C. R. Physique 18 (2017) 323–330

Contents lists available at ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

Prix Gustave-Ribaud de l'Académie des sciences 2016

Superconducting millimetre-wave cameras

Caméras supraconductrices millimétriques pour l'astronomie

Alessandro Monfardini

Institut Néel, CNRS and Université Grenoble Alpes, 25, rue des Martyrs, 38042 Grenoble cedex 9, France

ARTICLE INFO

Article history:
Available online 19 May 2017

Keywords:
Millimetre astronomy
Superconducting detectors
Kinetic inductance
Multiplexed electronics

Mots-clés :
Astronomie millimétrique
Détecteurs supraconducteurs
Inductance cinétique
Électronique multiplexée

ABSTRACT

I present a review of the developments in kinetic inductance detectors (KID) for mm-wave and THz imaging-polarimetry in the framework of the Grenoble collaboration. The main application that we have targeted so far is large field-of-view astronomy. I focus in particular on our own experiment: NIKA2 (Néel IRAM KID Arrays). NIKA2 is today the largest millimetre camera available to the astronomical community for general purpose observations. It consists of a dual-band, dual-polarisation, multi-thousands pixels system installed at the IRAM 30-m telescope at Pico Veleta (Spain). I start with a general introduction covering the underlying physics and the KID working principle. Then I describe briefly the instrument and the detectors, to conclude with examples of pictures taken on the Sky by NIKA2 and its predecessor, NIKA. Thanks to these results, together with the relative simplicity and low cost of the KID fabrication, industrial applications requiring passive millimetre-THz imaging have now become possible.

RÉSUMÉ

J'expose les récents développements concernant les détecteurs à inductance cinétique (KID) appliqués à l'imagerie-polarimétrie millimétrique et THz. Ces développements s'inscrivent dans une collaboration grenobloise. J'insiste en particulier sur la description de notre caméra NIKA2 (Néel IRAM KID Arrays 2), qui est aujourd'hui la plus grande caméra millimétrique disponible pour des observations ouvertes à l'ensemble des astronomes. NIKA2 est un instrument double bande capable de séparer la polarisation du rayonnement incident. Il est installé sur le radiotélescope de 30 mètres de l'Iram (Institut de radio astronomie millimétrique) au Pico Veleta (Espagne). Après avoir décrit le contexte physique et instrumental dans lequel se situent ces études, je présente quelques exemples d'observations effectuées par NIKA2, et son prédécesseur NIKA.

E-mail address: alessandro.monfardini@neel.cnrs.fr.

http://dx.doi.org/10.1016/j.crhy.2017.05.002
1631-0705/

1. Introduction

Low-temperature detectors are, for a number of applications requiring extreme sensitivity, essential. In fact, the thermal noise "hides" the tiny amounts of energy that we try to resolve. Moreover, these small amounts of energy can only be measured adopting even smaller "units" like individual excitations in superconductors (quasi-particles) or ultra-low temperature phonons (quanta of lattice vibrations). This is why the ultimate search of sensitivity ends up inexorably in lowering the temperature of the sensing part until reaching almost the absolute zero. In most cases, modern cryogenics detectors contain superconducting elements.

Superconductivity arises, below a given critical temperature T_c and for selected materials, thanks to an effective attractive force between electrons. Each electron "polarizes" the surrounding medium (lattice + electrons), generating a net excess positive charge. This charge will in the end be able to attract other electrons. This mechanism, that is submitted to the laws of quantum mechanics, leads to the formation of the so-called *Cooper pairs*, i.e. systems of coupled electrons. A minimum energy, the superconducting gap, is required to break the link within the pair. At $T < T_c$, the Cooper pairs, also known as superconducting carriers, cannot be split by thermal phonons. They can thus live in the lattice itself. Under the action of an external electric field, they will move without the Ohmic losses associated with the electron–phonon interaction. At $T > T_c$, the attractive force is still present, but too small to win against the thermal agitation of the lattice.

When a Cooper pair, for any reason, is broken, the two resulting electrons living in the peculiar sea of Cooper pairs and the lattice are called *quasi-particles*. At any non-vanishing temperature below T_c, a given number of quasi-particles co-exist with the Cooper pairs (two-fluid model).

The "fragility" of all these mechanisms for low-T_c ($< 4K$) superconductors is extremely useful for detection applications. The lower the critical temperature is, the less energy is needed to perturb the microscopic equilibrium. This is the base of the use of superconductors as building blocks for ultra-sensitive detectors. For example, incident photons exceeding twice the superconducting gap energy ($2 \cdot \Delta_g \approx 3.6 \cdot k_B \cdot T_c \approx 0.3$ meV, equivalent to a wavelength of roughly 4 mm, in the case of a critical temperature of 1 K) result in pair breaking and a concurrent rise of the quasi-particle density. At sufficiently low temperature ($T << T_c$), and in high quality films, these non-equilibrium quasi-particles exhibit a long lifetime due to the low quasiparticle–phonon interaction. For example, typical lifetimes in high-quality aluminium films at 100 mK can exceed a millisecond. For certain specific geometries, in particular very thin films, the elevated quasi-particle density results in a change in the surface reactance of the material. In normal metals, the inductive reactive energy is stored in the magnetic field generated by the current itself. In superconductors, an additional energy is stored by the Cooper pairs, accelerating without losses and in consequence accumulating kinetic energy. This (kinetic) energy translates, electrically, into an additional inductance term named "kinetic inductance", L_k. The number of Cooper pairs, modulated by the incoming pair-breaking radiation, determines the value of L_k and the electrical behaviour of the superconducting film itself.

It can be demonstrated that for thin, e.g., $t < 40$ nm for Al, $T_c = 1.4$ K, superconducting films, the kinetic inductance, and the detectors sensitivity, is inversely proportional to the film thickness, t. Kinetic inductance detectors (KID) harness this changing reactance of the superconductor by embedding it in a high-quality resonant circuit electromagnetically coupled with a transmission line. Slight deviations in the kinetic inductance results in a measurable shift in the resonant frequency of the device.

In order to achieve the best detection (e.g., a faint primordial galaxy, the cosmic microwave background polarisation, dark matter, double beta decay or any other challenging item like these), the largest number of detectors, each exhibiting the best achievable sensitivity, is required. In these severe environmental conditions, the practical problem of wiring thousands of "pixels" (or detectors) down to the absolute zero becomes so important to drive in most cases the design of our instruments. For these reasons, we have since 2009 oriented our developments toward the amazingly versatile KID (kinetic inductance detectors) technology. A complete review of the rich physics underlying superconducting microresonators, the basic KID component, is beyond the scope of this document. Please refer to [1] for further details.

2. Millimetre and sub-millimetre astronomy

For thousands years, until the 1930s, astronomical observations have been restricted to the narrow visible band. The first detection of extraterrestrial radio-waves, peaking toward the constellation of Sagittarius [1], was for a long time almost ignored by most of the astronomers. Despite that, in 1935, Jansky was already speculating about the origin of the "radio excess noise", attributing it to an ionized interstellar medium. Military technological developments during World War II allowed, in the 1940s, the real birth of the new "radio-astronomy". Since then, instrumental developments tend steadily toward higher sensitivity, higher angular resolution and shorter wavelengths (higher frequency). In fact, millimetre and sub-millimetre, i.e. where the radio meets the IR, is traditionally tricky from the instrumental point of view. The real boosts for specifically developing mm-wave instrumentation came from the discovery of the Cosmic Microwave Background (CMB) in 1965 [2], and the first detection, in 1970, of the 2.6-mm CO molecular lines [3]. The related questions concerning the origins and evolution of the Universe are evident. The CMB is the top observational evidence of the Big Bang, having changed forever our perception of the once immutable cosmos. On the other end, the presence of several molecules in the interstellar medium shows clearly that the rich chemistry of our Solar System is not an exception in the Galaxy. This consideration justifies concrete hopes for detecting extra-solar life.

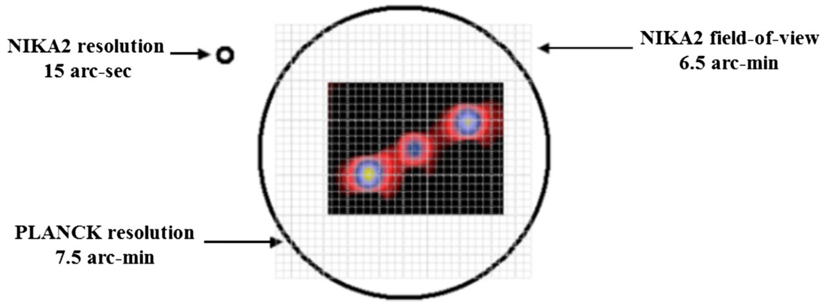

Fig. 1. NIKA2 angular resolution (150 GHz) and field of view compared to one *Planck* beam. The famous Cygnus A radio-galaxy, mapped by NIKA, is shown in the inset (real data). While NIKA and NIKA2 maps are clearly showing the morphology of the jets and the radio-lobes, *Planck* only sees a single blob.

The development of large arrays of detectors coupled with single-dish telescopes operating at millimetre and THz wavelengths is motivated by (a) the study of the star forming regions in the Galaxy; (b) the investigation of high red-shift (distant) galaxies, and (c) the measurement of CMB temperature anisotropies (either primordial or induced along the line of sight) [4].

The complete understanding of the physical processes determining millimetre emission of celestial sources is only possible thanks to the combination of a survey (e.g., Planck satellite), pointed observations of singles dishes from the ground (e.g., NIKA2), and in-detail study of small regions from large interferometers.

Thanks to the efforts of the low-temperature physics community during the past decades, the state of the art today shows multi-thousand pixels, i.e. large-field-of-view imaging cameras operating at these wavelength and installed on big telescopes. Our NIKA2 imager/polarimeter at the 30-m telescope is for example the most spectacular example of a general-purpose camera operating in the band 100–300 GHz. Other instruments, using different focal plane technologies (bolometers), are operating mainly at higher frequencies ($\geq$ 350 GHz) and on smaller (10-m class) telescopes. Concerning interferometric observations, the ALMA (Chile) and NOEMA-IRAM (Plateau de Bure, French Alps) telescopes arrays allow one to study very small patches of the sky with much higher angular resolution. The *Planck* satellite, to which our Institute has significantly contributed with the 0.1-K space-compatible dilution refrigerator [5], has provided a unique all-sky survey in the range $30 \div 850$ GHz. This achievement was possible thanks to the clean deep space environment, i.e. free from the atmosphere and the Earth thermal emissions. Planck was however a small telescope (1.5 m), dedicated only to the survey purposes and not designed to target (point) and integrate particular sources. NIKA2, thanks to the bigger telescope, is able to resolve a single Planck beam (“pixel”). In fact, the whole NIKA2 array footprint on the Sky is roughly as big as a single Planck pixel (see Fig. 1). Moreover, the large collecting area makes NIKA2 much more sensitive. For a single pointing, NIKA2 is able to achieve the *Planck* survey sensitivity in much less than one second of integration time. As a consequence, NIKA2 can detect weaker sources, by orders of magnitude, than *Planck*.

Among the main science goals of NIKA2 is the study of a cosmologically representative sample of galaxies clusters through the Sunyaev–Zeldovich (SZ) effect. Through their path toward us, the CMB photons interact with free hot electrons within the clusters. Following this interaction, a small fraction of the primordial photons is moved to higher energies, with a resulting flux decrement (increment) at frequencies below (above) about 220 GHz. The amplitude of the spectral deformation is proportional to the integral of the pressure of the electron population along the line of sight, and contains important information about the cluster physics.

3. Kinetic inductance detectors

A KID is a properly shaped superconducting film able to change his surface impedance in consequence of radiation absorption. This causes a perturbation of the kinetic inductance $Ł_k$, associated, as explained above, with the kinetic energy of the superconducting charge carriers, i.e. the Cooper pairs. If the film is integrated into an LC resonating structure, the inductance change translates into a shift of the resonance frequency. The natural resonance frequency is in fact equal to $f_0 = (2 \cdot \pi \cdot L \cdot C)^{-0.5}$. A parasitic resistive term is always present in real LC resonators. For each oscillation cycle, a part of the energy is thus dissipated, breaking the otherwise perfect monocromacity of the frequential response. In superconductor resonators, the resistive term can be extremely small, allowing reaching very high quality factors Q.

The Q-value in a KID acts as a kind of “internal gain”, providing also the opportunity of placing many (e.g., hundreds to thousands) such resonators, tuned by design at different frequencies, on the same readout/excitation line. This is precisely the concept of RF frequency multiplexing (see Fig. 2).

When designing a KID, the resonance frequency is tuned by setting the geometry of the resonant section pixel-per-pixel. The design of the coupling area between the resonator and the feedline is also of importance as it affects the external quality factor Q_e. By moving the KID away from the feedline, i.e. reducing the coupling capacitance C_c, the Q_e increases. As a result, the resonance dip shrinks. The use of electromagnetic simulation tools is unavoidable to find a good trade-off.

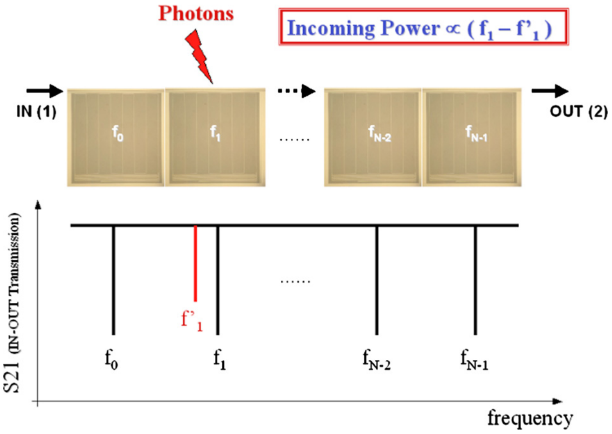

Fig. 2. KID working principle.

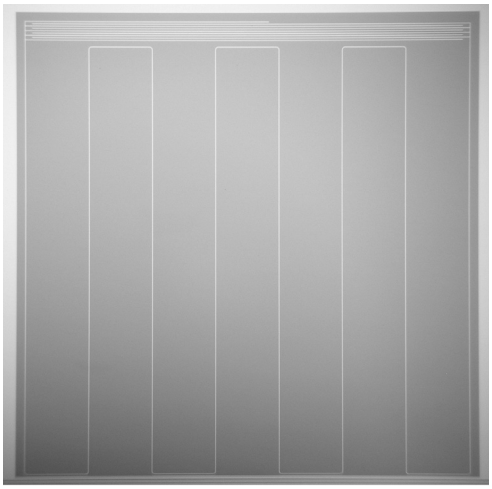

Fig. 3. A classical (single-polarisation) LEKID pixel micrograph. Dark regions are silicon, bright areas are the thin aluminium film making the detector itself.

The performances of KID devices depend on multiple parameters: The sensitivity, for example, is related to geometrical aspects such as device volume and film thickness. As for other Cooper-pair-breaking detectors, the KID sensitivity scales with the quasi-particles lifetime τ_{qp} which is material related but also depends on the quality of the deposition process. The choice of the material affects the sensitivity also because it determines the value of the kinetic inductance fraction in the resonant circuit. The photon frequency detection threshold is governed by the energy gap: $\nu_{\rm min} = 2\Delta_g/h \approx 3.6 \cdot k_{\rm B} \cdot T_{\rm c}/h$. So far, most millimetre-wave applications adopt aluminium films ($\nu_{\rm min} \approx 100$ GHz). The KID fundamental limitation comes from the statistics of quasiparticle generation and recombination.

As for now, two main KID designs have been proposed. The first one, known as distributed KID, consists of a standard quarter-wave CoPlanar Waveguide (CPW) [6] whose short-ended extremity is coupled, for example, with an antenna. Micro-lenses are usually employed to focus the radiation onto the antenna. Associated with planar microwave filters, this approach allows frequency selective applications. I have opted, for my part, for the second configuration, proposed by the group of the University of Cardiff and referred to as Lumped Element KID or LEKID [7]. LEKID comprises an inductive meander section and a interdigital capacitor. The meander exhibits little current variations along its length and can be shaped to act as a radiation absorber. By tuning the width, the geometry and the number of meandered lines, one can impedance-match the absorber to the free space. By adopting either a classical configuration presented in Fig. 3, or a peculiar fractal geometry that we have invented, one can select sensitivity to one or both polarisations of the incoming radiation [8]. Finally, optimal optical coupling is achieved by adding a reflective back-short tuned to the band of interest. This device employs only one layer of metal, with thickness usually lower than 30 nm. Its fabrication is very simple, still ensuring a quantum efficiency approaching 100%. The strongest point in using KID detectors compared to more classical bolometers is actually the ability of multiplexing a lot of channels on the same read-out electronics. For this reason, we are continuously developing new electronic systems based on FPGA (Field Programmable Gate Array) and able to handle the more and more detectors with

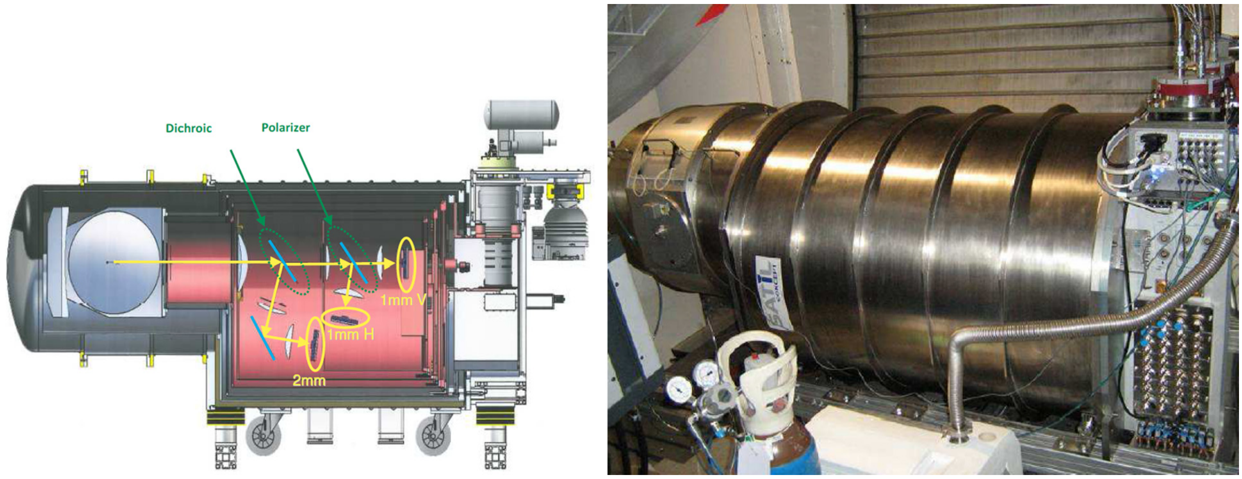

Fig. 4. The big (1.3 tons, 2.5 m in length) NIKA2 camera. Left: the optics scheme characterised by the presence of a dichroic to split the two bands (lower frequencies are reflected on the 2.0-mm array) and a polarizer projecting the modulated polarisation onto two arrays H and V operating at 1.15 mm. Right: a picture of NIKA2 in the telescope receivers cabin.

steadily increasing performances [9–11]. In parallel, we are continuously improving the real-time data conditioning routines, mostly motivated by the need of linearizing the electrical response of the resonators and adapt them naturally to detection applications [12].

4. The Néel IRAM KID Arrays 2: the big millimetre eye on the sky

The New IRAM KID Arrays 2 (NIKA2) is a dual-band camera operating with three frequency-multiplexed kilopixels arrays of lumped-element kinetic inductance detectors (LEKID) cooled at 150 mK. NIKA2 is designed to observe the intensity and polarisation of the sky at wavelengths of 1.15 and 2.0 mm from the IRAM 30 m telescope. The NIKA2 instrument represents a huge step in performance as compared to the NIKA pathfinder instrument, which has already proved to be a state-of-the-art detector and shown photometric performance on a smaller field of view [13–15]. The camera has been permanently installed at the IRAM 30-m telescope in October 2015 [16,17], and is expected to be available to the broader astronomical community in 2017. The targets of the NIKA2 camera are to perform simultaneous observations in 2-mm bands (1.15 mm and 2.0 mm) of very faint point sources as well as to map extended continuum emission up to about 6.5 arcmin scale, and beyond, with diffraction limited resolution and background limited performances. In addition, the NIKA2 instrument hosts polarisation capability in the 1.15-mm arrays. The adopted solution is the use of a rotating warm Half-Wave-Plate (HWP) to modulate the astrophysical polarised signal and a polariser mounted at the 100-mK stage to analyse the linear polarisations on the two 1.15-mm arrays. These specifications will make NIKA2 a revolutionary instrument for the coming years.

Cooling down the three KID arrays at a nominal temperature of 150 mK is the major requirement that drove the architecture of the NIKA2 instrument. The cryostat has been designed at the Néel Institute and it consists of about 3000 mechanical pieces for a total weight of 1.3 tons. The cool-down process is completely remote-controlled and does not require cryogenics liquids. The whole process lasts about 5 days: four full days of pre-cooling (down to 4 K) and about one day, with the dilution at work, to reach the base temperature (see Fig. 4).

The NIKA2 detectors are lumped-element kinetic inductance detectors (see Fig. 5). In order to ensure a safe up-scaling between the 300 pixels of NIKA up to the 3000 of NIKA2 we have adopted new microstrip resonators, more robust and reliable for very large arrays due to the purest RF properties of the microstrip configuration and the reduced technological constrains. In this way, we have augmented the arrays production yield from less than 50% to more than 90%, preserving the same final performance.

5. Example of observations with NIKA and NIKA2

The Universe in which we live today has been shaped by the gravitational collapse of large-scale structures that started to form about 14 billion years ago, right after the Big Bang. Today, the largest gravitationally bound objects, which constitute the building blocks of our Universe, are the clusters of galaxies. Despite their name, galaxy clusters are mainly composed of dark matter ($\approx$ 85%) and hot ionized gas ($\approx$ 12%), with only a few percent of the mass contained in galaxies. Cluster formation is driven by the gravitational collapse of the dark matter, the gas and the galaxies are simply "following" this process. During their assembly, clusters can collide with high velocity. These mergers are the most energetic events since the Big Bang and are fundamental to understand the assembly of structures in the Universe.

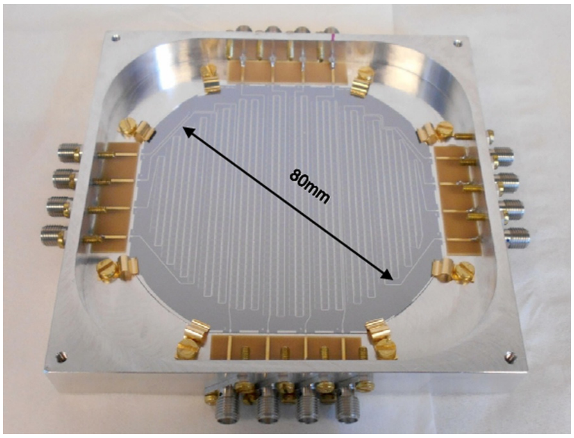

Fig. 5. The NIKA2 detectors are microstrip-feed resonators. I show here a picture of one of the 1.15-mm arrays actually mounted in NIKA2. The connections to the readout electronics are provided by superconducting micro-bondings, 50-Ω launchers pads and SMA connectors.

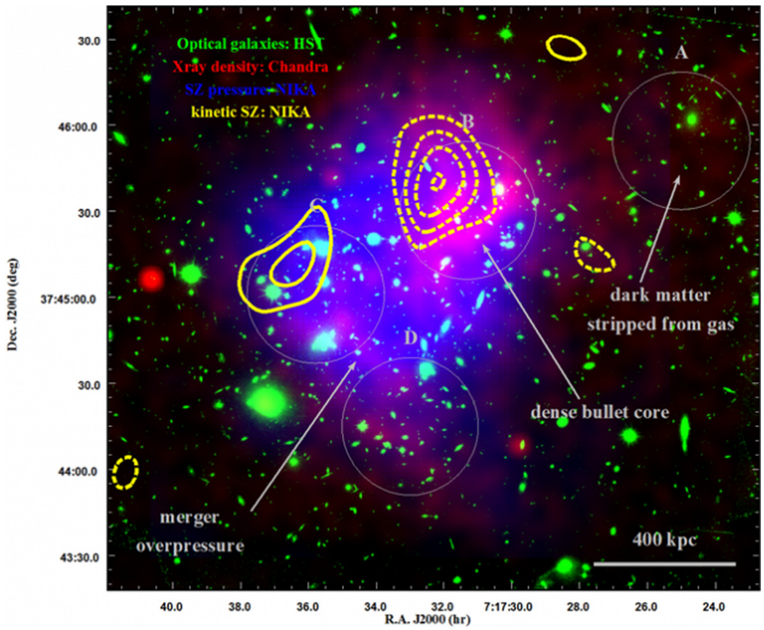

Fig. 6. Multi-wavelength image of the galaxies cluster MACS J0717.5+3745 showing the galaxy distribution (green, Hubble Space Telescope data), the gas electron density (red, Chandra X-ray data), the gas electron pressure (blue, NIKA) and the kSZ signal (yellow contours, NIKA). Solid yellow contours indicate regions of the clusters that are moving toward us, dotted lines show regions moving farther. Taken from [18].

One way to study the velocity of clusters is to measure the imprint of their motion in the Cosmic Microwave Background (CMB) radiation through the use of the kinetic Sunyaev–Zeldovich (kSZ) effect. This effect arises from the Doppler shift of CMB photons when they interact with fast-moving electrons in the intra-cluster gas. The kSZ effect is the only known way to directly measure the peculiar velocity of objects at cosmological distances, because unlike other methods, the CMB radiation itself provides an absolute reference for the measurement.

NIKA, opened to the astronomical community for the period 2014–2015, has obtained for the first time an image of the gas velocity in a merging cluster of galaxies (see Fig. 6).

The NIKA2 bigger camera will be able to routinely carry out this kind of measurements, following the path opened by NIKA. The NIKA2 camera is currently undergoing the science commissioning phase, during which the astronomers execute a large number of tests intended to establish the performance and stability of the instrument. During the commissioning, however, we could point, detect and map a number of scientifically interesting sources. We provide in Fig. 7 just one representative example of a first light image obtained on DR21OH with a integration of only a few minutes. DR21OH is a well-known star forming region inside the Cygnus X molecular cloud complex.

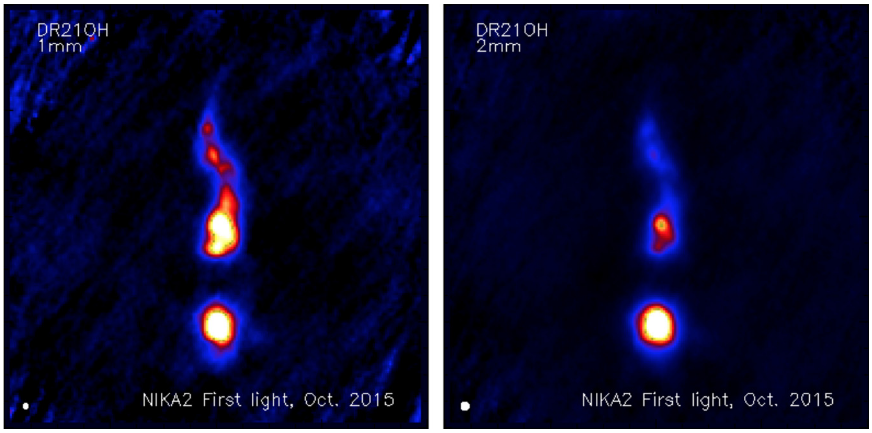

Fig. 7. Preliminary map of DR21OH observed at 1.15 and 2 mm. Maps are 13 arcmin large, the angular resolution in each band is represented as a white disk at the bottom of the images.

The big improvement of NIKA2 with respect to NIKA consists in a one-order-of-magnitude increase in the instantaneous field of view. This allows gaining a factor of around ten in the integration time (or in the so-called “mapping speed”) in the case of extended sources. NIKA2 will be available, via semestral calls, to the international astronomical community for the next ten years.

6. Conclusions and plans

In the framework of our collaboration in Grenoble, we have pioneered the development of large millimetre-wave cameras. Our main driver, as is often the case for new detectors, has been Astronomy. Key parts of the NIKA cameras, like for example the design of the detectors and the readout electronics, have inspired the first prototype instrument dedicated to the use of millimetre imaging for security applications [19]. Our developments have for the first time demonstrated on the field the great potential of the KID technology and opened the way to a number of practical applications, in which KID are going to replace the more expensive and fragile low-temperature bolometers.

Acknowledgements

The results that I have summarized here represent a collective effort of the NIKA2 international Consortium, under the joint coordination of Alain Benoît and myself. I acknowledge the financial support of a number of agencies including ANR, CNES, CNRS, Nanoscience Foundation, LabeX FOCUS and others.

References

[1] J. Zmuidinas, Superconducting microresonators: physics and applications, Annu. Rev. Condens. Matter Phys. 3 (2012) 15.1.
[2] A.A. Penzias, R.W. Wilson, A measurement of excess antenna temperature at 4080 mc/s, Astrophys. J. 142 (1) (1965) 419–421.
[3] R.W. Wilson, K.B. Jefferts, A.A. Penzias, Carbon monoxide in the Orion Nebula, Astrophys. J. 161 (1970) L43–L44.
[4] P. de Bernardis, P.A.R. Ade, J.J. Bock, et al., A flat universe from high-resolution maps of the cosmic microwave background radiation, Nature 404 (6781) (2000) 955–959.
[5] S. Triqueneaux, L. Sentis, P. Camus, A. Benoît, G. Guyot, Design and performance of the dilution cooler system for the Planck mission, Cryogenics 46 (4) (2006) 288–297.
[6] P.K. Day, H.G. LeDuc, B.A. Mazin, A. Vayonakis, J. Zmuidzinas, A broadband superconducting detector suitable for use in large arrays, Nature 425 (6960) (2003) 817–821.
[7] S. Doyle, P. Mauskopf, J. Zhang, A. Monfardini, L. Swenson, J.J.A. Baselmans, S.J.C. Yates, M. Roesch, A review of the lumped element kinetic inductance detector, Proc. SPIE 7741 (2010) 77410M.
[8] M. Roesch, A. Benoît, A. Bideaud, N. Boudou, M. Calvo, A. Cruciani, S. Doyle, H.G. Leduc, A. Monfardini, L. Swenson, S. Leclercq, P. Mauskopf, K.F. Schuster, Development of lumped element kinetic inductance detectors for NIKA, arXiv:1212.4585, 2012.
[9] L.J. Swenson, J. Minet, G.J. Grabovskij, et al., A fast, ultra-sensitive and scalable detection platform based on superconducting resonators for fundamental condensed-matter and astronomical measurements, Low Temp. Detect. 13 (1185) (2009) 84–87.
[10] O. Bourrion, A. Bideaud, A. Benoît, A. Cruciani, J.F. Macias-Perez, A. Monfardini, M. Roesch, L. Swenson, C. Vescovi, Electronics and data acquisition demonstrator for a kinetic inductance camera, J. Instrum. 6 (6) (2011) 6012.
[11] O. Bourrion, C. Vescovi, J.-L. Bouly, A. Benoît, M. Calvo, L. Gallin-Martel, J.F. Macias-Perez, A. Monfardini, NIKEL: electronics and data acquisition for kilopixels kinetic inductance camera, J. Instrum. 7 (7) (2012) 7014.
[12] M. Calvo, M. Roesch, F.X. Désert, A. Monfardini, A. Benoît, et al., Improved mm-wave photometry for kinetic inductance detectors, Astron. Astrophys. 551 (2013) L12.
[13] A. Monfardini, L.J. Swenson, A. Bideaud, F.-X. Désert, et al., Nika: a millimeter-wave kinetic inductance camera, Astron. Astrophys. 521 (2010).
[14] A. Monfardini, A. Benoît, A. Bideaud, L. Swenson, A. Cruciani, et al., A dual-band millimeter-wave kinetic inductance camera for the iram 30 m telescope, Astrophys. J. Suppl. Ser. 194 (2) (2011) 24.

[15] A. Catalano, M. Calvo, N. Ponthieu, NIKA Collaboration, Performance and calibration of the NIKA camera at the IRAM 30 m telescope, Astron. Astrophys. 569 (2014) A9.

[16] M. Calvo, A. Benoît, A. Catalano, J. Goupy, A. Monfardini, N. Ponthieu, NIKA Collaboration, The NIKA2 instrument, a dual-band kilopixel KID array for millimetric astronomy, J. Low Temp. Phys. 184 (3–4) (2016) 816.

[17] A. Catalano, NIKA Collaboration, The NIKA2 commissioning campaign: performance and first results, arXiv:1605.08628, 2016.

[18] R. Adam, et al., Mapping the kinetic Sunyaev–Zeldovich effect toward MACS J0717.5+3745 with NIKA, arXiv:1606.07721, 2016.

[19] S. Rowe, et al., A passive terahertz video camera based on lumped element kinetic inductance detectors, Rev. Sci. Instrum. 87 (3) (2016) 033105.