The QUBIC Experiment
A bolometric interferometer to detect the CMB B-mode polarization

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QUBIC is a dedicated CMB B-mode experiment based on a novel instrumental technique, bolometric interferometry, which could combine some very specific advantages of interferometry in terms of systematics control and the advantages of bolometric techniques in terms of sensitivity. We introduce bolometric interferometry key concepts and give the specifications of the QUBIC instrument. A first module is planned to be installed at the Concordia station (Antarctica) in 2012; the final instrument will have the sensitivity to detect a tensor to scalar ratio of 0.01 with one effective year of data. QUBIC is a collaboration between France, Ireland, Italy, U.K. and U.S.A, which results from the merging of the MBI and BRAIN projects.

1 Context

1.1 Detecting CMB B-mode

Measuring the Cosmic Microwave Background (CMB) B-mode polarisation appears nowadays as the most powerful way to place constraints on inflationary theories. The detection of such a weak signal is however a tremendous experimental challenge. Future experiments will need, in addition to a high statistical sensitivity, a reliable foreground removal and an unprecedented control of systematic effects [12].

1.2 The path towards bolometric interferometry

Most future B-mode experiments (EBEX [9], PLANCK [10], SPIDER [11], PolarBear) will have a similar imaging concept, sharing the same kind of instrumental systematic errors. Another kind of instrumental concept has proven successful in the past : the DASI[7] and CBI[8] interferometers, which were the first experiments to detect E-mode polarization of the CMB. Unfortunately, the sensitivity of this kind of instrument (heterodyne interferometer) is intrinsically limited because they rely on coherent detection : the electromagnetic signals collected by the horns are amplified (by HEMTs) and mixed to lower frequencies before being correlated by pairs. Another strong limitation is the cost of the correlator (which does not grow linearly with the number of horns N since $N(N-1)/2$ correlations must be done).

Bolometric interferometry offers a promising alternative for detecting B-modes, which combines some very specific advantages of interferometry in terms of systematics control and those of bolometric techniques in terms of sensitivity.

2 Bolometric Interferometry : key concepts

2.1 Fizeau combination

The QUBIC instrument concept is represented on figure 1. A bolometric interferometer can be seen as a millimetric version of the first interferometer ever dedicated to astronomy, the Fizeau one, which was obtained by placing a mask with two holes in front of a telescope; the millimetric sky is directly observed in our case through an array of back-to-back horns, acting as diffractive pupils. Interference patterns are formed in the focal plane of the beam combiner (which is just a telescope). This focal plane is filled with an array of bolometers, which are sensitive to polarisation.

A rotating half-wave plate (HWP) is located after the array of reemitting horns in order to modulate the polarisation (in the same way as for imaging experiments). It can be shown that the power measured by a bolometer located at $\vec{d_p}$, is:

$$R_{\vec{d_p}}(t) = S_I(\vec{d_p}) \pm \cos(4\omega t)\ S_Q(\vec{d_p}) \pm \sin(4\omega t)\ S_U(\vec{d_p}) \tag{1}$$

where ω is the HWP angular velocity and where S_X is defined by:

$$S_X(\vec{d_p}) = \int X(\vec{n}) |A_s(\vec{d_p} - \vec{n})|^2\ d\vec{n} \tag{2}$$

where $X = \{I, Q, U\}$ stands for the Stokes parameters. This quantity S_X is usually called the *dirty image* in interferometry : this is an image of the sky filtered by the *baselines* (which are the vectors defined by every pair of horns, in wavelength units). Equivalently, this is an image of the sky observed through the *synthesized beam* $A_s(\vec{d_p} - \vec{n})$, which is approximately given by the discrete Fourier transform of the horn distribution. This beam has much more structure than a Gaussian function (it is for instance the product of a Gaussian by a sinc function in the case of a square-grid array of horns having Gaussian primary beams).

The dirty image can equivalently be written as a linear combination of the *visibilities*. These are the standard observables in traditionnal radio-interferometry : the Fourier transform of the sky field observed through the primary beam. The CMB power spectra are roughly given by the variance of these visibilities in the flat sky approximations.

We therefore see that there are two ways to deal with the data measured by a bolometric inteferometer: one can make maps of the sky observed through the synthesized beam (the data analysis is then very close that of an imager) or one can invert the linear system instantaneously and store the visibility measurements (the data analysis is then very close that a heterodyne CMB interferometer). We are studying which way is better.

2.2 Sensitivity

We have shown [1,2] that the sensitivity of a bolometric interferometer is roughly equivalent to that of an imager having the same number of horns, provided that the horn distribution presents a high degree of redundancy: the average number of redundant baselines should scale as the number of horns. This condition would be satisfied by the QUBIC compact square-grid array.

The question of bandwidth often used to be raised about our concept by specialists in radio-interferometry; indeed, if the raw sensitivity of detectors grows as the square root of the bandwidth, there is a secondary effect, known as *bandwidth smearing* which can largely degrade the global sensitivity of an interferometer. However we have shown [3] that this sensitivity loss is very acceptable in the QUBIC case (about a factor 1.6 loss for 25% bandwidth).

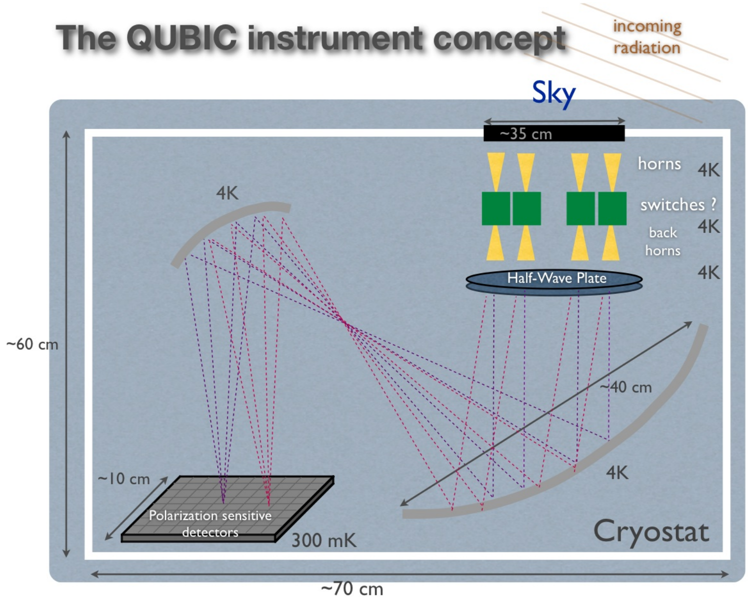

Figure 1: The QUBIC instrument concept is a millimetric Fizeau interferometer with image-plane beam combination (see text).

2.3 Self-calibration

The high degree of redundancy of the QUBIC horn array enables a powerful self-calibration procedure. The main idea is to take advantage of the fact that in an ideal instrument, redundant visibilities (defined by redundant baselines) should exactly equal each other, while in a real experiment, they will slightly differ because of systematic errors. These small differences can be used to calibrate the gains, phases and polarization couplings of each channel (these quantities are the sources of instrumental errors when mis-estimated). We emphasize the fact that this self-calibration procedure is very different from the usual calibration used in imaging experiments that must rely on models of the calibration source.

The use of redundant baselines for self-calibration is a known but rather uncommon method in radio-interferometry [6]. Traditionally, radio-interferometers aim at achieving the maximal angular resolution; with a fixed number of antennas, it is usually best to arrange them to optimize the sampling in Fourier space, rather than to maximize redundancy.

In our case, we will need a self-calibration period during which we will measure separately the $N(N-1)/2)$ visibilities : this would be possible thanks to polarized switches inserted between each back-to-back horn pair.

Details on this self-calibration procedure will be given in an article in preparation.

3 The QUBIC collaboration

The MBI [4] and BRAIN [5] collaborations, which were both involved in bolometric interferometry development, decided to join their efforts in 2008. The BRAIN collaboration has already launched three site testing (atmosphere, logistics) pathfinder campaigns at Dôme C during the Antarctic summers 2006, 2007 and 2009. The MBI collaboration has built a four horn prototype interferometer, MBI-4, and taken data in 2008 and 2009. Fringes have been observed, that demonstrate bolometric interferometry with Fizeau combination. QUBIC is now a worldwide collaboration between France (APC Paris, CESR Toulouse, CSNSM Orsay, IAS Orsay), Ireland (Maynooth University), Italy (Università di Roma La Sapienza, Università di Milano Bicocca), United Kingdom (University of Manchester) and USA (University of Wisconsin, Brown University, Richmond University).

3.1 The Dôme C site

We plan to install the QUBIC instrument in the French/Italian Antarctica Concordia Station located at the Dôme C site (3233 m altitude). This site offers many advantages for millimetric astronomy : a very low brightness temperature of its atmosphere (around 14 K) and excellent transmission due to its very low precipitable water vapor level, its exceptional atmospheric stability within the polar vortex, and a low sun set on the horizon. These favorable experimental conditions are furthermore available most of the year.

3.2 Instrumental R&D

Important instrumental developments are going on within the QUBIC collaboration regarding the instrument's key components.
Detectors. Our collaborators at APC are currently developing filled TES arrays (which will be combined with a polarized grid), while our collaborators at Università di Roma La Sapienza are developing KIDs array.
HWP & switches. Our collaborators at the University of Manchester are now developing saphire and metal-mesh achromatic half-wave plates. They are also taking charge of the development of polarized switches in wave guide (which are required for a self-calibration procedure).
Combiner. Our collaborators at Maynooth University and at Università di Milano Bicocca are designing the fast off-axis telescope which carries out the beam combination.

3.3 Instrument specifications

A possible configuration of the QUBIC instrument would be as follows: 2x3 modules of 144/256/512 back-to-back horns in a compact square array at respectively 90/150/220 GHz (25% bandwidth). The focal plane of each module $\simeq$ 900 Transition Edge Sensors. The primary beams would have a FWHM of 14°. The cryogenics would involve a 4K pulse-tube cooler for each module and a 100-300 mK dilution unit for the focal plane. The multipole range would be approximately $25 \leq \ell \leq 150$. Such an instrument would allow us to reach $r \sim 0.01$ in one year of continuous operation at Dôme C. The QUBIC collaboration intends to deploy a first module in 2011/2012. More details and references can be found at www.qubic.org.

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