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The MISTRAL instrument

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Abstract. In this contribution, we describe the design and the laboratory tests of the detector array of the MISTRAL instrument. This detector array is made of 415 lumped element kinetic inductance detectors (LEKIDs). MIISTRAL is a cryogenic, high-angular-resolution, W–band camera for the Gregorian focus of the Sardinia Radio Telescope (SRT), an Italian 64 m diameter radio telescope. MISTRAL operates at a base temperature in the range between 200 and 240 mK under an optical load of few pW. Electrical and optical characterizations of the array have been carried out in several laboratory tests and its performance has been measured. We show the results of the performance measurements such as detector quality factors, quasiparticle lifetime, electrical and optical responsivity, optical efficiency. We also describe the procedure of the pixel identification on the focal plane.

Key words. kinetic inductance detectors, MISTRAL, W–band

1. Introduction

Observations with high angular resolution of the millimeter sky could lead astronomers to answer many open questions in astrophysics and cosmology, such as the missing baryons problem (Fukugita & Peebles (2004)). Census of the baryons in the early universe indicates a discrepancy with the amount of baryons in the current universe: half of the baryon seem to miss today. One possible explanation could be the presence of filamentary structures of baryonic matter between clusters of galaxies that account for the missing part. These filamentary structures could be detected with high–angular–resolution millimetric observations of specific regions in the sky. The current state of the art in this field is represented by few instruments: NIKA2 and MUSTANG-2. NIKA2 (Catalano et al. (2018)), at the 30 m IRAM telescope, Spain, has 11 and 17.5 arcsec of angular resolution at 260 and 150 GHz frequency bands respectively and an instantaneous field

Fig. 1. MISTRAL in its final position on the SRT turret structure, a rotating structure that carries several instruments and allows observers to position them at the Gregorian focus one at a time. Credits: M. Murgia, INAF–OAC.

of view (FOV) of 6.5 arcmin. MUSTANG-2 (Dicker et al. (2014)), at the 100 m Green Bank Telescope, USA, has 9 arcsec of angular resolution and 4 arcmin of instantaneous FOV at 90 GHz band. MISTRAL (Millimeter Sardinia Radio Telescope Receiver based on array of lumped element Kinetic Inductance Detector) is a novel cryogenic, high angular resolution camera, sensitive to the W–band radiation (from 77 GHz to 103 GHz), and it has recently come into play at the focus of the Sardinia Radio Telescope (SRT), an Italian 64 m diameter radio telescope located at the Astronomical Observatory of Cagliari, 600 m above the sea level, about 40°N. MISTRAL has been built in collaboration with QMC Instruments Ltd[1] and the Italian Institute for Photonics and Nanotechnologies (CNR–IFN) and will be operated by the Italian National Institute for Astrophysics (INAF). (Isopi et al. (2023)) describes the expected performance of the instrument at the SRT site. The instrument has been installed successfully at the Gregorian focus of SRT in May 2023, see Fig. 1, and in this contribution we will briefly discuss the instrument focusing on the development and laboratory tests of its array of 415 lumped element kinetic inductance detectors (LEKIDs). KIDs are superconducting, low temperature detectors that allow us to reveal photons able to break Cooper pairs in a superconductive thin film. They are shaped as microwave resonant circuits and their resonant frequency changes with the absorption of pair–breaking radiation. KIDs are lumped element KIDs, or LEKIDs, when the size of their electrical components are much smaller than the corresponding wavelength of their bias signal at their resonant frequency. In this case the inductor coincides with the radiation absorber.

2. MISTRAL in a nutshell

The instrument is composed of several subsystems: cryogenics, vacuum system, optical assembly, housekeeping, detector readout and detectors (Battistelli et al. (2023-a); Battistelli et al. (2023-b)). The schematic in Fig. 2 shows a block diagram of MISTRAL. The cryogenics subsystem comprises a multi–stage cryostat cooled down by a pulse tube refrigerator and a ^{3}He/^{4}He sorption refrigerator and the system is able to reach a base temperature of about 200 mK for 15 hours. The pulse tube head is connected to its compressor unit by means of more than 100 m of helium gas lines that go down to the compressor room at the base of the radio telescope (Coppolecchia et al. (2022)).

[1] https://www.qmcinstruments.co.uk/

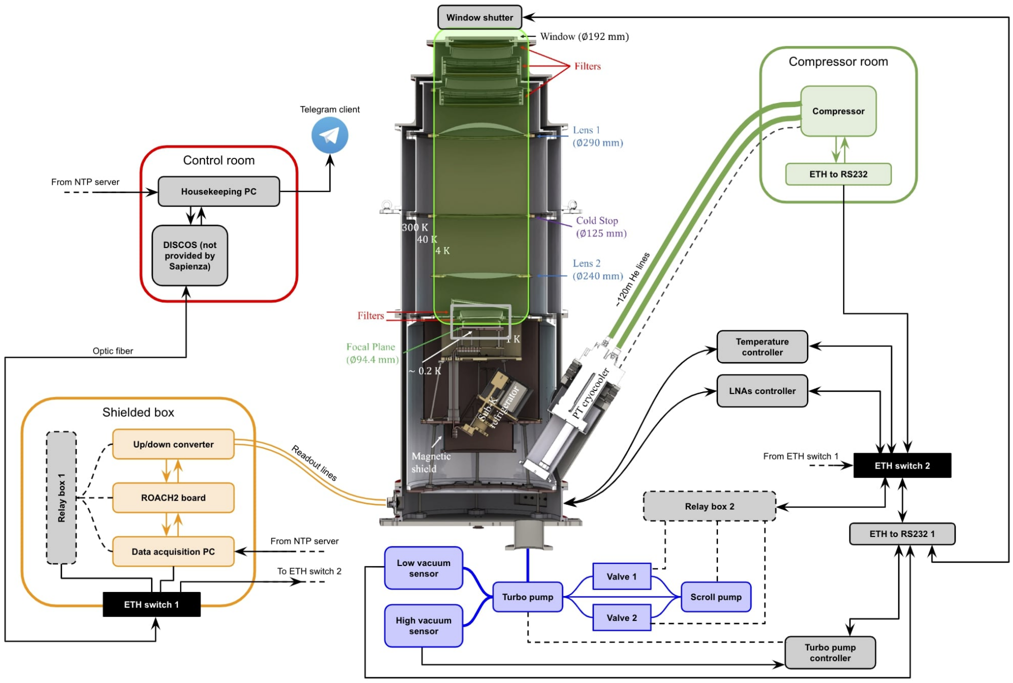

Fig. 2. Block diagram of the MISTRAL camera showing the various components: the vacuum subsystem, in blue, composed of a scroll pump, a turbo pump and a system of electrovalves, the cryogenic subsystems, in dark green, with a pulse tube cryocooler and a sub-kelvin sorption refrigerator, the optical assembly in light green, that includes a vacuum–tight UHMW polyethylene window, two anti–reflection–coated silicon lenses, a cold stop and a series of thermal, low pass and band pass filters. The readout electronics, in orange, placed in a shielded cabinet on the radio telescope, includes a ROACH2 board and a dedicated acquisition computer. The housekeeping subsystem, in dark gray, interconnects all the instrument devices, allowing the user to control and monitor its functionalities. The light gray rectangle indicates the focal plane with the array of LEKIDs.

The performance of the MISTRAL cryostat has been measured during laboratory tests and the results are discussed in Coppolecchia et al. (2023). Those cryogenic capabilities are made possible by the good high–vacuum conditions inside the cryostat (order of 1.0×10^{-7} mbar): a turbo pump and a scroll pump, with a computer–controlled vacuum valves and impedances, have been used to reach such pressures. The optical assembly comprises a vacuum–tight window of UHMW polyethylene (D'Alessandro et al. (2018)), a set of two anti–reflection–coated silicon lenses of 25 and 30 cm in diameter, a set of thermal block, low pass filters a band pass filter and a cold stop that is used to reduce straight light effect induced by the shaped parabolic profile of the radio telescope primary mirror, decreasing the entrance pupil from 64 to 60 m. The focal plane of the telescope is then reimaged on the instrument focal plane of about 80 mm in diameter. Through the housekeeping subsystem, a user is able to control and check the status of the various instrument elements: vacuum and cryogenic components such as valves, pumps, pressure sensors, thermometers and heaters and external mechanical components such as the window shutter. It also features a remote Telegram client that allows the user to quickly check the instrument status through a smartphone. This subsystem is handled by the housekeeping computer located in the main building of the

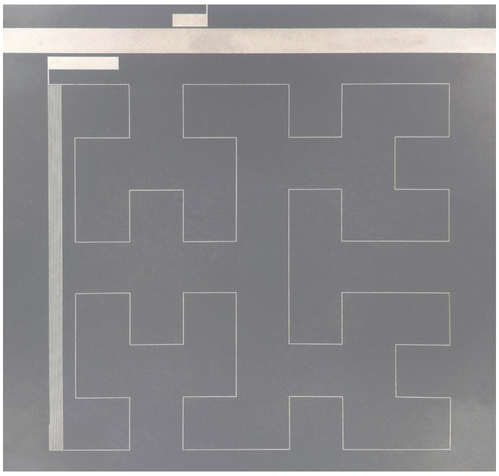

Fig. 3. MISTRAL LEKID geometry: the Hilbert curve (3×3 mm in size) is the inductor and radiation absorber of the KID while the interdigital capacitor is clearly seen on the its left. The KID is capacitively coupled to the feedline (at the top) through a superconductive strip. Credits: G. Pettinari, CNR–IFN.

observatory. The detector readout subsystem consists in a dedicated computer unit coupled to a ROACH2 board, an FPGA–based readout electronics developed at the Arizona State University (Gordon et al. (2016)). The readout components are placed inside a shielded cabinet in the Gregorian room connected to the cryostat through a pair of 6 m long SMA cables. On the MISTRAL focal plane, there is an array of 415 LEKIDs, designed by our team at Sapienza University and fabricated at the CNR–IFN facilities. The typical MISTRAL LEKIDs shape is shown in Fig. 3. The picture shows the superconductive film as a bright area over the darker silicon wafer. The Hilbert curve is the KID inductor, which acts also as the radiation absorber. The KID capacitor is made of several interdigital fingers, seen on the left of the inductor. The upper horizontal strip is a section of the feedline, while in the upper left corner, below the feedline, there is the coupling capacitor that couples the KID to the feedline.

3. Array design

The design of the LEKID array has been driven by optical and electrical simulations. Optical simulations, carried out with the Ansys HFSS software and meticulously described in (Paiella et al. (2022)), have been used to put constraints on the wafer material and thickness and to optimize the LEKID absorption band and efficiency with an appropriate absorber geometry, the same for all the detectors. Electrical simulations, using the Sonnet software, have been used to determine the electrical properties of the feedline and KIDs, such as the resonant frequencies and quality factors and the feedline impedance. Since MISTRAL only has a single feedline and a readout electronics optimized in the range 200 MHz to 700 MHz, all the 415 KIDs must have different resonant frequencies in this range, thus a different geometry. The two geometric parameters that can be changed in order to determine a different resonant frequency are the length of the coupling strip ℓ_{cc} and the number of fingers of the KID capacitor n_c. As described in (Cacciotti et al. (2023)), we ran hundreds electrical simulations with different values of ℓ_{cc} and n_c. For each pair (ℓ_{cc}, n_c) we determined the resonant frequencies ν_r and the quality factors (Q_i, Q_c, Q_{tot}) using the simulated transmission scattering parameter S_{21}, building up, using interpolation, a parameter space that allowed us to determine 415 different pairs of (ℓ_{cc}, n_c) in a desired region of $(\nu_r, Q_i, Q_c, Q_{tot})$.

4. Laboratory tests

The MISTRAL array of LEKIDs has been characterized (electrically and optically) inside the instrument cryostat, at an operational temperature of 200 mK. The results of the electrical characterization are described in (Cacciotti et al. (2023)), while the optical characterization in (Paiella et al. (2023)).

4.1. Electrical characterization

The purpose of the electrical characterization was the measurement of the array yield (or the number of working pixels), resonant frequencies, quality factors and electrical responsivities in dark conditions, i.e. with the minimal optical load on the detectors. We found the 82% of working pixels: their resonant frequencies, frequency separation and quality factors reflect the simulated values from the design step. We tested several prototypes and based on their yield and electrical responsivities, we selected the best one for the optical characterization.

4.2. Optical characterization

With the optical characterization, we identified the KIDs on the focal plane and we measured their optical responsivity. The KID identification is needed to map their resonant frequencies with their position on the focal plane, not known *a priori*. To identify the KIDs, we used a W–band noise source attached to a pair of Cartesian linear stages placed in front of the cryostat window. The source, together with a reimaging optic next to it, creates a two dimensional Gaussian spot on the focal plane, with a size slightly larger then the KIDs absorber. By moving the source on its (x, y) plane and monitoring the KIDs response, we were able to reconstruct the noise source spot seen by each KID and thus their position on the focal plane. Using the same noise source, knowing the W–band optical power emitted by it, we measured the optical responsivity.

5. Conclusions

The key features of MISTRAL are the high sensitivity provided by 415 KIDs, the high angular resolution of 12 arcsec, an instantaneous FOV of 4 arcmin and a mapping speed between 170 and 1500 $\mathrm{arcmin^2 mJy^{-2} h^{-1}}$ depending on the weather conditions. The two main competitors of MISTRAL are MUSTANG-2 and NIKA2. The former has 223 transition edge sensor bolometers, 9 arcsec of angular resolution, 4 arcmin of instantaneous FOV and a mapping speed of about 500 $\mathrm{arcmin^2 mJy^{-2} h^{-1}}$. The latter employs about 2900 KIDs between the 150 and the 260 GHz frequency bands, with 17.5 and 11 arcsec respectively with 6.5 arcmin of instantaneous FOV and mapping speeds of about 1400 and 110 $\mathrm{arcmin^2 mJy^{-2} h^{-1}}$ at 150 and 260 GHz respectively. MISTRAL has been installed at the radio telescope and its on–site calibration and scientific commissioning are expected for the first half of 2024. We electrically characterized several array prototypes and we selected the one with the 82% of working KIDs and the highest electrical responsivity for the optical characterization, where it showed promising performance.

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