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Latest Progress on the QUBIC Instrument

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Abstract QUBIC is a unique instrument that crosses the barriers between classical imaging architectures and interferometry taking advantage from both for high sensitivity and systematics mitigation. The scientific target is the detection of the primordial gravitational waves imprint on the Cosmic Microwave Background which are the proof of inflation, holy grail of modern cosmology. In this paper, we show the latest advances in the development of the architecture and the subsystems of the first module of this instrument to be deployed in Dome Charlie Concordia base - Antarctica in 2015.

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1 Introduction

The Cosmic Microwave Background (CMB) has been heavily observed and studied in the last decades. From this keen interest, emerged a number of experiments, backed by important R&D efforts, that put tight constraints in favour of inflationary cosmology models. One last prediction, the presence of primordial gravitational waves resulting in tensor mode perturbations in the metric is still undetected. These space time fluctuations would have left a faint but indelible trace on the polarization of the CMB photons. Today, thanks to the development of large arrays of photon noise limited detectors, this detection seems to be within reach. One last barrier could prevent us from detecting it: uncontrolled systematic effects. In the landscape of imaging instruments, usually suffering from uncontrolled time varying systematics (e.g. atmospheric contamination), one outsider architecture is making its way through theoretical and technological developments: bolometric interferometry[5,6]. It uses background limited incoherent detectors but takes advantage of baseline redundancy to make interferometry a viable option without significant sensitivity loss[1] thanks to a special self calibration technique[7]. In this type of architecture, equivalent baselines are coherently summed on every detector avoiding the need for expensive, complex and noisy correlators, mixers and amplifiers. QUBIC (Q and U Bolometric Interferometer for Cosmology) is today the only instrument based on bolometric interferometry.

In this paper, we report latest advance on the development of the 1st module of the QUBIC instrument. After introducing the QUBIC instrument, we will go through each of the instrument subsystems developments.

2 The QUBIC Instrument

QUBIC will ultimately be composed of 6 modules, operating at 97GHz, 150GHz and 220GHz with 25% bandwidth. Each module will respectively comprise 144, 400 and 625 horns. The first module will be centred around 150GHz as the base CMB channel, taking advantage of recently released data (Planck HFI) for foreground removal and a specific self calibration strategy to mitigate instrumental systematic effects[7]. For that purpose, it will use electromagnetic switches sandwiched between the primary and the secondary horns array. The primary horns look at the sky through optical filters and a cold rotating half wave plate. The secondary horn array re-emits the signal to illuminate a beam combiner. The latter realizes the necessary path phase shift to allow coherent summation of equivalent baselines on the focal plane after polarization separation. The focal planes will be made of two arrays of 1024 TES bolometers each cooled to a temperature of 0.3 K. The current stage of the project is subsystems fabrication, test and assembly. First light at the observation site is scheduled for 2015. The expected tensor to scalar ratio after one year of observation is 0.05 with one module and 0.008 with 6 modules[1]. The observation site will be at Dome Charlie Concordia Station in

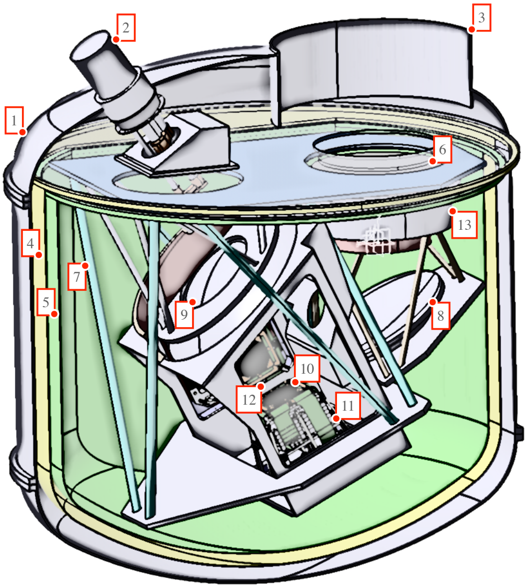

Fig. 1 Cryostat sketch design. (1) 300 K enclosure (2) pulse tube cooler (3) optical window (4) 60K shield (5) 4 K shield (6) optical filters + IR filters + HWP (7) optical mount (8) primary mirror (9) secondary mirror (10) focal plane (11) cold readout electronics (12) 1 K shield (13) entrance horn array + switches + output horn array. (colour figure online)

Antarctica, a site that has proven to be one of the best on earth for CMB observations[4]. Previous campaigns at Dome C have already allowed the characterization of the atmosphere as well as the improvement of the logistics[3,4].

3 First Module Instrument Subsystems

3.1 Cryogenics

The large size of the horn array, the optical combiner and the focal plane drives the overall dimensions of the cryostat (see figure 1). The cold volume is of the order of 1.3 m^3, and a large (60 cm in diameter) window is required by the large optical throughput of the system. An all-aluminum construction[2] is necessary to limit the weight of the system and the requirements on the mount. For operation in the harsh Dome-C environment, where supply of cryogenic liquids is difficult, we opted for a dry cryostat cooled by a Sumitomo pulse tube refrigerator, adapted for operation at low temperatures in Dome-C by means of suitable heaters[3]. The detector arrays are cooled at 0.3 K by a ^{3}He sorption cooler, while the cold optics is cooled below 4 K by a ^{4}He sorption cooler.

3.2 Optics

3.2.1 Filters and Half Wave Plate

Spectral filters will be located inside the dewar to perform several roles. First, the selection of the spectral band of observation is achieved by the combination of the back to back waveguide section and metal mesh interference filters. Second, metal mesh interference filters located at the entrance aperture of each thermal stage reduce radiation load on the cryogenics and the detectors.

The rotating half-wave plate modulates the signal coming from the sky. It is therefore a critical component that needs to be designed carefully and tested extensively. A dielectrically embedded half wave plate[9] will be used at 4 K in order to reduce systematic effects[8]. The rotating mechanism will be based on the design made for the PILOT experiment[8], allowing for a rotation control better than 0.1 deg.

3.2.2 Horn Array

The first module will have 400 primary horns backed by similar horns sandwiching a stack of aperture shut-off switches. These horns, operating around 150GHz, will be single moded and corrugated to increase polarization purity. They will have a beam of 14 deg FWHM and will be made of a stack of aluminum platelets mounted with an accuracy better than 30μm. The mounting technique has proven to be very efficient and shown excellent properties and agreement with simulations for 90GHz horns[10].

3.2.3 Switches

400 switches are required during the calibration procedure but are not used during data acquisition. They are used as shutters that are operated independently for all channels. They will be made of ”guillotine” shutters operated by electromagnets, controlled and de-multiplexed by a cold ASIC. The measurement of magnets inductance will allow a cross verification of the state of the switches. These devices have been successfully tested at 77K and shown a power dissipation of 150mW.

3.2.4 Beam Combiner

Beam combination in QUBIC is performed by means of an optical system that propagates the fields radiated by the back-to-back horn array to a detector plane where Fizeau interference fringes can be observed. The beam combiner is an off-axis Gregorian dual reflector, designed using the Mizuguchi-Dragone condition to have low spherical aberration, astigmatism and geometrical cross polarization across as large a field-of-view as possible. A polarizing grid separates the signal into two orthogonal polarizations that are imaged onto separate detector grids and the entire combiner fits inside a $\sim 1.3\,\mathrm{m}^3$ cold volume (see figure 1). A field-of-view of 14deg together with a focal length and entrance aperture diameter of 300 mm makes the design extremely challenging but simulations have shown that the

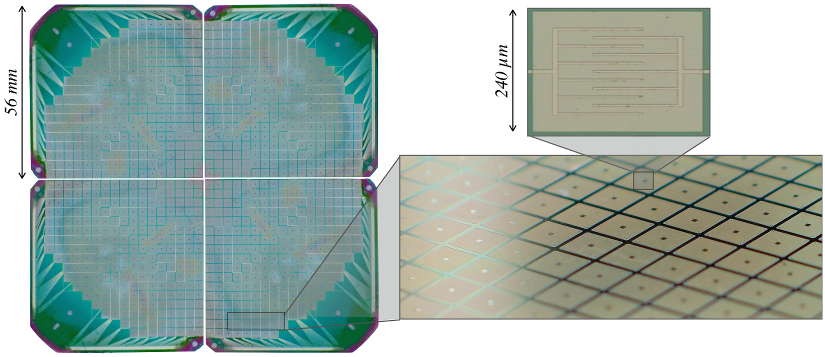

Fig. 2 Picture of preliminary realizations of detector sub-arrays with a zoom on the thermistor.

effect of aberrations in our design is to reduce the overall sensitivity, compared to an ideal combiner, by approximately 10%.

3.3 Detection Chain

3.3.1 Detectors

The focal plane will be covered with two filled arrays in order to Nyquist sample the interference image. Each array will detect a linear polarization either transmitted or reflected by a polarized grid. The 1024 detectors of each array (figure 2) are based on 0.3 K cooled Transition Edge Sensors with a target noise equivalent power (NEP) of 4 $10^{-17}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$ and a time constant shorter than 20 ms. A single bolometer is made of an island of suspended TiV absorber on a low stress SiN_x membrane heating an Nb_xSi_{1-x} thermistor. Four SiN_x legs provide the thermal link to the bulk silicon. This design has the advantage of independently tuning the critical temperature by varying the concentration of Si and Nb in the Nb_xSi_{1-x} alloy and the normal resistance by tuning the geometry of Nb made interdigitated electrodes[11] (see figure 2). A target Tc of 0.4 K and normal resistance of 200 mΩ has been set to reach the required NEP and time constant. These parameters result on a tradeoff between the required sensitivity, the saturation power to observe the artificial calibration source and the cryogenic system that will be used for the first module. A first array is being fabricated and is scheduled for september 2013. In the meanwhile, 23 pixels detectors arrays have been characterized and showed an NEP of 4 $10^{-17}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$ for a Tc of 0.5 K[12].

3.3.2 Readout Electronics

The readout electronics use SQUIDs as a first time domain multiplexing stage followed by a cryogenic full custom BICMOS SiGe ASIC. This ASIC controls the capacitive SQUID addressing for row readout and second stage amplification. The advantages of such a system are a simplification of the architecture, miniaturization of the readout electronics, low power consumption and very low noise properties. It uses a single voltage supply of 3.3V and consumes only 15 mW per

ASIC. This technique has been demonstrated[13] with a 24 pixel readout in a 24:1 multiplexing scheme (done in two steps: 8:1 by SQUIDs stage and 3:1 with the ASIC). The current design is based on a new ASIC that is able to readout 128 detectors with a 128:1 multiplexing factor (32:1 SQUIDs and 4:1 ASIC). The full detector array will therefore be read out with 2048 SQUIDS and 16 SiGe ASICs.

Data acquisition and control software and warm electronics design and fabrication are ongoing at IRAP Toulouse. This important task will allow to overcome the challenges of operating a scientific instrument during the winter in Antarctica.

4 Conclusion

Important progress has been made in the design, fabrication and characterization of the subsystems for the first module of QUBIC. Its deployment at Dome C will allow us to achieve a tensor to scalar ratio of 0.05 within one year of observation. It will also allow the demonstration of the importance of the self calibration strategy to reach unprecedented levels of systematics control in CMB instruments. The 5 modules that will follow will be a real breakthrough with a target tensor to scalar ratio lower than 0.01. For future modules several improvements will be considered such as a dilution fridge, planar orthogonal mode transducers, superconducting switches and Kinetic Inductance Detectors. It is important to note that the first QUBIC module is not only a scientific demonstration on CMB photons of the capabilities of bolometric interferometry but also a technology demonstration of new techniques for a future cosmology space mission.

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