Contribution Prospectives 2020

Cosmologie millimétrique du futur: développements instrumentaux critiques.

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Abstract:

The goal of this document is to show and argument the effort of the R&D activities on experimental cosmology within the collaboration of IN2P3 laboratories (APC, CSNSM, LAL and LPSC), INP (Institut Néel) and INSU (IPAG) laboratories. This collaboration has strong roots starting with the Grenoble collaboration (Institut Néel, LPSC and IPAG), which has pioneered the utilisation of Kinetic Inductance Detectors (KID) at millimetre frequencies through the NIKA2 instrument (dual-band, dual-pol, 3.5 k-pixels) observing the millimetre sky from September 2015 at the IRAM 30-m telescope at Pico Veleta. The Grenoble collaboration will be consolidated through a GIS (*Groupement d'intérêt scientifique*). In a parallel development, APC and CSNSM have designed and implemented superconducting detector arrays and the associated multiplexed readout electronics for the QUBIC project as well as carrying out preliminary work on antenna coupled devices. Today, all these laboratories participate together to the preparation of the next generation instrument based on KID technology for cosmology and millimetre science. In order to be a competitive candidate for the next generation instruments devoted to cosmology, we need to develop and test new focal plane with tens of thousand 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 the detector technology.

INTRODUCTION

The scientific picture, which drives this development, is essentially focused on the study of primary and secondary anisotropies of the Cosmic Microwave Background (CMB) and the distortion of the spectrum. In Particular: **CMB B-mode** of polarisation (main scientific topic for the S4 collaboration [1]), **Sunyaev Zel'dovich** effect (already investigated by k-pixel KID array instrument NIKA2 [2] and in the next future by KISS [3] and CONCERTO [4] KID arrays interferometers), **Distortion of the CMB spectrum** (needs observations from space using spectrometers or interferometers), **Foregrounds from dust emission** (high frequencies instruments for balloon or space applications). Based on these scientific cases, we have both a fundamental R&D on the detectors-readouts, and an instrumental program in order to develop and optimise photometers devoted to observe polarization (we are negotiating a participation to the S4 network), and spectrometers to observe distortion of the CMB spectrum and S-Z effect (KISS and CONCERTO instruments).

Considering the sensitivity of existing CMB-dedicated ground-based experiments such as ACT [5], BICEP2/Keck [6], SPT [7], Polar Bear [8] and expectations for upcoming CMB Stage III experiments, characterised by of order 10,000 detectors as the Simons Array [9] and the LAT experiments [10], it is obvious that access to an experiment with the same order of detectors will be needed to remain at the forefront of CMB science. While it is not the case in the US, in France, for the 50 to 300 GHz frequency range, Kinetic Inductance Detectors (KID) are currently the most advanced solution in terms of technology readiness. It has been shown with the NIKA2, 3,000-pixel camera that KIDs can have Background Limited Instrument Performance (BLIP) for ground-based applications in the range of frequencies between 120 and 300 GHz.
The final goal of all this 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*** *(2019-2020)*: maintaining activity with existing instrument NIKA2 and KISS ensuring upgrades to increase the performances.
- ***Mid-term goal*** *(2020-2024):* installation of CONCERTO (2021). Maintain the observations for several years. Begin studying the design for S4-like instruments.
- ***Long-term goal*** *(2024-2030):* be ready to answer to the expectations of the S4 network. 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.

EXPERIMENTAL CONTEXT

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),

are to extend our range of action both in the frequency coverage (60-600 GHz, from the present 120-300 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). We also work on the different architectures of the planar antennas coupled with KID (antenna-coupled KID) in order to reduce the size of the focal plane and to be directly sensitive to polarisation. We complement these studies by our “spectroscopic” work carried on in parallel and described in this document. In parallel to these studies which are essentially focused on single pixel optimisation, we transfer our knowledge on bigger arrays of detectors (of the order of few 10k-pixels). Together with the development directly related to the KID, we study also all the aspect related to the readout and more in general the instrumentation.
In particular we can distinguish and detail four axes of objectives that we want pursuit:

LEKID Detectors

- *Low-frequencies (50-100 GHz):* since the frequency range below 120 GHz is not accessible using pure Aluminum KIDs due to the superconducting gap cut-off, we propose to investigate new materials, alloys and multi-layers in order to acquire the best performance in the range of frequencies between 60 and 120 GHz approaching a Noise Equivalent Power close to the one of photon noise limited detectors for typical ground-based and space-borne optical loads.
- *CMB frequencies (100-300 GHz):* Aluminum KID (LEKID) represents the state-of-the-art in this frequency range. Our collaboration will actively maintain the design, production, and testing processing of such technology in order to ensure best performance and upgrades for existing instrument (NIKA2) and will optimise and test such technology for next generation instruments (S4 network as Simons observatory and LAT). In parallel, this technology will be adapted for space application.
- *High frequencies (300-600 GHz):* this development is devoted to balloon-borne and space-borne applications. The goal is to design, optimise and test arrays of KID in the bands 320-400 GHz (centred on 360 GHz) and 450-650 GHz (centred on 550 GHz). The goal of this study will be primarily to demonstrate that even for bands centred at 360 and 550 GHz we can establish the capabilities of Aluminum LEKID in the whole band of interest. On the other hand, we investigate new higher-Tc superconducting materials as Tantalum or Vanadium lie in the matching of the superconducting gap with the band to be detected.
- *Broadband KID for interferometry:* The peculiarity of the interferometric application is the requirement for a very large bandwidth of operation: for example, 80-300 GHz for the KISS instrument and 120-400 GHz for CONCERTO instrument. This includes in principle three distinct atmospheric windows. This requirement imposes strong constraints on the detectors and optics design.

Antenna-coupled KID

Today, only simple absorbers are used with LEKIDs. While simple, the use of an absorber has the disadvantages of being not intrinsically sensitive to polarisation and sensitive to a very large solid angle. This last point especially leads to the need of using heavy horns or cold Lyot stop to couple detectors with the telescope in order to control side-lobes to very low level as required to detect the tiny B-mode signal on the sky. The aim of this project is therefore to go further to what is being developed for antenna-coupled cryogenic detectors and replace heavy horns with planar structures able to get performances as close as possible to horns. This work package will allow the development for the first time of a multi-band planar polarisation sensitive architecture based on a planar broadband antenna coupled to LEKIDs. This architecture paves the way for a simplification of the focal plane of a future space instrument. It may also be applied to ground or balloon instruments, which will also increase the maturity level of these technologies. In particular, the European scientific community is considering a contribution to a large ground instrument (S4 project) with a focal plane of several hundred thousand detectors. The architecture we will develop in this project will be perfectly adapted to an instrument of this type because it will reduce the surface area of the focal plane and thus benefit from better optical performance.

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 250-500, for a total bandwidth of 500 MHz. For future instruments, new boards must handle up to 1 GHz of band. For 3,000 pixels, the experiment will require no more than twelve readout boards.

General Instrumentation

In order to focus light into the KID arrays, modulate the polarisation or produce interference, we need to optimise optical elements specifically designed to work with KID detectors. All these aspects have to be designed and fabricated and tested first in laboratory in order to mimic as much as possible the environment of a given experiment, then implemented in the instrument and installed properly in situ. In our laboratories we have complementary skills related to the cryogenics, mechanics, optics, readout and software which permitted to design and install new instrument based on KID technology. For the future we need to acquire more skills in AR-coating techniques on curved silicon dielectric coating using thermal compression; dicing saw machining; silicon grain pulverisation; 3D lithography. More, we need to enlarge the competence in handling the data acquisition and processing of KID-based instruments in the different laboratories of the collaboration.

CONCLUSIONS AND PERSPECTIVES

IN2P3 has a strong implication on the activities described above. In particular in terms of direct costs (personnel, equipment, maintenance, etc...)about 14 engineers and 4 scientists are involved in this R&D including LPSC, CSNSM and APC. The Néel Institute is strongly involved as well with 6 engineers and 1 scientist.
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.
We have already developed wide competences on KIDs detection chain development and fabrication. We have a plan to enlarge it and further develop new characteristics of the detectors and improve their readout electronics. The aim of this program is to be recognized as key partners in Europe for the next generation of instruments devoted to cosmology through the observation of the sky in the submm domain.

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