation.

Readouts

Intrinsic Frequency Division Multiplexing (FDM) makes the KID detectors a very competitive technology compared to others. Programmable digital electronics is used to perform a fully synchronous transmission measurement of the arrays of KIDs detectors. The readout electronics for KID consists of :

● The cold electronics: it is simple and it consists of a small number (one per 250-500 pixels) of cryogenic low-noise amplifiers mounted at a physical temperature of 4K and coaxial cables. For the future, the plan is to enlarge the know-how on cryogenic ASIC design to GHz range for KID readout using SiGe technology. Ultra-low noise and wide dynamic range amplifiers will be specifically designed for the KID purpose.

● The warm readout: the existing electronics allows today a multiplexing factor in the order of 400, for a total bandwidth of 1GHz. For future instruments, new boards must handle a higher multiplexing factor and a wider bandwidth in order to be able to readout 10k-pixels arrays with a reduced number of boards. Today for example CONCERTO (4,000 on-sky pixels), requires twelve readout boards.

CONCLUSIONS AND PERSPECTIVES

KID for millimetre and submillimetre sky observations is one of the most active areas of research, with several groups in Europe, United States and Japan actively developing detectors and KID-based instruments. Today, several instruments observe the millimetre sky using large-format focal plane arrays. A number of projects operating at millimetre (ToITEC [Toltec web page], SuperSpec [Shirokoff et al. (2014)], GroundBIRD [Nagasaki et al. 2018], OLIMPO [Paiella et al.2020]) and submillimetre (AMKID [Baselmans J. 2018], Deshima [Takekoshi et al. 2020], BLAST-TNG [Galitzki et al (2014)]) wavelength. The first instrument making science with KID was the first prototype, NIKA, detecting the cluster of Galaxy RX J1347.5-1145 via the Sunyaev Zel'dovich effect in February 2012 [Adam et al. 2014]. This instrument was designed, fabricated and exploited by our collaboration.

To date, experiments designed specifically to measure the CMB have been led by instruments based on arrays of transition edge sensors (TESs) [Benson et al. 2014, Thornton et al. 2016]). State-of-the-art CMB experiments are at *Stage 2-3*, with focal planes containing 5000–10,000 TES. KID are coming into play in particular thanks to the discussions in progress for a participation of our collaboration in the Stage-4 network. Further improvements in sensitivity can only be achieved by increasing total focal plane area and number of detectors which is a significant technological challenge. The advantages of KIDs could therefore play an important role in this sense.

IN2P3 has a strong implication on these activities. In particular in terms of direct costs (personnel, equipment, maintenance, etc...) about 14 engineers and 7 scientists are involved in this R&D including LPSC, CSNSM and APC. The critical parts of the developments described in this document are designed and often fabricated in-house. The fabrication of the most challenging sub-systems will be done in our labs by our highly-skilled technical groups. Local subcontractors will be in charge of the standard (lower cost and risk) mechanics and electronics subsystems. This makes the cost of this development plausible. We think that it is very important that the French community maintains and develops its expertise on CMB science related instrumentation. Few key persons are still in a non-permanent position therefore there is a high risk coefficient that skills are lost in the years to come. In addition, the growing number of projects requires a growing man-power.

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