Technical Design Report

The QUBIC Collaboration

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QUBIC Technical Design Report
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Preface

QUBIC, now in its construction phase, is dedicated to the exploration of the inflation age of the Universe. By detecting and characterizing the Cosmic Microwave Background B-mode polarization, QUBIC will contribute to find the “smoking gun” of inflation and to discriminate among the numerous models consistent with current data. The primordial B-modes (as opposed to E-modes) is the unique direct observational signature of the inflationary phase that is thought to have taken place in the early Universe, generating primeval perturbations, producing Standard Model elementary particles and giving its generic features to our Universe (flatness, homogeneity...).

Recent results from the BICEP2 and the Planck collaborations have brought the importance of the quest for B-modes to the attention of a wide audience well beyond the cosmology community. The original claim from BICEP2, contradicted by Planck later on has also shown how challenging the search for primordial B-mode polarization is, because of many difficulties: smallness of the expected signal, instrumental systematics that could possibly induce polarization leakage from the large E signal into B, brighter than anticipated polarized foregrounds (dust) reducing to zero the initial hope of finding sky regions clean enough to have a direct primordial B-modes observation.

QUBIC is designed to address all aspects of this challenge with a novel kind of instrument, a Bolometric Interferometer, combining the background-limited sensitivity of Transition-Edge-Sensors and the control of systematics allowed by the observation of interference fringe patterns, while operating at two frequencies to disentangle polarized foregrounds from primordial B mode polarization.

QUBIC is the only European ground based B-mode project with the scientific potential of discovering and measuring B-modes. It is the natural project for the European CMB community to continue at the edge-cutting level it has reached with Planck.

With the measurement of the Cosmic Microwave B-mode Polarization in two bands at 150 and 220 GHz, with two years of continuous observations from Alto Chorillos near San Antonio de los Cobres, Argentina, the first QUBIC module would be able to constrain the ratio of the primordial tensor to scalar perturbations power spectra amplitudes with a conservative projected uncertainty of $\sigma(r) = 0.02$, while having a good control of foregrounds contamination thanks to its dual band nature.

Depending on the scientific and technological results of the first module we could envisage to construct more QUBIC modules operating at three frequencies (90, 150 and 220 GHz) that could feature design upgrades in order to achieve a higher sensitivity, and could preferentially be deployed in Antarctica to take benefit of its exquisite atmospheric conditions. These could include different detectors (eg MKIDs), larger horn arrays or number of detectors, different optical combiner design, ... QUBIC is therefore a project dedicated to grow and could be a European Stage-IV CMB Polarization experiment.

QUBIC has been and will be implemented through successive steps:

1. R&D to design the instrument (now finalized)
2. Validation of the detections chain (now finalized)
3. Validation of the technological demonstrator (less detectors and horns than the final instrument, but in the nominal cryostat). This will occur in the course of 2017.
4. Construction and operations of the of the first module which will happen in the second half of 2017.
5. Optionally, construction and operations of a number of additional modules to complete the QUBIC observatory.

More details can be found on the QUBIC website: [http://qubic.in2p3.fr/QUBIC/Home.html](http://qubic.in2p3.fr/QUBIC/Home.html)
1 Science Case

1.1 Context: the Quest for primordial B-modes

1.1.1 Primordial Universe, Inflation and the CMB Polarization

Our understanding of the origin and evolution of the Universe has made remarkable progress during the last two decades, thanks in particular to the observations of the Cosmic Microwave Background (CMB). The diverse and more and more numerous probes, such as CMB anisotropies, SNIa, BAO (...) give complementary informations, enabling consistency tests of the standard cosmological model (aka ΛCDM model). This concordance model is based on General Relativity and is parameterized, in its simplest form, with six parameters. From the determination of those cosmological parameters using the observations, we have learned that the Universe is spatially flat, contains a large fraction of dark matter, and experiences accelerated expansion. The latter can be accommodated within the Friedman-Lemaître framework through the presence of a mysterious dark energy Λ (or cosmological constant).

![Figure 1](image_url)

Figure 1: (left) Recent B-modes measurements compiled in [21], with results from BICEP2/Keck [18] (dominated by dust), PolarBear [19], ACTpol [20] and SPTpol [21] due to lensing. The reionisation and recombinations bumps can be seen at respectively $\ell \simeq 7$ and $\ell \simeq 100$. (right) Total B-modes (primordial + lensing + dust) expected signal for different values of the tensor-to-scalar ratio with dust level set by Planck and BICEP2 measurements [50] (black dotted line).

Regarding the most primordial Universe history (i.e. shortly $-10^{-38}$ sec – after the Big Bang), all the observational data are up to now perfectly consistent with the inflation paradigm in which the young Universe undergoes a period of accelerated expansion that results in a flat, almost uniform space-time when inflation ends. Besides explaining flatness and homogeneity (which has originally motivated its introduction), inflation appears as the best theory able to produce the observed almost scale invariant spectrum for the Gaussian primordial density fluctuations without fine-tuning, only relying on the evolution of the quantum fluctuations of the scalar field(s) driving inflation. One of the most important predictions of inflation is that, on top of the density anisotropies (corresponding to scalar perturbations of the metric), it is expected to produce primordial gravitational waves (corresponding to tensor perturbations of the metric). This specific prediction of inflation remains to be tested and is the core motivation for the QUBIC instrument, together with the measurement of their amplitude to further constrain the inflation models.

CMB polarization can be decomposed into two modes of opposite parities: E-modes (with even parity) and B-modes (with odd parity). In total, four different power spectra describe the correlations of CMB temperature (T) and polarization (E and B) anisotropies. Density perturbations only give rise to E modes, while gravity waves are also source of B-modes. In other words, an observation of primordial B-modes would be the “smoking gun” betraying the presence of primordial gravity waves generated by inflation. B-mode detection is today one of the major challenges to be addressed in observational cosmology. This signal is parameterized using the tensor-to-scalar amplitude ratio $r$ which value would allow us to distinguish between various inflation scenarios and is directly related to the energy scale of inflation [3]. Theoretical predictions on the tensor to scalar amplitudes ratio are rather weak however but the simplest inflationary models predict $r$ to be higher than 0.01 as the corresponding energy level would be too low with respect to Grand Unified Theories for smaller values or $r$. We plan to explore this very range (between 0.01 and 0.1) with QUBIC.
1.1.2 A major observational challenge

Unfortunately, B-modes appear to be very difficult to detect because of their small amplitude: a tensor-to-scalar ratio of 0.01 corresponds to polarization fluctuations of the CMB of a few nK while the well observed temperature fluctuations are around 100 microK. Even if such a sensitivity can be achieved using background limited detectors such as bolometers from low-atmospheric emission suborbital locations or from a satellite, the challenge to face for this detection remains huge because of two main reasons: instrumental systematics and foregrounds.

Instrumental systematic effects of usual telescopes (sidelobes, cross-polarization) may become too large to be disentangled from a small primordial B-mode signal. Indeed any instrument, even designed with care, exhibits cross-polarization, beam mismatch, inter calibration uncertainties, cross-talk, . . . All of these instrumental systematics mix the electric fields in the two orthogonal directions inducing a mixing between the Stokes parameters Q and U and possibly a leakage from intensity into polarization. This induces leakage from I and E into B-modes that, given the smallness of the primordial B-modes, may completely overcome those B-modes. A new generation of instruments achieving an unprecedented level of control of instrumental systematics is therefore needed for the B-mode quest. QUBIC was precisely designed with this objective.

B-modes anisotropies are also produced by foregrounds (summarized in the right panel of Figure 1):

1. The lensing of the B-modes by intervening large scale structure in the Universe converts part of the E-modes into B-modes, mostly at small scales (ℓ ≳ 300). The spectrum of those lensing B-modes however has a well defined shape and has been detected recently by PolarBear [19], ActPol [20] and SPTpol [21] (see Figure 1, left panel). This contribution is not expected to affect the primordial B-modes detectability on the large scales observed by QUBIC (around the so-called recombination peak at ℓ=100) if the tensor-to-scalar ratio is sufficiently high, but would become a strong limitation if r is below ~ 0.01.

2. Thermal emission from dust grains in the Galaxy is expected (and measured) to be linearly polarized due to the elongated shape of the grains which align along the magnetic field. The dust e.m. spectrum is different from the CMB one so that multiple frequencies (above 150 GHz) can be used to remove it and obtain cleaned maps of the CMB B-modes. This was the motivation for adding a 220 GHz channel in QUBIC besides the initial 150 GHz one.

3. Synchrotron emission from electrons swirling around magnetic fields in the Galaxy is also expected to produce B-modes. The synchrotron EM spectrum is falling with frequency so that it can be monitored with channels at lower frequencies that the CMB ones the same way as dust. Synchrotron polarization is not expected to be highly significant at 150 nor at 220 GHz, the QUBIC operation frequencies [1] [41].

4. For ground based observations, atmosphere is also a possible source of contamination. However, the main effect of atmosphere is to increase the loading on the detectors in a time-variable manner that increases the variance of the data. A recent study with PolarBear data [35] has shown that the polarization induced by atmosphere remains at a small level when observing from the Atacama plateau, which is known to be worse than in South Pole.

Searching for B-modes in the Cosmic Microwave Background polarization is therefore a major challenge that requires instruments observing at multiple frequencies with high sensitivity and unprecedented control of instrumental systematics. The current best upper-limit on r is r < 0.07 at 95% C.L. [50] and is obtained by combining BICEP2, Keck Array and Planck data.

1.1.3 Ongoing and planned projects

Two kinds of instruments have been used so far in the Cosmic Microwave Background polarization observations:

- **Imagers** where an optical system (reflective as in Planck or refractive as in BICEP2) allows us to form the image of the sky on a focal plane equipped with high sensitivity total power detectors. Bolometers have been successfully used because their intrinsic noise is lower than the photon noise of the observed radiation (so-called «background limited»). This is achieved by cooling the bolometers down to sub-Kelvin temperatures. The detection principle is that incoming radiation heats the bolometers whose temperature is being monitored through the variation of a resistance (resistively or using the normal-superconducting transition). Recently, Kinetic Inductance Detectors (KIDs) have been developed, they present the advantage of an easier fabrication process and natural ability for multiplexed readout (a major issue at cryogenic temperatures). Imagers directly
measure the temperature on the sky in a given direction (with a resolution given by that of the telescope and horns) and therefore allow building maps of the CMB Stokes parameters I, Q, and U that further enables us to reconstruct T, E and B power spectra.

- **Interferometers** where the correlation between two receivers allows us to directly access the Fourier modes (known as visibilities) of the Stokes parameters I, Q and U without producing maps. The observation of interference fringes with an interferometer allows for an extra control of systematic effects in comparison with an imager. That explains why interferometers were used for the first measurements of sub-degree temperature anisotropies (with VSA [38]) and E-mode polarization (with CBI [40] and DASI [39]). However, they suffered from a degraded sensitivity due to their heterodyne nature: signals at the frequency of the CMB (from a few GHz to a few hundreds of GHz) need to be amplified and down-converted to lower frequencies before being detected. This amplification process adds an irreducible amount of noise that prevents such interferometers from being background limited. Furthermore, the complexity of traditional CMB interferometers (based on multiplicative interferometry, making the correlation by pairs of detectors) prevent them from growing to the large number of receivers that is now required to achieve the sensitivity needed for the B-mode quest (if $N$ is the number of channels, their complexity increases as $N^2$ while that of an imager grows as $N$). This is the reason why, despite their better ability to handle instrumental systematics, interferometers have no longer been considered, until QUBIC, for CMB polarization observations.

Most of the on-going or planned projects are lead by U.S. teams. They are all based on the concept of a traditional imager with a broad variety of technical choices regarding the modulation of the polarization, the optical setup, the detector technology, the frequency coverage or the instrument location. They also use different instrumental apertures, that sets the angular accuracy hence the multipole coverage and therefore are optimized for different science goals: high angular resolution instruments are better suited for the lensing B-modes study (allowing one to constrain neutrino masses for instance), and have published results on this (PolarBear, SPTpol, ACTpol) while low resolution suborbital instruments aim at detecting the recombination peak of the primordial B-modes at $l=100$. Satellite missions are considered by the community and aim at covering both science goals with the additional advantage of a full sky coverage allowing one to search for the reionization peak at $l=7$. However, no such mission has been selected up to now by Space agencies, neither in the U.S.A. nor in Europe. LiteBird is a possible mission to be flown in the early 2020 by the Japanese Space Agency (JAXA) and would be an extremely sensitive project (targeting $r=0.001$) with low angular resolution, therefore only focused on primordial B-modes.

Table 1 summarizes the situation in terms of competitors for QUBIC. We know since the BICEP2/Planck controversy that foregrounds cannot be neglected. This is why, when the foreground-free forecasted sensitivity of the QUBIC first module, from Argentina, is $\sigma(r) = 0.01$, we can only achieve $\sigma(r) = 0.02$ when accounting for realistic foregrounds. The observation efficiency is taken to be 30% in those QUBIC sensitivity forecasts. Besides

![Table 1: Summary of the main ground and balloon projects aiming at measuring B-modes. The label “fg” or “no fg” corresponds to the assumption on the foregrounds, numbers have been extracted from [31]. [∗] The LSPE value is an upper limit at 99.7% CL. [1] Ref. [31] did not include this frequency.](image)
Most of the current projects aiming at detecting the B-mode radiation are based on the architecture of an imager because of its simplicity and the high sensitivity allowed by bolometers. However, imagers do not allow for the same level of control of instrumental systematics and could potentially reach a sensitivity floor because of E-modes leaking into B-modes. Bolometric Interferometry is a novel concept combining the advantages of bolometric detectors in terms of sensitivity with those of interferometers in terms of control for systematics. It was initially proposed in 2001 by Peter Timbie (University of Wisconsin) and Lucio Piccirillo (University of Manchester). Two collaborations on both sides of the Atlantic (BRAIN in Europe and MBI in the U.S.A.) started to develop the concept and decided to merge their efforts in the QUBIC project in 2008. The QUBIC collaboration now includes six laboratories in France, all members of the CNRS (APC in Paris, LAL, IAS and CSNSM in Orsay and IRAP in Toulouse), three Universities in Italy (Universitá di Roma – La Sapienza, Universitá Milano Bicocca and Statale in Milano), Manchester and Cardiff Universities in the UK and NUI/Maynooth in Ireland, three universities in the USA (University of Wisconsin at Madison, WI ; Brown University at Providence, RH ; Richmond University, VI). NIKHEF (Netherlands) have joined QUBIC in 2014.

1.2 Bolometric Interferometry and QUBIC

QUBIC will observe interference fringes formed altogether by a large number of receiving horns with two arrays of bolometric detectors (operating at 150 and 220 GHz) at the focal planes of an optical combiner. The image on each focal plane is a synthesized image in the sense that only specific Fourier modes are selected by the array of receiving horns. A bolometric interferometer is therefore a synthetic imager whose beam is the synthesized beam formed by the array of receiving horns. The interferometric nature of this synthesized beam allows us to use a specific self-calibration technique that permits to determine the parameters of the systematic effects channel by channel with an unprecedented accuracy [16] [36]. As a comparison, an imager can only measure the effective beam of each channel. We therefore have an extra-level of systematics control. The use of bolometric detectors allows us to reach a sensitivity comparable to that of an imager with the same number of receivers [17].

The QUBIC instrument is made (see Figure 2) of a cryostat cooled down to 4K using pulse-tubes. The cryostat is open to the sky with a 45 cm diameter window made of high-density polyethylene (HDPE) providing an excellent transmission and mechanical stiffness. Right after the window, filters ensure a low thermal load inside the cryostat is open to the sky with a 45 cm diameter window made of high-density polyethylene (HDPE) providing an excellent transmission and mechanical stiffness. Right after the window, filters ensure a low thermal load inside the cryostat. Before the focal plane, a dichroic plate splits the signal into its 150 and 220 GHz components that are each imaged on a focal plane equipped with 1024 Transition-Edge-Sensors (TES) from which 992 are exposed to the sky radiation and a rotating Half-Wave-Plate (HWP) similar to that of the Pilot instrument [33] modulates the polarization. Then, a polarizing grid selects one of the two polarization angles w.r.t the instrument. An array of 400 corrugated horns (called « primary horns » designed to be efficient throughout the 150 and 220 GHz bands with a ∼ 13 degrees FWHM at 150 GHz) selects the baselines observed by QUBIC. These primary horns are immediately followed by back-horns re-emitting the signal inside the cryostat towards an « optical combiner » which is simply a telescope that combines on the focal plane the images of each of the secondary horns in order to form interference fringes. Before the focal plane, a dichroic plate splits the signal into its 150 and 220 GHz components that are each imaged on a focal plane equipped with 1024 Transition-Edge-Sensors (TES) from which 992 are exposed to the sky radiation (blind ones are used for systematics studies) cooled down to 320 mK and read using a multiplexed cryogenic readout system based on SQUIDs and SiGe ASIC operating at 4K. Finally, the signal measured by each detector p at in the focal plane with frequency ν at time t is:

$$R(p, ν, t) = S_I(p, ν) + \cos[4ϕ_{HPW}(t)] S_O(p, ν) + \sin[4ϕ_{HPW}(t)] S_U(p, ν)$$  \hspace{1cm} (1)
where $\varphi_{\text{HWP}}(t)$ is the angle of the HWP at time $t$, $S_{I/Q/U}$ the sky signal at frequency $\nu$ convolved with the synthesized beam (see Figure 3). With a scanning strategy offering a wide range of polarization angles on the sky and thanks to the HWP rotation, one can recover$^1$ the synthesized images of each of the three Stokes parameters $I$, $Q$ and $U$. In contrast with traditional interferometry, the observables of QUBIC are not the visibilities (Fourier Transform of the observed sky for modes corresponding to the baselines), but the synthesized image, which is nothing else but the observed sky filtered to the modes corresponding to the baselines allowed by our instrument. This particular feature is a crucial one in QUBIC as each of these modes can be calibrated separately using the « self calibration » procedure (see section 1.2.3 and [36]) allowing QUBIC to reach an unprecedented level of instrumental systematics control.

One important aspect of the QUBIC design is the presence of the polarizing grid right after the half-wave plate, i.e. very close to the sky. It may appear undesirable from the sensitivity point of view to reject half of the photons at the entrance of the instrument. However, this a very nice feature from the point of view of polarization systematics because this is associated with bolometers that are not polarization sensitive: the rejection of the undesired polarization with the polarizing grid is very efficient and whatever the cross-polarization of the rest of the instrument, the detectors will measure the polarized sky signal modulated by the HWP. This means that we expect a very low level of instrumental cross-polarization for QUBIC.

1.2.2 The QUBIC synthesized beam and map-making

In QUBIC, each primary horns pair defines a baseline (a Fourier mode on the sky) that is transmitted through the instrument and forms an interference fringe on the focal planes. In the standard « sky observing » mode, the fringes formed by all the baselines are coherently combined on the focal and form a synthesized image of the sky, which is the sky image convolved by the QUBIC synthesized beam than can be calculated from the combination of all baselines.

The QUBIC horn array and synthesized beams are shown in Figure 3. As can be seen on this Figure (left

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$^1$It is worth noting that given the approximate cost of 5 k€ for a traditional correlator, a 400 elements traditional interferometer would require 800000 of them (one per baseline) and would therefore cost the amazing price of 400 M€. Using an optical combiner as in QUBIC therefore appears as a very cheap way (by a factor 100) of performing interferometry with a large number of channels, leading to a better sensitivity thanks to the use of bolometers.
The synthesized beams shape is significantly different from the beam offered by a classical imager and typical of that of an interferometer: it has a central peak, with 0.54° FWHM and has replications around, damped by the primary 14° FWHM that are due to the fact that the primary horn array has finite extension. These replications are not sidelobes as they are a desired feature of an interferometer that only observes well defined and well « calibrable » baselines (see Sect. 3.3.1). It however makes the map-making procedure much more complicated than with an imager as it involves partial deconvolution to disentangle the small contamination by secondary peaks with respect to the main one.

We have shown that using super-calculators and a specific map-making algorithm based on « inverse problem solving » [32], one can recover the input I, Q and U maps provided the fact that the scanning strategy offers a wide enough variety of polarization angles on the sky (which is ensured by the combination of sweeps in azimuth with constant elevation and the rotation of the Half-Wave-Plate, cf. Figure 4 and Figure 5).

1.2.3 Self-calibration and the systematic effects mitigation with QUBIC

Interferometry is known [2] to offer an improved control of instrumental systematics with respect to direct imaging thanks to the observation of individual interference fringes that can be calibrated individually. This feature is conserved with bolometric interferometry, in QUBIC, thanks to the presence of electromagnetic switches between the primary and secondary horns (cf. sections 2.3.4 and 2.3.5). This apparatus consists in a waveguide that is closed or open using a cold (4K) shutter operated by solenoid magnets. In the self-calibration mode, pairs of horns are successively shut when observing an artificial partially polarized source (we do not need to know its polarization). As a result, we can reconstruct the signal measured by each individual pairs of horns in the array and compare them. As redundant baselines correspond to the same mode of the observed field, a different signal between them can only be due to photon noise or instrumental systematics. Using a detailed model of the instrument incorporating all possible systematics (through the use of Jones matrices for each optical component), we have shown that we can fully recover all of these parameters through a non-linear inversion involving hundreds of parameters (horn locations and beams, components cross-polarization, detector inter calibration, . . . ). The updated model of the instrument can then be used to reconstruct the synthesized beam and improve the map-making, reducing the leakage between Stokes parameters. We have shown in [38] that with 2.5% of the observing time, we can reduce the impact of the instrument systematics on the E to B leakage to a level allowing us to measure the B modes down to r=0.05 (see Figure 6). No such feature exists with a usual imager justifying the fact that QUBIC will have extra-control on instrumental systematics with respect to all the other running or planned instruments listed in Table 1.
Figure 4: (left) Current results with the QUBIC mapmaking under the Gaussian peaks assumption. First row shows the input I,Q and U maps in the region observed by QUBIC, second row shows the recovered maps using the full simulation pipeline, last row shows the residuals w.r.t. the input maps.

Figure 5: Results of the current version of the map-making: the multiple-peaked feature of the synthesized beam (green) present in the TOD is deconvolved efficiently in the maps where we show the recovered profile for a point source (blue line). The achieved resolution (FWHM of the blue central peak) is 23.5 arcmin.
Figure 6: “Self-calibration” simulated result [36]. The leakage from E to B due to instrumental systematics is reduced by more than an order of magnitude spending only 2.5% of the observation time on self-calibration.

### 1.3 QUBIC sensitivity to B modes

The first module of QUBIC will be installed in Argentina, on the Puna plateau in the Salta Province, near the city of San Antonio de Los Cobres, on the site of the LLAMA experiment (cf. Sect. 4.2 for more details). Still, in the initial phase of the project, we considered installing QUBIC in Dome C, Antarctica. For this reason, some results presented below refer to this site.

#### 1.3.1 E/B power spectra from realistic simulations

The outputs of the mapmaking are I, Q and U Stokes parameters maps. However, the polarized fields of interest for cosmology are the scalar E and B fields instead of the spin-2 Q and U. They are related through a non-local transformation in harmonic space that is trivial when full sky Q and U maps are available. However, on a cut sky (a few percent of the celestial sphere for QUBIC), this transformation cannot be applied anymore since the Spherical Harmonics are no longer a complete basis. As a result, some of the modes are ambiguous (neither E nor B) and even in the absence of instrumental systematics, the cut sky induces massive leakage of E into B when just expanding the cut sky Q and U maps onto E and B power spectra. This mixing is however easy to revert as we know the exact geometry of the cut-sky. Unfortunately, although this inversion is unbiased and allows to recover unaltered E and B fields in average, the variance of the recovered fields contains contribution from both the sample variance of E and B so that the uncertainty on the small B field is largely dominated by the E sample variance [56]. It is nonetheless possible to reduce the non-optimality of the B measurement by applying apodization functions [4] [6] [58]. Finally, near-optimality can be reached (within a factor ~ 2) but requires a large amount of work with simulations in order to find the optimal apodization scheme for the Q and U maps.

Figure 7 shows in red the anticipated error bars on the 150 GHz channel assuming a perfect cleaning of the dust by the 220 GHz. They have been calculated using a full end-to-end Monte-Carlo Simulation (from time-ordered data to maps) for Dome C.

#### 1.3.2 QUBIC Sensitivity to B-Modes

Thanks to the extreme dryness of the Dome C site in Antarctica, the atmospheric emission in the millimeter wavelengths is extremely small [60] [53]. The Precipitable Water Vapor average in Dome C has been measured to be 0.6mm in January and well below 0.5mm the rest of the time. By comparison, it is below 0.5mm only 50% of the time in Chajnantor, Chile, where a number of B-modes experiments are installed (see Table 1). The QUBIC detectors, cooled down to 320mK, will be background limited, where the background is dominated by the atmosphere. We will therefore fully benefit from the former extreme location which would ensure QUBIC to have an exquisite sensitivity.
Figure 7: Full end-to-end Monte-Carlo simulation (from time-ordered data to maps and then to power spectra) error-bars (dispersion), at 150 GHz, assuming a perfect dust cleaning from the 220 GHz channel, are shown in red along with the expected signal from B-modes for $r=0.05$ for observations from Dome C.

Figure 8: (left) Expected noise-only error bars for QUBIC for the three BB cross-spectra that can be formed along with $r=0.2$ and dust levels extrapolated following [37] for the BICEP2 field. (right) Expected forecasts on dust spectral index and tensor-to-scalar ratio with QUBIC using a full likelihood with three configurations: QUBIC alone (blue), QUBIC with Planck 353 GHz information added (red), QUBIC if no foregrounds were present (green). The sensitivities on $r$ are estimated from a marginalization over the dust spectral index and assume 2 years of continuous observations from Dome C and an overall efficiency of 0.3.

Another advantage of being close to the South Pole is that the interesting fields in the sky (with minimal dust contamination [37]) are not far from the Southern Equatorial Pole and therefore visible 100% of the time above 30 degrees elevation from Concordia, while this is not the case from Argentina, nor Chile where several other CMB observatories are based, forcing these experiments to define multiple observation fields which is not optimal. Expected errors on the B mode spectra obtained from Dome C are shown on the left panel of Figure 8.

We have performed full likelihood forecasts for QUBIC including lensing B-modes and dust foregrounds at the level measured by Planck in the BICEP2 field [Planck Intermediate Results XXX, 2014]. We use our two bands to form three cross power-spectra (150x150, 150x220 an 220x220) and multipole range from 25 to 300 to constrain the dust spectral index and primordial tensor-to-scalar ratio (dust amplitude is fixed by Planck 353 GHz). Those results (see Figure 8 right) show that using the two bands of QUBIC alone (blue) or with Planck 353 GHz added (red) allows to reach $\sigma(r) = 0.01$ while this value goes down to $\sigma(r) = 0.006$ in the absence of foregrounds (green). These forecasts assume two years of continuous observations from Dome C, Antarctica and an overall 30% efficiency. It is worth noting that Planck 353 GHz does not bring much gain with respect to QUBIC dual band (difference between red and blue).

Finally, when accounting for all the aspects, QUBIC, when deployed in Argentina, will reach $\sigma(r) = 0.01$ in two years of observation with an overall 30% efficiency as quoted in Table 1. (see also Figure 128, more details on the site comparison can be found in Section (siteComparison).
Table 2: General requirements on the bolometric interferometer design.

| Requirement                                       | Specification                        |
|--------------------------------------------------|--------------------------------------|
| Frequency channels                               | 150 and 220 GHz                      |
| Bandwidth                                        | 25%                                  |
| Number of horns (interferometric elements)       | 400                                  |
| Primary beam FWHM at 150 GHz                    | 12.9 degrees                         |
| Primary beam FWHM at 220 GHz                    | 15 degrees (not gaussian)            |
| Number of detectors                              | 2x1024                               |

Table 3: Requirements on horns

| Requirement                             | Specification                        |
|-----------------------------------------|--------------------------------------|
| Horn diameter (internal)                | 12.33 +/- 0.1 mm                     |
| Back-to-Back Horn array diameter        | 33.078 cm                            |
| Horn Return loss across the bands       | < -25 dB                             |
| Horn secondary lobe level               | < -20 dB                             |
| Horn cross-polarization level           | < -25 dB                             |
| Horn interaxis                          | < 14 mm                              |

2 Overall Description of QUBIC

2.1 Main characteristics of the Instrument

The final sensitivity and deep control of systematics quoted in the previous section assumes that a series of requirements are fulfilled. They are listed in this section. The technical details on how these requirements are fulfilled in the instrument design are detailed in the rest of the Technical Design Review. Basic characteristics of the instrument are summarized in Table 2. The QUBIC detectors (TESs) are cooled down to 320 mK thanks to a $^3$He/$^4$He adsorption refrigerator. They are illuminated by an optical system (optical combiner, horns,...) cooled down to 1K. This experimental system is encased in a liquid-free cryostat housing a Pulse Tube cryocooler with base temperatures of 40K and 4K respectively for the 1st and 2nd cryogenic stage. Summaries of the characteristics of these various parts are listed below, and detailed further in this document.

The QUBIC instrument is composed of the following elements (see Figure 2):

**Optical Chain**

The optical chain of the QUBIC instrument starts from the window, opportunely coated with antireflection coating, directly observing the sky and extends to the detectors. It also includes the external baffling of the instrument that prevents ground pickup on the detectors.

QUBIC horns are quasi diffraction-limited apertures at 150GHz. This implies a relationship between their operating frequency, beam FWHM and aperture size: $S \Omega \sim \lambda^2$ which conditions their size to be 13.3mm (an internal diameter of 12.3mm to which 1 mm of metal wall thickness is added) for single mode operation at 150 GHz (HE11). The same horn structure support three modes at 220 GHz (HE11, TM02, EH21), with a consequently larger FOV (15 degrees, as shown in Table 2) and increased throughput. This gives its dimensions to the whole instrument.

The size of the horn array is thus 33.078 cm diameter as shown on Figure 3 (left hand side), driving the requirements summarized in Table 3. The horns need to have a low level of cross polarization (< -25dB) and secondary lobes (< -20dB), and to transmit a large fraction of the incoming power (Return Loss < -25dB) across both 150 and 220 GHz bands.

On the other hand, the detector size needs to be approximately the observed wavelength (2mm at 150 GHz) so that the overall ~ 1k detectors array has a diameter of about 11 cm if it is maximally filled (which is of course highly desirable). This implies a focal length for the optical combiner of $f \sim 330$mm [10]. Such a focal length was found to be achievable with a minimal level of optical aberrations with an off-axis Gregorian system with the following characteristics: (1) it is nearly telecentric, (2) it fulfills the Rusch and Mizuguchi-Dragone condition,
Table 4: Requirements on cold optics chain

| Requirement                                      | Value       |
|-------------------------------------------------|-------------|
| Window diameter                                  | 39.9 cm     |
| Filters diameters                                | 39.2 cm     |
| Polarizer diameter                               | 32.6 cm     |
| Half-Wave plate diameter                         | 32.7 cm     |
| Half-Wave plate, filters and polarizer transmission | -0.2 dB     |
| Half-Wave plate, filters and polarizer cross-polarization | -20 dB     |

Table 5: Requirements on mirrors and optical properties

| Requirement                                      | Value       |
|-------------------------------------------------|-------------|
| Optical combiner focal length                    | 30 cm       |
| Number of mirrors                                | 2           |
| M1 shape and diameter                            | 480mm x 600mm |
| M2 shape and diameter                            | 600mm x 500mm |
| Optical combiner sensitivity loss from aberrations | < 10%      |

The requirement for the amount of optical aberrations was that the sensitivity loss is less than 10% when calculated by the ratio of the synthesized beam with and without optical aberrations. Requirements on cold optics and mirrors are summarized on Tables 4 and 5.

The different diameters have been calculated assuming that 95% of the power goes through the aperture, but similar values have been calculated to get 99% of the power.

The possibility to monitor departure from idealities is provided by the self-calibration procedure. This procedure (see Sect. 3.3.1) is indeed one of the main advantages of QUBIC with respect to other more traditional designs (see Sect. 1.1.3). In order to perform it efficiently, one needs to be able to switch on and off some of the horns while observing a calibration source. This requires waveguide switches placed in between the back-to-back horns. Such switches need to be closed enough when in off position (-80 dB) while open enough when set to the on position (-0.1 dB). Both of these criteria need to be fulfilled simultaneously across the 150 and 220 GHz bands. The switches also need to have low cross talk between neighbouring switches. The switching between on and off needs to dissipate minimal power at the 4K stage (60 mW) in order not to heat this stage and perturb observations. Such requirements are summarized on Table 6.

External shields are required to prevent ground pickup in the detectors and make sure that photons coming from a large angle with respect to the optical axis are absorbed or reflected before entering the cryostat. This is achieved thanks to:

- a cylindrical forebaffle attached to the cryostat with a 1m length and a 14 deg opening angle. This allows to reduce by more than 20dB the radiation coming from 20deg < \( \theta < 40\deg \) from the optical axis, and by more than 40dB beyond.
- an external shield around the instrument mount or the experiment module’s roof (therefore fixed with

Table 6: Requirements on switches

| Requirement            | Value |
|------------------------|-------|
| Switches OFF transmission | -80 dB |
| Switches ON transmission   | -0.1 dB |
| Switches Cross-talk     | -40 dB |
Baffling reduction $20^\circ < \theta < 40^\circ$ 
-20 dB
Baffling reduction $40^\circ < \theta < 80^\circ$ 
-40 dB
Baffling reduction $\theta > 80^\circ$ 
-80 dB

| Table 7: Requirements on the external shields |
|---------------------------------------------|

Figure 9: schematic “top-view” of the TES bolometers for one focal plane of the QUBIC 1st module. Active detectors are shown in blue.

respects to the ground) that allows a reduction of the radiation by another 40dB beyond 80 degrees from the zenith and minimize scan synchronous pick-up.

Detectors:

Transition Edge Sensors (TES) are the state of the art of bolometric detectors already employed in several millimetric and sub-millimetric astronomical experiments all over the world. They have been chosen as detectors for the QUBIC first module, relying on the extensive developments made in France over the last few years. We may however consider other types of detectors such as KIDs (Kinetic Inductance Detectors) for future QUBIC modules as they may offer an easier fabrication and readout, and larger scalability although they are not yet completely competitive in terms of noise with the TES.

A QUBIC TES focal plane is made of an array of $4 \times 256$-pixels arrays disposed in an overall diameter of the order of 110 mm. The TES matrix for one focal plane of “QUBIC 1st module” is made of four identical pieces. The full focal plane TES matrix will have a quasi-circular shape as shown in Figure 9.

A quarter of a focal plane is composed by 248 “usable” TES elements plus 8 blind sensors for $1/f$ noise monitoring. Thus a full focal plane include 992 “usable” TES bolometers, and the QUBIC 1st module will have 1984 usable TES. A quarter of a focal plane is presented in Figure 10.
Figure 10: Picture of a TES array covering a quarter of the focal plane. Yellow lines are wires used for the reading of the TESes signal. The TES in red is not used.

| Requirement                                | Value  |
|--------------------------------------------|--------|
| TES size                                   | 2.6 mm |
| Power loss on TES                          | < 10%  |
| Power integrated on focal plane            | > 80%  |
| Number of bolometers / focal plane         | 1024   |
| Number of 256 TES wafers                   | 4      |
| Fraction of operational detectors / wafer  | > 90%  |

Table 8: Requirements on the TES detectors

The shape of one single TES and its electromagnetic wave absorber part are shown on Figure 11.

As mentioned above, the detector size is approximately defined by the central wavelength of the 150 GHz band, namely 2.7mm. Detectors, however, need to exhibit the same efficiency at 220 GHz as at 150 GHz. This efficiency is driven by the thickness of the backshort below the detector plane. We have set the power loss requirement at 10% for each and as it will be seen in Figure 12, we achieve 4% at 150GHz and 6% at 220 GHz. The number of detectors is determined by the required fraction of the secondary beam from the horns to be integrated in the focal plane. The requirement of 80% of the power integrated sets the number of detectors to 992, namely 4 wafers of 256 TES assembled together (minus the 8 blind detectors per wafer). We require that the fabrication yield of the TES is larger than 90%.

In order to ensure a fruitful exploitation of the QUBIC instrument data, the detectors sensitivities need to be close to the background limit, despite the fact that the focal planes are cooled down to 320 mK. Such a situation is achieved with TES noise below $5 \times 10^{-17} \text{W/}\sqrt{\text{Hz}}$. We also require the time constants to be less than 10ms. Accordingly, the data rate for scientific data is required to be 100 Hz.

Cryogenics:

The whole instrument will be integrated in a cryostat that needs to be operated without the use of cryogenic liquids in order to be usable in any remote observation site. The 4K stage is therefore ensured thanks to a
Figure 11: (left) Picture on one of the QUBIC focal plane TESes; (right) Absorbing part of one TES (in blue).

Figure 12: Simulated power loss of a detector at 150GHz and 220GHz with respect to backshort distance. An optimal value for the backshort is 400µm.

An optimal value for the backshort is 400µm.
Detector stage temperature spec. | 350 mK
---|---
Detector stage temperature goal | 320 mK
Bolometers NEP | $5 \times 10^{-17} \text{W Hz}^{-1/2}$
Bolometers time constant | < 10 ms
Number of bolometers / focal plane | 1024
Number of 256 TES wafers | 4
Scientific Data sampling rate | 100 Hz

Table 9: Requirements on the sensitivity

| 4K cooling | Pulse Tube Cooler |
|---|---|
| Pulse Tube Cooler 4K cooling power | > 1 W |
| Pulse Tube Cooler Electrical consumption | < 15 kW |
| Pulse Tube Cooler angle range | +/- 20 degrees |
| 1K stage refrigerator | $^4\text{He}$ sorption fridge |
| 1K cooling power | > 2 mW |
| detector stage refrigerator | $^3\text{He}/^4\text{He}$ Sorption Cooler |
| detector stage cooling power | > 20 $\mu$W |
| Instrument Diameter | < 1.6 m |
| Instrument Height | < 1.8 m |
| Instrument Weight | < 800 kg |

Table 10: Requirement on cryostat and cryogenics

Pulse Tube Cooler achieving at least 1 W of cooling power at 4K. The electrical consumption of the Pulse Tube Cooler was required to be less than 15kW$^2$. A further requirement on the Pulse Tube Cooler is that it remains with unchanged cooling efficiency when the instrument is tilted in elevation during observations in the range required by the scanning strategy (30 to 70 degrees elevation, so ± 20 degrees). The 1K stage (secondary and primary mirrors, dichroic and detector structure) will be achieved using a $^4\text{He}$ sorption fridge. The cryogenic stage for detectors will be ensured through a $^3\text{He}/^4\text{He}$ sorption cooler achieving a cooling power of at least 20 $\mu$W at this temperature.

In order to be easily transported, the outer dimensions of the diameter of the cryostat is required not to exceed 1.6m and the height 1.8m. This requirement sets the dimensions of the whole internal cryogenic architecture. The weight of the instrument should not exceed 800 kg in order to be still transportable by helicopters if needed.

The overall internal structure of the cryostat will hold the horns+switches assembly, the mirrors, the dichroic and the detectors. It is cooled down to 1K. Such an assemble needs to weight less than 150 kg in order to prevent a too long cooling time for the cryostat. It also needs to bend by less than 400 $\mu$m when the elevation of the instrument varies in the observation range (30 to 70 degrees). The heat conduction of the attaches of this structure need to be less than 2 $\mu$W.

Self-calibration source:

This external calibrator is an active source able to radiate a typical power of few mW through a feedhorn with a well-known beam, and a low level of cross-polarisation (typically < -30 dB). Two similar systems, including a microwave sweeper followed by a cascade of multipliers, will be used to generate quasi-monochromatic signals to span both QUBIC bands. The external calibrator will be in the far-field of the interferometer, which means at about 40m. For this reason, it will be installed on top of a tower nearby the instrument. Due to the extreme environment conditions, the sources will be installed in an insulation box, suitable to maintain the devices in the desired temperature range.

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$^2$This was needed in the case of an installation of a QUBIC module in Dome C.
### Internal Structure

- **weight**: < 150 kg
- **temperature spec.**: < 1.4K
- **temperature goal**: 1 K
- **bending for +/- 20 deg.**: < 400 µm
- **attaches heat conduction**: < 2 µW
- **rotation**: < 0.2°

**Table 11: Requirements on instrument internal structure**

| Frequency coverage      | 110-170 GHz & 170-260 GHz |
|-------------------------|----------------------------|
| power output spec.      | 5 mW                       |
| power output goal       | 1 mW                       |
| Operation modes         | CW + amplitude modulation   |
| Polarisation            | Linear                     |
| Cross-polarisation      | ≤ -30 dB                   |
| Weight (estim., including insulation box) | 10 kg                    |

**Table 12: Requirements on calibration sources**

We resume the basic specification of the sources in Table 12. More details are given in Section 3.3.2.

The tower must be around 40 m tall, and endowed with a lift to carry the source box and other equipment on top. A platform must be accessible at least for one person to operate the source and/or perform basic maintenance and/or to switch from 150 GHz to 220 GHz channel if required (we might consider the option of a source having a single microwave sweeper, but two different multiplier chains).

In order to avoid uncontrollable power fluctuations during self-calibration, we require stability against the wind: the lateral displacement of the platform on top shouldn’t exceed ± 20 cm with respect to the nominal position.

**Mount**:

The main requirements on the mount system are summarized in Table 13.

**Slow control / data storage**:

Four operating modes have been identified:

- **Passive mode** (no signal is acquired),
- **Diagnostic mode** (acquisition of diagnostic data such as temperatures),
- **Calibration mode** (used during observation of calibration sources, acquisition of bolometric, matrix thermometer, mount, switches, diagnostic and calibration sources data),
- **Observation mode** (acquisition of science data during sky observation, i.e. bolometric, matrix thermometer, mount and diagnostic data).

In the nominal observation mode (with an acquisition frequency of the scientific signal tuned at 2 kHz), the data rate (including raw and scientific signals, excluding house keeping signals) of the instrument will be 0.6 Mo/s. At that acquisition frequency, the needed data storage will be 20 To/year (see also section 2.4.7 and tables 27 and 28).

The slow control of the instrument allows to operate properly the overall system and especially the cryogenic system. It will be implemented in the QUBIC studio data acquisition system which has all the needed interfaces already implemented (serie, USB, GPIB...). All subsystems will provide their slow control system which will be further interfaced with QUBIC studio.
| Parameter                                      | Specification |
|-----------------------------------------------|---------------|
| Maximal diameter                              | 2500 mm       |
| Maximal height                                | 2500 mm       |
| Mass (without the instrument)                 | < 2300 kg     |
| Mass to be supported by the mount             | 700 kg        |
| Diameter of the instrument                    | 1600 mm       |
| Height of the instrument with forebaffle      | 1800 mm       |
| Electrical consumption of the mount           | < 1 kW        |
| Rotation in azimuth                           | -220° / +220° |
| Rotation in elevation                          | +30° / +70°   |
| Rotation around the optical axis              | -30° / +30°   |
| Pointing accuracy (all axis)                  | < 20 arcsec   |
| Angular speed (all axis)                      | Adjustable between 0 and 5°/s with steps < 0.2°/s |

Table 13: General requirements on the mount system.

### 2.2 Cryogenic systems

#### 2.2.1 Cryostat design / Mechanic architecture and CAD

The cryogenic system of QUBIC aims at cooling the detector arrays at 0.3K, the beam combiner optics at 1K, and the rotating HWP, the polarizing analyzer, the horn array, and the switches at 4K. It is based on:

- A self-contained 3He refrigerator cooling the detector arrays
- A self-contained 4He refrigerator pre-cooling the 3He fridge and cooling a large 1K shield surrounding the optical system (the beam combiner optic)
- Two 1W pulse-tube (PT) refrigerators working in parallel and cooling the experiment volume at 3K and the surrounding radiation shield at 40K respectively
- A large vacuum jacket surrounding the entire system, including a large (50 cm) optical window
- Heat switches, Heaters, Thermometers, Control Electronics to run the system.

In the following we describe the basic design choices, and the dimensions and interfaces of the cryogenic system.

#### 2.2.2 Cryostat vacuum

The purpose of the outer shell of the cryostat is to allow the setup to operate under high-vacuum conditions in the internal volume of the cryostat, to support all the internal elements, and to permit mm-wave radiation under study to reach the cryogenic part of the instrument through the optical window. The size of the outer shell of the cryostat is driven by the volume of the cryogenic instrument, which includes the polarization modulator, the horns array, the beam combiner mirrors, and the focal plane assembly, for a total volume of the order of 1 $m^3$. The cryostat has been designed around the cryogenic instrument, and its dimensions are a trade-off between the total size limit imposed by the transportation and the need for sufficient thermal insulation between the cryogenic instrument and the room-temperature shell.

The resulting vacuum shell has a diameter of 1.4m and a height of 1.55m. Its shape and structure has been optimized for withstanding the stress from atmospheric pressure outside and vacuum inside, with sufficient safety factors. The structure is made out of Aluminium alloy sheets, roll-bent and welded, reinforced by a stiffening ribs structure. The vacuum jacket is obtained by closing a vertical cylinder with two flanges (using indium seals) as shown in Figure 13. The axes of the two PTs are tilted by 40° with respect to the vertical, to allow optimal elevation coverage during the observations of the sky at the latitude of operation, while maintaining the Pulse Tube head close to the vertical position where its operational performance are maximized.

Figure 13 also shows the two pulse-tube (PT) heads, mounted on dedicated flanges on the cylinder. The top flange differs from the bottom one because it includes the vacuum window.
Figure 13: Schematics of the cryostat shell, with outer dimensions indicated, including the two Pulse-Tube heads.
2.2.3 Main Cryostat Cooling System

The cryogenic system is cooled down by two PTs, each providing cooling power of the order of 1W at 4K and 30Wm at 40K.

The two-stages pulse tubes refrigerate two temperature stages: a 40K shield, surrounding the lower temperature stages and intercepting warm radiation loads and supporting low-pass filters on the optical chain, and a 4K stage and shield, surrounding the lower temperature stages, intercepting radiation loads, and supporting directly low-pass filters, the horns array, the wave-plate rotator assembly, and the hexapod of the 1K stage.

A superinsulation blanket is placed between the outer shell and the 40K shield to reduce the radiative load. The two shields are shown in Figure 14 and Figure 15.

The interfaces between the PTs and the shields, flexible enough to accommodate for differential thermal contraction of the cryostat parts are shown in Figure 16. The key flexible conductive elements are gold-plated copper flaps, optimized for flexibility and heat conduction. Further copper belts are used to thermalize the large shields, especially the 4K one, as shown in the right panel of Figure 16.

The 40K stage is held firmly in place by a system of insulating fiberglass tubes assembled as in a drum, as visible in Figure 17. A similar drum is used to hold firmly in place the 4K stage. The support structure is completed by a system of radial fiberglass straps mounted on the bottom of the 40K and 4K shields.

Results from a preliminary simulation of the heat loads on the two stages of the system are reported in Table 14. With a total load of about 0.1W on the 3K stage and of about 16W on the 40K stage, operation with a single pulse tube is possible. We maintain the second pulse tube mainly to handle unexpected large thermal gradients in the system and extra loads from the window and warm filters. Moreover, when cycling the sub-Kelvin fridges, operation with a single PT would be marginal. Pre-cooling of the cryogenic sections of the systems is obtained through suitable gas switches.

2.2.4 1K-box

As shown in Figure 18, the 1K box contains the followings parts:

- The primary and secondary mirrors
- The cold stop
- The dichroic
- The focal plane

The purpose of the 1K box is, on the one hand to assure the mechanical holding and the alignment of these different parts, and on the other hand to ensure a thermal shielding at 1K.
Figure 15: Views of the 4K shield (second PT stage) with main dimensions.
Figure 16: Left: flexible thermal interfaces between the PTs and the shields. Right: system of copper belts used to thermalize the shields.

Figure 17: Views of the fiberglass tubes “drum” holding firmly in place the 40K and 4K shields.
|        | T1    | T2    | T3    |
|--------|-------|-------|-------|
|        | 3.0 K | 40 K  | 300 K |
| top fiberglass tubes | 16    |       |       |
| bottom fiberglass straps | 6     |       |       |
| area of 4K shield | 5.81 m² |       |       |
| area of 40K shield | 6.12 m² | 6.12 m² |       |
| window diameter | 0.50 m |       |       |
| number of superinsulation shields 1-2 | 10    |       |       |
| number of superinsulation shields 2-3 | 30    |       |       |
| number of ASICs | 16    |       |       |
| W cond (1,2) | 91.68 | 1615.68 mW |
| W wires (1,2) | 0.18  | 2180.00 mW |
| W rad window | 0.28  | 901.77 mW |
| W rad (1,2)  | 8.43  | 9369.72 mW |
| W ASIC (2)  | 1600.00 mW |       |
| Q dot (1,2)  | 100.58 | 15667.20 mW |

Table 14: Summary of simulated heat loads on 4K and 40K stages.

![Figure 18: 1K box and its inner parts](image-url)
The 1K box is fixed on the 4K stage of the cryostat through its upper support frame (see Figure 19) which will be made of Carbon fiber hexapods (which temperature will thus lie between 4K and 1K). On this upper support frame will also be assembled the horns and switches. The 1K box itself is assembled on its upper support frame by 6 carbon fiber tubes of thin section for thermally insulating the 1K box of the 4K stage of the cryostat. The 1K box will be connected to the 1K subsystem.

The 1K box is made of aluminium alloy sheets and plates with stiffening ribs screwed between them to allow their assembly and to mount and align inner parts (mirrors, cold stop, dichroic, focal plane ...). Its design is optimized to reduce its mass (in particular for thermal reason), but also to increase its stiffness. The requirements are that, under the effect of gravity during the displacement of the instrument while scanning the sky, the 1K box must be stiff enough to guarantee the alignment of the optical components, in particular the mirrors and the focal plane. Its dimensions are outlined by Figure 20 and summarized in Table 11.

2.2.5.1 Requirements This system is dedicated to cool down the optics box from 4.2 K to 1 K. Since the requested temperature is in the K-regime, the best option is use an $^{4}$He sorption cooler. The optics box is a system of about
165 kg: 140 Kg of Aluminium-6061 (Al6061), 11 Kg of Stainless Steel 304 (SS304), 10 kg of Copper and 4 kg of Brass. In order to support the optics box, there are two possibilities, the first one is the use of Stainless Steel 304 hexapod. Instead, the second one is the use of Carbon Fibre (CF) support. The difference between these two material is mainly due to the thermal load that will be on the optics box. Indeed, the SS304 will introduce a heat load of 168 J/day at 1 K, while the CF heat load will be of 43 J/day at the same temperature. The minimum hold time of the fridge requested for this experiment is one day, plus the time of recycling. In order to cool down from 4.2 K to 1 K, the fridge should be able to provide 123 J. Other contributions (such as radiative transfer from cold environment of from window) can be considered negligible. Indeed, heat load coming from these sources is less than 0.2 J/day.

A typical $^4$He sorption cooler is able to provide a minimum cooling power of 2 mW at 1 K. Considering the latent heat of the $^4$He, an amount of 1.5 moles of helium to keep the optics box at 1 K for an entire day in case of the use of SS304 hexapod with a previous cooling power. While using CF, only 0.55 moles of $^4$He are requested. During the cooling phase, a certain amount of gas will evaporate to cool itself. In particular, it is possible to find that the number of moles evaporated is equal to 2.5 mol for the SS304 support and less than 1 mol for the CF (This value changes as function of temperature of the pulse tube cold head as it is possible to see in figure 21).

Therefore, the final requirements for the 1 K fridge are:

- cooling power of at least 2 mW,
- total time of operation 24 hrs (hold time) plus cooling time,
- 4 mol of $^4$He using SS304 or 1.5 mol using CF.
amount of energy, some thousands of Joule, on the $4.2\ K$ flange. This is due to heat capacity, and so the enthalpy difference, of the copper and of the stainless steel that are the main components of pump (in a first instance, it is possible to neglect the heat capacity of the charcoal which is significantly lower). The releasing of this energy will be in a short time corresponding to a power of $2 - 3\ W$, which is greater than the cooling of the pulse tube ($1.4\ W$). This means that the $4.2\ K$ flange will increase its temperature (with a steep spike) and all the other elements attached too. To avoid this problem (which is present in both the cases considered for the support), it is possible to use two different pulse tubes, one of them dedicated only to the $^4\text{He}$ fridges (fridge). This implies that only the pulse tube attached to the fridges (fridge) will suffer the temperature drift, while the other components will remain at $4.2\ K$ thanks to the other pulse tube.

2.2.5.3 Testing  The testing phase will start with the commissioning of the new cryostat. This cryostat will use a Gifford-McMahon (GM) mechanical cooler to precool the $^4\text{He}$ fridge at suitable temperature to allow the condensation of the gas. The system is presented in figure 23. The sorption cooler will be attached to the cold stage of the GM cooler, which is the lowest copper flange in the picture on le left hand side of Figure 23.

The $^4\text{He}$ fridge is presented in figure 23. The indium tube coming from the top of the charcoal pump is visible. This will be connected to a gas line, in this way it is possible to charge, and consequentially test, the fridge with different quantities of the gas.

2.2.6 sub-K systems
2.2.6.1 Sub-K System Description  The $^4$He + $^3$He sorption fridge selected to cool the QUBIC focal plane was manufactured by Chase Cryogenics and is shown in Figure 24 (left). It is presently installed within another experiment (cryogenic electron paramagnetic resonance). We are negotiating a calendar for final operations of this system, but for now we have only limited data from earlier tests.

2.2.6.2 Sub-K Performance Tests  Figure 24 (on the right) shows a load curve measured with the Chase fridge installed into the EPR system. No loads were connected to the fridge (other than unintentional stray loads, e.g. radiative loading, but we would expect these to be similar).

We do not at this stage have a predicted hold time for the power considered. This fridge has a large charge, however. We will run the fridge with the expected load applied to obtain an expected run-time figure at a later date.

2.2.6.3 Sub-K Interfaces  The fridge requires a certain volume within the system and must be mechanically connected to the 4-K PTC second-stage cold plate and to the focal plane attachment. A crude CAD model of the fridge has been provided. When we have full access to the fridge again we will verify the dimensions of these mechanical interfaces.

Heat will flow into the fridge from the focal plane attachment and from the fridge to the 4-K plate. The heat lift from the FP will be characterized as described above. The energy flow to the 4-K stage will be substantial. This is illustrated by Figure 25, which shows the response of the 2nd stage of a Sumitomo RDK415 GM cooler from 3 cycles / part cycles of the Chase fridge. Admittedly no particular effort has been made to be gentle with these cycles, but the peak temperature of 7 K corresponds approximately to a peak load of 7 W. For sure careful operation of the fridge can reduce this, perhaps by a factor of two.

The operating conditions of the heaters will be confirmed later, but are 25 V max 100 mA max. Currently we are using 0.1-mm copper twisted pair to supply power to the heaters, but in the past we have used 0.1-mm Manganin.

Operation of the fridge will require readout of the cold stage temperature. This could be a thermometer mounted as close as possible to the cold stage for this purpose. However, a thermometer elsewhere on the load should be adequate. A thermometer on the intermediate stage can be useful.

A heater on the cold stage can be useful for verification of fridge operation (load curves) or warming up the system. It could also be used for thermostatic control. However, it is not vital.

Currently a micro-D connector is mounted to the fridge for these connections. Gender and pin-out will be confirmed at a later date.

The readout of the thermometers can be by typical equipment (e.g. Lakeshore 370, 318). We use computer-controlled heaters capable of driving up to 25 V at 100 mA.

Our in-house control system uses an xml script to describe a state machine for fridge cycling. For example, one state might set heat switch drive Voltages, with a test condition that would progress to a timed wait state once both heat switch thermometers are reading a high enough temperature. This script should easily translate to whatever control system is employed.

2.2.6.4 Sub-K Verification  Tests as described in section 2.2.6.2 have been conducted to check for adequate hold time at the expected power, the results are summarized in tables 16 and 17.
Figure 25: The effect on GM cooler 2nd-stage T from operation of the fridge

| Type     | Location                | No. Wire Pairs | Notes  |
|----------|-------------------------|----------------|--------|
| Diode    | $^4\text{He}$ heat switch | 1             |        |
| Heater   | $^4\text{He}$ heat switch | 1             |        |
| Diode    | $^3\text{He}$ heat switch | 1             |        |
| Heater   | $^3\text{He}$ heat switch | 1             |        |
| Diode    | $^4\text{He}$ cryo pump  | 1             |        |
| Heater   | $^4\text{He}$ cryo pump  | 1             |        |
| Diode    | $^3\text{He}$ cryo pump  | 1             |        |
| Heater   | $^3\text{He}$ cryo pump  | 1             |        |
| RTD      | Cold stage              | 2             | Optional|
| RTD      | Intermediate stage      | 2             | Optional|
| Heater   | Cold stage              | 1             | Optional|

Table 15: Sub-K fridge electrical interfaces

| $P_{\text{load}}$ (µW) | Days | Hours | Seconds | Joules | $T$ (mK) |
|-------------------------|------|-------|---------|--------|---------|
| 19.5                    | 3.75 | 89.92 | 323700  | 6.31   | 336 mK  |
| 43.9                    | 2.45 | 58.83 | 211800  | 9.29   | 349 mK  |

Table 16: $^3\text{He}$ hold times for two load values.

| $P_{\text{load}}$ (mW) | Days | Hours | Seconds | Joules | $T$ (K) |
|-------------------------|------|-------|---------|--------|---------|
| 4.39                    | 0.03 | 0.70  | 2520    | 11.05  | 1.2 K   |

Table 17: $^4\text{He}$ hold times for one load value.
2.2.6.5 Transportation Issues It should be noted that this fridge (and the 1-K fridge) relies upon thin-walled tubing to contain high-pressure gas. This makes it necessary to take extra precautions whilst shipping. The fridge will be shipped from Manchester with any shipping stays considered necessary, and comparable arrangements must be put in place to stiffen the assembly sufficiently for onward shipping after integration.

2.2.7 Heat Switches

2.2.7.1 Heat Switches Description For the base-line configuration two types of heat switch are considered (see Figure 26):

Convective Heat Switch Two thermal stages (OFHC copper) are connected with a twin-pipe circulation system (thin-wall stainless steel). Helium is injected into the circuit using a small cryo pump. So long as the physically-higher stage is colder than the lower stage the gas will convect around the circuit. Gas is cooled by the upper stage and warmed by the lower stage, effecting a transfer of heat. If the switch is operated across a phase transition (i.e. the stages are above and below the boiling point) heat transfer is especially effective due to the latent heat taken / given up by condensing / boiling.

Minimal Gap Heat Switch This new design uses a single stainless-steel tube, which is almost filled with a copper rod, with a small gap around the rod such that it is not in contact with the inside wall of the tube. This is not connected to the bottom, but at room temperature it might just touch the bottom stage. At cryogenic temperatures differential contraction opens a very small gap at the bottom of the rod. This means that the off conductance will be determined solely by the conductance of the stainless steel tube. Helium from a cryo pump (not fitted in the photo) is released into the volume to turn the switch on. Conduction across the small gap by helium gas is very effective. When the low end temperature is low enough to condense liquid to bridge the gap the conductance rises further, and further still with the formation of super-fluid helium.

We use convective switches routinely, for example to cool large sorption-fridge cryo pumps. In fact the example presented here has been designed for use with the large ⁴He fridge we propose for cooling the 1-K Box. This design uses larger tubes than previously for higher heat transport. For use at lower temperatures where the off resistance should be optimized we would probably choose finer tubes.

2.2.7.2 Heat Switch Performance Tests Results from on and off conduction measurements of the convective switch are given in Figure 27 on the right and left hand side respectively (note the different power scales). These were taken with a range of ⁴He charge pressures. As may be anticipated increasing the charge results in higher heat transport. However, the 10-bar charge clearly shows that the off conductance has been compromised. We intend to repeat this test with a larger cryo pump.

Whilst we have not made a test with a negative temperature difference imposed on the switch we would expect the residual conductance to be, at worst, no more than the y-intercept of the off measurements. We would expect a reduction in practise, since whilst an residual vapour can contribute heat transport by convection when the bottom stage is warmer than the top, with the bottom stage now held cold than the top this should be suppressed.
Our tests of the minimal-gap arrangement have so far been unsatisfactory. We will report further as this develops. We expect to be able to provide adequate conductance with the convective switch if the MGHS is unsuccessful.

### 2.2.7.3 Heat Switch Interfaces

The mechanical interfaces to the heat switches are the 4-hole mounting points at top and bottom. Correct orientation is paramount, with the item to be cooled attached to the lower stage. The height of the switches is to-be-decided. The volume taken by the switch may be inferred from the CAD model. There is some flexibility in terms of reorienting the cryo pump, but note that we might want to double the size over that shown in the model. A weak link wire will be required to bring the cryo pump to 4 K.

Thermally, the switch will accept thermal power at the bottom and couple it to the top. The load on the fridge will be determined mostly by the power extracted from the cooled stage. A small amount of power is added by the cryo pump.

Electrical interfaces are described in table 18. Provision of thermometers / heaters has not been discussed. The type preferred elsewhere may be used for the switch, for operation from room temperature to 4 K. The maximum power to the heater is typically less than 500 mW (actually more usually about 200 mW) but up to a few W can be useful when a rapid heating is desired. We use 330R, max 32 V 100 mA with 0.1-mm copper wire (but we have used 0.1-mm Manganin in the past).

As for the fridge our usual computer control uses a state machine language. Operation of a heat switch is trivial and this approach may readily be translated to the language of choice.

### 2.3 Optical chain

As shown in Figure 2, the sky radiation experiences several steps as it propagates through the optics of the QUBIC 1st module; all of them are described in this section.

The optical chain shown on Figure 28 is completed with a selection of spectral conditioning before the combiner: in intensity, by filters, and in polarization, by a modulator (HWP) and a polariser. A dichroic, before the focal planes, splits the radiation into the two bands at 150 and 220 GHz. Finally a couple of radiation shields in front of the cryostat and around the whole instrument allow a reduction of local spillover.
Figure 28: The off-axis dual reflector chosen for the QUBIC beam combiner. The rays, at -7°(green), 0°(blue) and +7°(red) represent the beams from the re-emitting horns.

Figure 29: Detail of the window mounting system.

2.3.1 Window

The window is the first optical element encountered by the incoming radiation beam, and separates the high vacuum present in the cryostat jacket from the room-pressure environment, while allowing millimeter waves in the cryostat. A cylindrical slab (560 mm diameter, 20 mm thick) of high-density polyethylene (HDPE) has been used, as the best compromise between transparency at mm waves and stiffness (the window must withstand an inward force of about 2.4 tons due to atmospheric pressure).

The HDPE slab is pressed against the top cover of the cryostat by an Al ring (see Figure 29) with a suitable number of screws. The vacuum seal is obtained using an elastomer o-ring for laboratory tests, and an indium seal for operation in Concordia, at very low ambient temperatures. The pressing ring is designed to mitigate the effects of differential thermal contractions, which is significant for HDPE vs aluminum.

2.3.2 Half Wave plate

2.3.2.1 Mesh Half Wave plate The QUBIC mesh HWP is designed to work across the two bands of the QUBIC first module instrument (see Figure 19). This means that good RF performance needs to be achieved across a large relative bandwidth, of the order of 73%. The required diameter is 500mm clear aperture.

The QUBIC HWP is based on metamaterials (Figure 30). These devices are alternative solutions to the more massive, expensive and limited-diameter birefringent Pancharatnam multi-plates. The metamaterials are developed...
Table 19: Mesh-HWP bandwidth requirements.

| Channel    | ν₁ (GHz) | ν₂ (GHz) | Bandwidth |
|------------|----------|----------|-----------|
| 150 GHz    | 127      | 171      | 30%       |
| 220 GHz    | 192      | 272      | 34%       |
| 2 channels | 127      | 272      | 73%       |

using the embedded mesh filters technology. Very large bandwidth mesh-HWPs (≈ 90%) have been successfully realised in the past. They have been used for millimetre wave astrophysical observations at the 30m IRAM telescope with the NIKA and NIKA2 instruments [Calvo et al. (2016)]. The measured performance of a typical prototype, in terms of transmissions and cross-polarisation, are reported in Figure 31 which shows a very good agreement between model and data.

The QUBIC final design is very similar to the prototype discussed above. The bandwidth requirements are less challenging and this allows to achieve better in-band RF performance. The design is based on 12 anisotropic mesh grids and the overall thickness is of the order of 3.5mm. The expected performances of the QUBIC mesh HWP are reported in Figure 32. The averaged transmissions, absorptions, differential phase-shift and cross-polarization are listed within the same figure.

2.3.2.2 Rotational system for the HWP

Polarization modulation is achieved by rotating a large diameter HWP (Half Wave Plate). Since the HWP is mounted on the 3K stage of the cryostat, a cryogenic rotation mechanism is needed. The one designed for QUBIC inherits several of the solutions developed for cryogenic rotator developed for the PILOT balloon-borne instrument successfully flown by CNES [61]. This is a stepping rotator, able to position the HWP in 8 different positions, in steps spaced by 11.25°, for redundant coverage of the needed position angles. The system is shown in Figure 33. The HWP is rotated by a stepper motor mounted outside the cryostat shell. Motion is transmitted through the shell by means of a magnetic joint. A fiberglass shaft transmits the rotation to the cryogenic part of the system, with negligible heat load, and rotates a pulley driving a Kevlar belt. The HWP support ring has a groove for the Kevlar belt, which is tensioned by a spring-loaded capstan pulley. The HWP support ring is kept in place by three spring loaded hourglass shaped pulleys at 120°, as shown in Figure 33. All the pulleys rotate on optimized-load thrust-bearings for minimum friction. The step positions of the HWP are set by holes sets precisely
Figure 31: Large bandwidth (~93%) mesh-HWP prototype: modeled and measured performance.

Figure 32: Expected performance of the QUBIC broadband mesh-HWP design.
located on a section of the HWP support ring: this builds a 3-bits optical encoder read by optical fibers (see [61] for more details).

The HWP is mounted on the ring by using a custom made block in order to reduce the differential thermal contraction between Al and Polyethylene (see Figure 34).

### 2.3.3 Filters / Polarizer / Dichroic

The general philosophy in filter provision is two-fold: 1. To minimise the thermal loading at the various temperature stages by sequentially rejecting short wavelength radiation. This is achieved with thermal filters in combination with baffling and careful optical design, to ensure that the out of band and thermal load at the detector arrays is suitable for the scientific requirements. 2. To define the required spectral passband at the arrays and maximise the in-band optical transmission. There will be an optimization procedure on the entire filter chain to maximise transmission (i.e. to manage the relative fringing between filters) and minimise out-of-band radiation. In addition the filters must be able to withstand cryogenic cycling and maintain flatness within their mounts. These specifications have been proven in the past with the AIG’s strong heritage in space mission filter production (e.g. ISO, Mars observer, Cassini, Herschel & Planck Space Observatories) and with ground-based instruments, such as SCUBA2, BICEP and SPT. The QUBIC development puts in place the need for larger diameter components than the AIG have previously provided.
Table 20: Metal mesh devices to be supplied by Cardiff University to the QUBIC project. Z coordinates are given in the Global Reference Frame (GRF). (*) emissivity could be lower. (**) low frequency in reflexion, high frequency in transmission.

| Component                  | Temp | Transm | Emissivity | Coord. Z GRF | Optical diameter | Useful diameter |
|----------------------------|------|--------|------------|--------------|------------------|-----------------|
|                            | K    | %      | %          | mm           | mm               | mm              |
| Common to 2 bands           |      |        |            |              |                  |                 |
| Window                     | 250  | 98     | 1          | 480.00       | 407              | 600             |
| IR blocker 1               | 250  | 98     | 1          | 460.00       | 401              | 600             |
| IR blocker 2               | 250  | 98     | 1          | 452.55       | 401              | 600             |
| IR blocker 3               | 100  | 95     | 1          | 342.10       | 385              | 430             |
| IR blocker 4               | 100  | 98     | 1          | 335.00       | 381              | 430             |
| IR blocker 5               | 100  | 98     | 1          | 327.10       | 381              | 430             |
| IR blocker 6               | 6    | 98     | 1          | 285.50       | 371              | 410             |
| 12cm-1 LPE                 | 6    | 95     | 2          | 276.30       | 371              | 410             |
| HWP                        | 6    | 95     | 2.5        | 237.80       | 361              | 380             |
| Polarizer                  | 6    | 99     | 1          | 183.60       | 352              | 380             |
| B2B horns + switches       | 6    | 99     | 5          | 0.0          | 330              | (*)             |
| Beam combiner              | 1    | 99     | <1         |              |                  |                 |
| Cold stop 10cm-1 LPE       | 1    | 95     | 2          |              |                  |                 |
| Dichroic filter            | 1    | 95     | 2          |              |                  |                 |

Band1: 150 GHz Singlemoded

|                  |      |        |            |              |                  |                 |
|-------------------|------|--------|------------|--------------|------------------|-----------------|
| 6cm-1 edge        | 0.3  | 98     | 2          |              |                  |                 |
| 8cm-1 LPE         | 0.3  | 98     | 2          |              |                  |                 |

$maxi = 0.11486$

Band2: 220 GHz Multimoded (bandpass 200-240 GHz)

|                  |      |        |            |              |                  |                 |
|-------------------|------|--------|------------|--------------|------------------|-----------------|
| 9cm-1 edge        | 0.3  | 98     | 2          |              |                  |                 |
| 11cm-1 LPE        | 0.3  | 98     | 2          |              |                  |                 |
| Band defining filters | 0.3 | 80     | 2          |              |                  |                 |

$maxi = 0.11486$

2.3.3.1 QUBIC optical configuration The QUBIC instrument optical layout/cryostat design is shown in Figure 28. A series of band-defining, blocking and thermal (IR) filters will be mounted at different temperature stages, with a large photolithographic polarizer and a single rotating mesh HWP at 6K. We have allowed provision for a high number of filters at critical apertures and temperatures, although these may later prove unnecessary.

2.3.3.2 Mesh Filter Specification The complete list of devices to be supplied by Cardiff University to QUBIC is given in Table 20.

2.3.3.3 Mesh Filter QO deliverables

IR Blocking filters

Up to 500mm active thermal filter devices are required of 2 or 3 basic pattern types. The transmission performance of prototype (300mm) devices is given in Figure 35. These thermal filters are single layer metal-mesh element devices that reflect a high proportion of the unwanted IR radiation. They require a simple aluminium support ring and the filter element itself is only 4µm thick.
Figure 35: Transmission performance of thermal filters for the QUBIC instrument.

Figure 36: Transmission performance of prototyped common LPE blocking filters

Blocking Filters (Low Pass Edges) - 6K, 1K, 0.3K stages. Throughout each optical chain there will be a series of 4 low-pass edge filters per band/pixel. These will be located at the 6K and 1K stages and at the 320 mK array. These are designed to block out-of-band FIR radiation, whilst maintaining high in-band throughput. The transmission performance of the 3 possible large low-pass elements common to both bands is given in Figure 36. Although, for the purposes of all large scale CMB instruments, we have recently prototyped a new, multi-element 12 cm$^{-1}$ LPE filter which will have improved FIR rejection (1 part in 104) - see Figure 37. The thickness of these current filter elements is as follows:

- 10 cm$^{-1}$ LPE 1.4mm without ARC, 1.8mm with ARC;
- 11 cm$^{-1}$ LPE 1.3mm;
- 12 cm$^{-1}$ LPE 2.2mm;

Figure 37: Transmission performance of possible 12 cm$^{-1}$ blocking filter.
Band Defining Filters - 150, 220 GHz
Band-defining filters are required at 150 and 220GHz:
- 150 GHz is single-moded with a band-edge at 5.6 cm\(^{-1}\) (25% BW)
- 220 GHz is multi-moded with 18% bandwidth, requiring a band-pass filter or a high-pass low-pass combination (6.7 cm\(^{-1}\) - 8.0 cm\(^{-1}\)).

Typical filter performance for a number of 150/220GHz options, with modelled atmosphere is given in Figure 38.

Dichroic
This filter is designed to transmit (>90%) the 220GHz band, whilst reflecting (>90%) the 150GHz band. Prototype hot-press and air-gap 6.5 cm\(^{-1}\) HPE devices have been produced by Cardiff AIG and shown to be effective in both reflection and transmission at up to 0°incidence. Figure 39 show normal incidence transmitted performance.

Further testing of prototype devices is underway, with emphasis on the mounting and flatness to these large components. A hot pressed device will be the preferred option, provided that the R and T performance are found to be comparable to that for an air-gap device and that flatness can be maintained through cryogenic cycling.

Photolithographic polarizer
A 10µm period wired polarizer is required for 6K operation. A prototype has been made at 450mm diameter. This is shown in Figure 40.
2.3.3.4 Quasi-Optical component fabrication, assembly and tests

All the Quasi-Optical (QO) components (mesh filters, half-wave plate, polarizer and dichroic) are manufactured by the Astronomy Instrumentation Group (AIG) in Cardiff. This group is the largest manufacturer and first world supplier of metal-mesh components. Devices from this group have been successfully used in tens of astronomical experiments ranging from ground-based to satellite missions.

The QO components are manufactured by using photolithographic techniques, specifically the mesh technology. The TRL level is 9 for mesh-filters, polarizers and anti-reflecting (ARC) coatings. Mesh-HWPs have been successfully used recently in ground-based experiments.

The devices will be completely built within the cleanrooms of the Cardiff AIG. All the grids for all the device will be visually checked. In addition, dimensional measurements will be required during the mesh-HWP development due to the criticality associated to the phase response of each grid. The assembly and the bonding of the grids will be carried out within our cleanrooms.

Depending on the type of device and on their thickness, different types of mechanical mounts will be used for the different components. These metallic rings will guarantee rigidity, flatness and operation at cryogenic temperatures.

The filters, the HWP, the polarizer and the dichroic will all be tested and characterised in our laboratories by means of different Fourier Transform Spectrometers. Different experimental setup will be adopted for each type of device. For example, the HWP tests will require transmission measurements along the two axes and cross-polarisation at 45 degrees rotation angle. The frequency range of the tests will cover the QUBIC operational bandwidth. For the thermal filters, the measurements will be extended up to the near-infrared region to check for unwanted leakage.

2.3.4 Horns

Similarly to the switches, we have been through a prototyping campaign of the QUBIC feed horn array.

This array is composed by two blocks of 400 horns each. The two blocks are placed back-to-back with a layer of switches that can open or close the optical path to the radiation (cf. previous section and section 3.2).

The feeds are corrugated horns optimized for a wide-band response (in the range 130-240 GHz). They are based on a modification of a previous design, which was optimized for 150 GHz only, when QUBIC was still designed for 150 GHz-only measurements. The left panel of Figure 41 shows the current profile of the QUBIC horns; we call this the QUBIC2 design. The right panel shows the original design adopted for the 150 GHz – only version of QUBIC; we call this the QUBIC1 design.

2.3.4.1 2x2 prototypes array

The manufacturing of several horns with complex internal geometry with sub-mm tolerance is a challenging task. To achieve the result we identified the platelet technique as the most suitable to build such a large array with affordable cost. According to this technique the horn is built from suitably drilled metal platelets that are subsequently stacked to form the horn structure.

For QUBIC, we chose Photochemical Etching and Milling to drill the platelets. This technology is applied to a wide range of materials for the fabrication of highly complex objects, with an achievable precision of the order of ±
Figure 41: Left panel: the current design of the QUBIC feed horns, optimized for wide band response. Right panel: the first design of the QUBIC feed horns, optimized for 150 GHz measurements.

| Prototype n. | # of elements | Design | Material | Scope | Tests performed | Status |
|--------------|---------------|--------|----------|-------|----------------|--------|
| 1            | 4 (2x2)       | QUBIC1 | Brass    | Check mechanical profile | Visual inspection | Completed |
| 2            | 4 (2x2)       | QUBIC1 | Anticorodal | Check mechanical tolerance and electromagnetic performance | Metrological measurements Return loss Insertion loss | Completed |
| 3            | 4 (2x2)       | QUBIC1 | Silver-plated anticorodal | Check effect of silver plating | Return loss Insertion loss | Completed |
| 4            | 4 (2x2)       | QUBIC1 | Aluminium | Check performance with pure aluminium | Return loss Insertion loss | Completed |
| 5            | 4 (2x2)       | QUBIC2 | Anticorodal | Double check with new design | Return loss | In progress |
| 6            | 128 (two 8x8 modules) | QUBIC2 | Silver-plated anticorodal | Check of manufacturing scale-up Verification of interface with switches Verification of feed-switch functionality | | In progress |

Table 21: List of QUBIC feed horn array prototypes

10% the material thickness.

To verify the applicability of this technology to QUBIC horns we set up a prototyping campaign with the following objectives:

- Verify the possibility to manufacture the horns and assess the achievable mechanical tolerance,
- Assess the electromagnetic performance of the obtained horns in terms of return loss, insertion loss and angular beam pattern and compare it with the simulations,
- Verify the scalability of this technique to a large number of elements.

In this prototyping phase we built 6 prototypes, which are detailed in Table 21.

In Figure 42 and Figure 43 we show pictures of the QUBIC1 brass prototype, which has been cut to perform a visual inspection of the corrugation details.

Figure 43, in particular, shows details of the inner structure of the feed corrugations, revealing the presence of small cusps on the top of each tooth and groove. These features likely result from a non-homogeneous action of the chemical agent on the metal.

We have analyzed with simulations the impact of such defects on the feed-horn performance and the result is that the impact is negligible. This analysis is presented in Section 2.3.4.2.

In Figure 44 and Figure 45 we show the complete set of 2x2 prototypes.
Figure 42: Outer view of the brass QUBIC1 prototype.

Figure 43: Inside view of the brass QUBIC1 prototype. Left: Cusp in groove. Right: Cusp on tooth.

Figure 44: Brass prototype (left), anticorodal prototype (middle), silver-plated anticorodal prototype (right).
2.3.4.2 Metrological measurements  Here we report the results of metrological measurements performed on the platelets of the brass module prior to its integration. We measured the diameters of the antenna holes with a Werth Scopecheck 200 metrological machine and compared measurements with the nominal values in the mechanical drawing. More details are given in Figure 46 which shows the absolute and relative deviations of the measured diameters with respect to the nominal one as a function of the diameter itself. From these results we can draw the following considerations:

1. The relative error is approximately constant, of the order of 0.5% or less, apart from diameters smaller than \( \approx 2 \) mm, for which the relative deviation is of the order of 1%

2. There is a systematic trend: smaller holes tend to be larger than the nominal, larger holes tend to be smaller. This trend could be in principle corrected in the manufacturing if necessary by correcting the drawings.

Figure 47 shows the deviation of the measured position of the holes center from its nominal value. We see that the distribution of these errors is not symmetrical around the origin but lies preferentially along one direction. This asymmetry can be mitigated during integration, by turning every other plate by 90°.

We see that the r.m.s. values of these deviations are in the range 10 – 20 \( \mu m \), so about two order of magnitudes less than the wavelength. Therefore we expect that they will not impact the electromagnetic performance of the feed significantly. This is confirmed by our return loss measurements reported in Section 2.3.4.4.

2.3.4.3 Effect of non mechanical non idealities on performance  We have analyzed the effect of cusps on the feed-horn electromagnetic performance, namely: (i) E-plane and H-plane radiation patterns, (ii) cross-polar maximum component in the 45 degree plane and (iii) return loss. This section discusses the main results, the details of this work are reported in [45]. We have used the SRSR code, modifying the mechanical profile of the horn adding a triangular cusp with 60 \( \mu m \) height on the top of each tooth and groove. This value corresponds to the maximum height measured on the brass prototype. We have considered three cases:
Figure 47: Deviation of the hole center position with respect to the nominal value. The distribution of these deviations is asymmetrical. This asymmetry can be mitigated during integration by turning every other plate by 90°.

- Nominal design with head plate of 0.3 mm thickness
- Baseline design with head plate of 3 mm thickness
- Baseline design with head plate of 3 mm thickness and 60 µm cusps on both teeth and grooves of all corrugations.

We have run simulations at different frequencies: \( f_0 = 150 \text{ GHz}, f_0 \pm 6.25\% \) and \( f_0 \pm 12.5\% \). Our study shows that these defects produce only minor effects on the feed-optical performance. The main effect is an increased level of reflections (max \( \approx 3 \text{ dB} \)) in the 135-160 GHz frequency interval (see Figure 48). The total return loss, however, is always less than \(-20 \text{ dB} \), in line with the QUBIC required value. The level of cross-polarization is practically unaffected (see Figure 49) while the H-plane beam pattern presents small differences from the ideal one only in the sidelobes below \(-40 \text{ dB} \) (Figure 50).

2.3.4.4 Electro-magnetic measurements on QUBIC1 prototypes

We have tested prototypes number 2, 3 and 4 to verify their electromagnetic performance in terms of return loss, insertion loss and beam pattern. Because we realized the three prototypes with various materials (Anticorodal, Silver-plated Anticorodal, Aluminium) we are also interested to check the impact of the material on the performance. We summarize below the main results, while the reader can find more details about the experimental setup and the analysis procedures in [48].

Return loss:

We have tested the return loss of the three prototypes with the Vector Network Analyzer of the Milano Bicocca Radio Group. In [48] we discuss the details of the measurement system calibration. In Figure 51 we show the measured return loss of the three prototypes. Our results shows essentially three things: the first is that the return loss does not depend on the details of the three adopted materials, as was expected; the second is that the three prototypes have very similar performance, demonstrating the repeatability of the manufacturing technique; the third is that the level of return loss is of the order of \(-30 \text{ dB} \), in line with the simulations without the cusps (see the magenta line in Figure 48) showing that the presence of such defects produce only a minor impact on performance.

Insertion loss:

We have measured the insertion loss on the three prototypes. This is a key parameter for the scientific performance of QUBIC and it is also difficult to measure with high accuracy. This is because the expected loss is less than 1 dB and it is, therefore, difficult to disentangle from other experimental artefacts. We used far field measurements, both in a laboratory optical bench and in an anechoic chamber, to measure the insertion loss. The idea of the measurement is to take the difference of the power transmitted between to standard horns and the power transmitted when one of the two horns is substituted with the QUBIC horn. Again, we refer to [48] for the details of the experimental setup and the data analysis. In Table 22 we summarize the insertion loss.
Figure 48: Impact of cusps on the feed-horn return loss. The effect is represented by the difference between the yellow and magenta curves. Here we see that these defects slightly increase the reflections in the frequency range between 135 and 160 GHz.

Figure 49: Effect of cusps on maximum cross-polarization. We see that cusps have practically no effect on the cross-polarization (compare yellow and magenta curves).
Figure 50: Simulated beam patterns showing the effect of cusps on the E and H planes (compare magenta and yellow curves). The blue curve shows the beam pattern of the nominal design with 0.3 mm head plate. The implemented design foresees a 3 mm head plate thickness.

Figure 51: Return loss measured on one horn of each of the three prototypes
Table 22: Measured Insertion Loss (IL) of the three QUBIC1 prototypes

| Prototype n | Material      | IL measured on lab bench [dB] | IL measured in anechoic chamber [dB] | Uncertainty [dB] |
|-------------|---------------|-------------------------------|--------------------------------------|------------------|
| 2           | Anticorodal   | 0.15                          | Not measured                         |                  |
| 3           | Aluminium     | 0.45                          | 0.5                                  | ± 0.3            |
| 4           | Silver-plated Anticorodal | < 0.10                        | 0.3                                  |                  |

Figure 52: Measured main beam patterns. Left: Aluminium prototype. Right: Silver-plated anticorodal prototype. Blue curve: E-plane. Red curve: H-plane.

(IL) values measured on the three prototypes according to the two methods. Notice that the IL of prototype n. 2 was not measured in the anechoic chamber, so we do not report its value. The results show that, within the measurement uncertainty of ±0.3 dB, the insertion loss is less than 1 dB, which is in line with the scientific requirements of QUBIC. Our measurements also suggest that silver-plating improves electrical conductivity, although by a slight amount. This result led us to the decision to adopt silver-plating as our manufacturing baseline.

2.3.4.5 Beam pattern: In the framework of the anechoic chamber measurements of the insertion loss we have also made a preliminary measurement of the main beam pattern. In Figure 52 we show these measurements for the two tested prototypes. Our results show that, at least at the level of the main beam, the pattern is as expected (compare with Figure 50) and that the type of material does not affect significantly the optical response. We plan to perform more detailed measurements on the QUBIC2 prototype (which is the current baseline) to characterize the beam sidelobes and the measurement errors. These measurements will be compared to the shape expected from simulations.

2.3.4.6 8x8 back-to-back horns : We have designed a 128-horn array arranged in two 8x8 blocks that will be interfaced with the 8x8 switch prototype. This is a complete and functional prototype of the QUBIC full array that will be integrated in the Technological Demonstrator (cf. section 2.6). Figure 53 shows the CAD design of the 8x8 prototype interfaced with the switch block. On the left we show one of the two 64 horns blocks interfaced with the top flange of the switch array. Notice that we show the inside of the block, constituted of drilled platelets. The platelets present two types of holes: one type reproducing the horn corrugated structure, the second to lighten the structure. On the right we show the two horn arrays interfaced with the switches block.

Figure 54 shows the first realization of the back flange of the 8x8 prototype, which interfaces with the switch block.

2.3.5 Switches

The QUBIC self-calibration technique is based on cross checking and comparing redundant baselines produced by equally spaced couples of horns. This requires the identification of the interferograms generated by equivalent baselines. The most obvious approach to do so is to enable only one couple of horns at a time (i.e. closing all but
two horns), still, it has been shown that an equivalent option is to enable all the horns but that particular couple\cite{34}. This second possibility provides the advantage to perform the self-calibration in very similar conditions with respect to the astronomical observations in terms of radiation loading on the detectors. In both cases a shutter for each back-to-back horn is needed. The QUBIC final module will have 400 horns with 400 switches working at 4K.

An important effort was made in these years to develop a low loss (mechanical), reliable, switch prototype compatible with both the RF specification and cryogenic requirements. A first single channel prototype was completed and successfully tested at APC to test the working principle. It is a single pole single through (SPST) realized by means of a blade (shutter) blocking the circular waveguide between the back to back horns. The blade is activated by an electromagnet pushing and pulling a ferrite soldered to a hook connected to the shutter (see Figure 55).

The single channel prototype was designed to have a very good return loss and low insertion loss. Also the instrumental polarization (different phase delay of the propagating modes) must be kept very low. A first design was done in Manchester studying the effects of the waveguide gap with respect to a shutter 100 µm thick (Figure 56). All the prototypes have been manufactured with 200µm gap.

The single channel prototype was successfully tested in liquid nitrogen to verify the capability of the device to keep moving at cryogenic temperature. A RF test was also performed at room temperature to verify the design performances (Figure 57) that are encouraging.

The University of Milano Bicocca (UNIMIB) is in charge of the realization of the electronics to drive the switch coils and to acquire the shutters’ positions. The idea is to excite the coil with a pulse and acquire the response time that depends by the resistance R and inductance L. When the switch is open (ON position) the ferrite is outside the coil and the inductance is lower than in the OFF position, causing a faster response time. When in OFF position the current to drive the coil can cause self-heating and the electronics can automatically compensate the change of R with temperature. Another advantage of the possibility to switch in the OFF position only one couple of switches at the time, as opposed to switch the all but two, is the drastic reduction of the dissipation during the self-calibration. A board equipped with an FPGA (XILINX Spartan-6) and the driving circuits to operate 16 switches has been developed (Figure 58). This is a scalar design which is ready for the 8x8 prototype simply using 4 boards and can be adapted to the final 20x20 array. The FPGA is in charge of the calculation of the switch positions and communicate with the

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Figure 53: CAD design of prototype #6 (128 horn array). On the left we show one of the two 64 horns blocks interfaced with the top flange of the switch array. On the right we show the two horn arrays interfaced with the switches block.

Figure 54: First realization of the back flange of the 8x8 prototype.
Figure 55: Particular of the waveguide shutter for the 8x8 prototype built as a replica of the single channel switch. In the center of this figure the blade (dark grey) and coil (light grey) can be seen.

Figure 56: Switch Performance forecast when in “ON” (Top Panel) and “OFF” positions for various gap width between the two facing waveguides. 200 µm gap was chosen.
The prototype of the 8x8 switch block was also realized by a milling machine at UNIMIB (Figure 59) and it will be assembled and tested at room and cryogenic temperature inside the cryofacilities of the millimetric lab. The main aim of the test is to verify the functionality of the 64 switches at 4K, make an estimate of the medium time between failures of the coils and quantify the heat dissipation during a typical self-calibration cycle.

2.3.6 Optical combiner

2.3.6.1 Optical combiner configuration The interferometric requirements described in Section 1.2 have been satisfied with a reflective configuration for the optical combiner. A comparative study among refractive and reflective
Figure 59: The 8x8 switch block prototype with the PCB to bias the coils is visible in the left picture. No component is already mounted inside. In the right picture the switch block is closed.

| mirror     | Size (x dimension) | Size (y dimension) | conic constant | Focal length               |
|------------|--------------------|--------------------|----------------|---------------------------|
| Primary    | 400 mm             | 600 mm             | -1             | 164.48 mm (parent parabola) |
| Secondary  | 600 mm             | 500 mm             | -0.1294        | 287.81 mm (focal point separation) |

Table 23: Combiner parameters (the primary mirror surface was further optimised using the Zemax ray-tracing package and the final design, specified by a set of quadratic surface parameters differs slightly from the conic surface specified here).

2.3.6.2 Mirrors The optical combiner is realized by two off-axis mirrors focusing the light remitted by the back-horns onto the focal planes. The primary mirror (M1, cf. Figure 60) and the secondary mirror, (M2, cf. Figure 61) are machined in aluminium. They are attached by 9 points on their supports. The supports are two identical hexapods for the 2 mirrors. Each hexapod has 6 degrees of freedom allowing the alignment of the mirrors and the correction of some possible minor errors in the manufacturing process.

The two mirrors, designed in Maynooth, will be machined at the University of Milano Bicocca. The material will be Aluminium processed with several thermal treatments from -200°C up to 340°C during the different machining phases, in order to relax all the internal tensions and guarantee the desired final profile. A reliable thermal sequence, conceived and optimized for VIRGO gravitational antenna [Need a reference] and successfully replicated by the Milano Bicocca team for the OLIMPO Fourier Transform Spectrometer3, will also be applied for the QUBIC optical combiner. A set of reduced size mirrors will be used for the technological demonstrator.

Once machined, the mirrors’ shapes will be verified at room temperature with a home-made 3D gauge realized by the Milano Bicocca team using a motorized 3 axis linear stage with an accuracy of ±3µm over 1 meter moving a digital indicator with an accuracy of ±2.5µ over 60mm. The same team will evaluate the surface roughness of the mirrors on some spots 1cm wide using interferometric techniques.

3http://planck.roma1.infn.it/olimpo/
Figure 60: M1, primary mirror.

Figure 61: M2, secondary mirror.
2.3.7 Cold stop / internal screening

In order to limit the beam propagation towards the detectors only due to the sky radiation passing through the feed horn array and the optical combiner, an analysis focused on the straylight impact has been conducted and cold shields have been considered in the final optical configuration. First an aperture between primary and secondary mirrors is inserted to minimize straylight and all the potential diffracted light reaching the detectors. This shield is named "Cold Stop" and it is maintained at 1K, such as the whole combiner. The size of this aperture has been inferred by a beam propagation analysis as described in Section 2.3.8.

A second shield is also planned to avoid unwanted radiation on the on-axis focal plane as shown in Figure 62. The decision to include these two screens has been derived from an analysis of the straylight contribution from the feed horn array on the two focal plane arrays without passing through the optical combiner, i.e. without reflection on both mirrors. At first we employed a geometrical optic code written in Mathlab and after a Physical Optics approach with GRASP [12] see as an example the rays in the 3D layout on the right of Figure 63 for a secondary feed horn on the edge of the array.

The additive noise in fringes generation and the unwanted radiative power extra-loading have been considered to estimate the straylight impact in the final instrument optical performances. Neither the Cold Stop nor the dichroic were included in this study then taking into account the worst situation.

The fringe patterns for two representative couples of feed horns (tangential and sagittal) are analysed for straylight \((s\textunderscore fringes)\) and for combiner propagation \((c\textunderscore fringes)\). The maps of the fringes are plotted in Figure 64 for all...
The amplitude of \( s_{\text{fringes}} \) is always 4 orders of magnitude lower than \( c_{\text{fringes}} \) assuming the same couples of feed horns and the spatial frequency of \( s_{\text{fringes}} \) is lower than \( c_{\text{fringes}} \) due to the different beam propagation. To avoid that a source with strong intensity at low spatial frequency (such as CMB anisotropies) could contaminate target observations (B mode), we decided to include shields to avoid straylight.

The increase in power due to straylight was estimated for a reference secondary feed horn on the edge of the feed horn array, ID-53. The power collected on the on-axis focal plane is almost 3 orders of magnitude lower respecting to the expected amount, see Figure 65.

### 2.3.8 Optical Simulations

The final optimisation of the dual-reflector combiner design was carried out using geometrical optics (ray-tracing) in order to take advantage of the speed and optimisation routines available in commercial software packages (e.g. [7]). However at these operating frequencies component sizes are not very large compared with the wavelength of radiation and so, for detailed analyses, techniques that do not ignore the effects of diffraction were used [8].

We started with the beams emitted by the secondary feed horns and propagated them through the optical system, primary then secondary mirror, and on to the focal plane. Initially we used a best-fit Gaussian beam for the horn beam and propagated it through an equivalent on-axis system using a Gaussian beam mode analysis and the ABCD technique [9]. Figure 66 shows the QUBIC combiner’s equivalent on-axis system and Figure 67 shows the Gaussian beam radius as a function of propagation distance \( (w(z)) \) for a selection of frequencies and a beam with a far-field divergence angle of 12.9°. The initial waist radius \( w(0) \) was calculated as

\[
w(0) = \sqrt{\frac{2\ln 2}{\pi \theta}}
\]

where \( \theta \) is the far-field divergence angle of the beam (FWHM of intensity in this case). This was useful for determining approximate beam sizes in the instrument and on the focal plane. For example, at 150 GHz an \( r = 51 \text{-mm} \) focal plane can capture \( \approx 80\% \) of the power in the 12.9° beam.
Figure 65: Power on the on-axis focal plane collected from the feed horn ID-53 passing through the combiner (right) and as straylight (left).

Figure 66: Equivalent on-axis system for the QUBIC beam combiner.

The focal length of the system is given by:

\[ f_{eq} = \left( \frac{1}{f_p} + \frac{1}{f_s} - \frac{d}{f_p \times f_s} \right)^{-1} \approx 300 \text{mm} \]  

(2)

For a more accurate determination of system performance and for the optimisation of the dichroic and cold stop size and location, a full vector physical optics (PO) analysis of all 400 beams was carried out with Maynooth University’s in-house software MODAL [11] and the commercially available software package GRASP [12] (Both use the same modelling technique and MODAL has previously been tested against GRASP). The beam emitted by the horns was calculated using a rigorous electromagnetic mode-matching technique [13] that views the corrugated structure as a sequence of smooth walled cylindrical waveguide sections each of which can support a set of TE and TM modes. At each corrugation there is a sudden change in the radius of the cylindrical guide and this change results in a scattering of power between the waveguide modes (the total power is conserved).

Calculating the footprint of these horn beams at various planes in the system allowed the optimum size and location of components to be determined [14]. The example in Figure 68 (left) shows the footprint of the beams on the secondary mirror. The figure is coloured to show the region where the intensity of each beam is above \( \exp(-2(r/w)^2) \) of its maximum (with \( r/w = 0.8, 1, 2 \) and 3). Green therefore shows the region which at least 99.9% of the power from each beam falls (this corresponds to much more than 99.9% of the total power, of course, since most beams fall entirely within this region).

This work was further developed [15] to fit a surface to the ‘edge’ of each of the beams in order to visualise their propagation through the optics (Figure 69). The edge can be defined as the points at which the intensity drops to a certain level or, for complex beam shapes, the radius required to encircle a given percentage of power. The beams are first calculated at a series of planes in the system using PO. The beam edges are joined using interpolation to check for beam truncation by supporting structures, electronics, ...

Once all the component sizes and locations were chosen, the 400 antenna beams were propagated through the system to the focal plane. The beams on the focal plane for the final configuration are shown in Figure 73 (150 GHz). The 400 plots of the focal plane beam are arranged so as to indicate the location of the horn antenna from which the
Figure 67: Gaussian beam width ($w$) as a function of propagation distance through the QUBIC beam combiner. The beam was chosen to have a far-field divergence angle of 12.9° at 150 GHz. The range of frequencies shown covers that of the dual-band instrument.

Figure 68: (left) Footprint of 400 antenna beams on a 600-mm diameter secondary mirror. The regions coloured red show where the intensity of each beam is greater than $\exp(-2(0.8)^2)$ of its maximum. Yellow, green and light blue correspond to $\exp(-2(1)^2)$, $\exp(-2(2)^2)$ and $\exp(-2(3)^2)$, respectively [14]. This particular simulation was carried out for the 14° beams of the original QUBIC design. (right) The same simulation for the outer ring of 12.9° horn beams (all 5 modes that could possibly propagate are included).
beam originated (the black line indicates the edge of the input array that will be used). Here we can see the effect of aberration and truncation on the beams, especially beyond the edge of the array that will be used. The plot on the right in Figure 73 shows the percentage of power from each of the horns that is captured by the main focal plane (limited to a maximum of approximated 80% for an unaberrated beam by the physical size of the bolometer array).

As the operating frequency of the instrument increases (up to 250 GHz) the back-to-back horns allow more hybrid modes to propagate, making the instrument multi-moded. We have used the surface impedance model [63] to calculate the dispersion curves of modes (up to azimuthal order \( n = 4 \)) in the QUBIC band. The surface impedance (hybrid mode) model is an approximate one that treats the corrugated wall of a horn as a surface with different average impedance in the longitudinal and azimuthal directions. It works well as long as there are several corrugations per wavelength but it cannot model detailed horn profiles. Here we have assumed that the waveguide section between the back-to-back horns is what allows modes through or not. The resulting dispersion curves are shown in Figure 70 which shows the HE11 mode propagating throughout the band. An \( n = 0 \) mode cuts on at around 190 GHz, an \( n = 2 \) mode cuts on just above 210 GHz and an \( n = 1 \) mode cuts on at about 240 GHz. There is a backward mode around 210 GHz.

We can use the more rigorous mode-matching technique to model the exact 12.9° QUBIC horn profile at a given frequency and to determine the relative power carried by each hybrid mode. This was done at several frequencies across the 220-GHz band. The actual hybrid modes themselves have not been identified merely the weighting of modes at azimuthal orders 0 to 4 (SCATTER uses many TE/TM modes to describe the aperture fields. The smaller
number of hybrid modes can be reconstructed from these, if we want to identify them without using Figure 70, for example. Comparison of Table 24 with Figure 70 shows broad agreement between the two models. It is clear that three modes dominate across most of the band (HE11, E02 and EH21) and carry approximately equal power. The HE31 mode carries a little power and there is also evidence for modes cutting on at the upper end of the band. For \( n > 0 \) modes, the orthogonal mode will also be supported. The five important modes are plotted in Figure 71.

The upper-band farfield beam patterns were calculated (including both sets of orthogonal modes) and are shown in Figure 72. The beam widens and flattens slightly towards the centre of the band and then narrows again. The beam changes significantly with the cut-on of extra modes between 240 and 250 GHz. For this reason 240 GHz was chosen as the cut-off of the upper frequency band.

At high frequencies the slightly narrower beams mean that we expect more power to reach the focal plane when compared with the 150-GHz results in Figure 73. The relative contribution of each of the five modes to the beam in the optical combiner will depend on how the input signal couples to the horns and so we have verified the combiner design (using their footprints) for each possible mode separately and for each of the 400 horns of the full instrument (including the central 8x8 of the technical demonstrator).

It was not possible to design a diffraction-limited imager for an instrument with such a low \( F/D \) (\( \approx 1 \)), where \( F \) is the effective focal length and \( D \) the entrance pupil aperture, and wide field-of-view (12.9° at 150 GHz) and so we know that the combiner will be affected by aberrations at some level. To illustrate the effect of such aberrations on...
Figure 72: (left) Farfield beam patterns calculated across the 150-GHz band (4GHz intervals) where the horns are single-moded and (right) the beam patterns across the 220-GHz band.

Figure 73: (left) Plots of the beam pattern from each of 400 input horns on the circular focal plane. The location of the input horn in the array is indicated by the placement of the focal plane plot. (right) The total percentage of power from each beam that is integrated on the focal plane (limited to \(\approx 80\%\) by the finite size of the focal plane). This calculation was carried out at 150 GHz [14].
the operation of the beam combiner we generated fringe patterns from a selection of 145 baselines ($\nu = 50$ in this case). Figure 74 shows the average pattern and also the standard deviation of intensity measurements on the focal plane. Because of aberrations, the fringe patterns are not identical, particularly at the edges of the focal plane, and so there interference is neither fully constructive nor fully destructive - the fringes become degraded. This means that the sensitivity of the interferometer to the corresponding angular scale will be reduced.

The resulting loss in sensitivity at all angular scales was calculated by considering the synthesised beam and resulting window function of the instrument [36]. The result for the original 14° beams, plotted in Figure 75 shows that the effect of the aberrations is to reduce the sensitivity of the instrument by 10%. The loss for the narrower beams is expected to be less than this.

The point-spread-function (PSF) calculated by exciting the input horn array with an on-axis plane wave and summing the 400 focal plane patterns is shown on the right of Figure 76. This example is the PSF of the dual-band instrument operating at 150 GHz. The location of the subsidiary peaks depends on the separation of horns in the aperture array and the width of the peaks depends on the number of horns. The amplitude of the peaks is determined by the amplitude of the horn beam pattern on the focal plane.

2.4 Detection chain

2.4.1 TES

2.4.1.1 Description

The QUBIC instrument detectors for the 150 and 220 GHz frequencies are composed of four 256-pixel arrays assembled together to obtain a 1024-pixel detector at the focal plane. The first QUBIC module is split into two focal planes for a simultaneous scan of the sky at both frequencies. The detectors are Transition Edge Sensors (TES) with a critical normal-to-superconducting temperature close to 500 mK, as illustrated by Figure 77. Voltage biasing of the sensors allows operation on the well known “extreme electro-thermal feedback” mode with increased bandwidth, direct power calibration and self-regulation of the TES at the superconducting transition temperature. The TES are made with a Nb$_x$Si$_{1-x}$ amorphous thin film ($x \approx 0.15$ in our case), a compound that has been extensively studied and whose production is well mastered. Its transition temperature $T_c$ and normal state resistivity $R_n$ can be easily adjusted to meet the QUBIC requirements for optimum performances and multiplexed read-out.

Given the expected background power of the QUBIC setup (5-50 pW in the 150-220 GHz range) an extremely low thermal coupling between the TES and the cryostat is needed to optimize signal to noise ratio. This is obtained using 500 nm thin SiN suspended membranes, which exhibit thermal conductivities between 50 and 500 pW/K depending on the precise pixel geometry. The total Noise Equivalent Power (NEP) is of the order of $5 \times 10^{-17}$ W/ $\sqrt{\text{Hz}}$ at 150 GHz, with a time constant in the 10-100 ms range. The pixels have 3 mm spacing while the membranes structure is 2.7 mm wide.

Light absorption is achieved using a Palladium metallic grid placed in a quarter wave cavity in order to optimize the absorption efficiency. A distance of 400 $\mu$m between the grid and the rear reflector is a good compromise for both 150 and 220 GHz photons. The array is not intrinsically sensitive to polarization.

The routing of the signal between the TES and the bonding pads at the edge of the array is realised by superconducting Aluminium lines. These lines are patterned at the front of the array, on the Silicon frame supporting the membranes.
Figure 75: Diagonal window function of the real beam combiner divided by that of an ideal non-aberrating instrument [36].

Figure 76: Simulated QUBIC PSF for the dual band combiner, operated at 150 GHz, for an on-axis source or central pixel: ideal PSF (left) and aberrated PSF (right).
2.4.1.2 Fabrication and AIT The fabrication of the TES arrays is based on commercially available silicon-on-insulator (SOI) wafers. The available TES electron-beam deposition machine at the CSNSM laboratory limits the maximum size of the wafers to 3 inches. Upgrade to 6 inches wafer technology in order to process a monolithic 1024-pixel array is possible but needs modification of several fabrication and test devices, including some of the cryogenic test facilities. For QUBIC it was decided to assemble four 256-pixel arrays for each of the focal planes of the instrument. The QUBIC TES design is shown on Figure 78.

The detector is realized using lithography process at the IEF-Renatech nanofabrication facility and electron-beam film deposition technology at CSNSM. The fabrication process can be resumed in the following main steps:

1. Commercial supply of 3 inches SOI wafers with a deposited layer of 500 nm ultra-low-stress SiN on both sides, using LPCVD (low pressure chemical vapour deposition). The SOI wafers are composed of a 400 µm thick Si substrate, followed by a 1 µm thick SiO₂ buried oxide (BOX), and a final 5 µm thick Si device layer. In our case, the choice of SOI wafers is related to the need of a stop-etching layer (the BOX) during the deep-etching of the 400 µm Si substrate.

2. Electron-beam deposition of a bilayer composed of 30nm NbₓSi₁₋ₓ (TES) followed by 200nm of Aluminium (comb TES electrodes + Routing + bonding pads) without braking the vacuum.

3. Wet etching of the Al and reactive ion etching (RIE) of the NbSi. The routing is composed of the NbₓSi₁₋ₓ-Al bilayer, characterized by a superconducting transition temperature very close to that of pure Al (∼1.2 K). At the end of this step the TES with its routing is patterned and can be tested. Using a bi-layer resolves the problem of the contact resistance and the step between the superconducting electrodes and the TES.

4. Realisation of the light absorption metallic grid by lift-off of a 10nm thick Pd layer. The grid has a filling factor of 4% in order to get a square electrical resistivity that matches the vacuum impedance (377 Ω square).

5. The next steps are related to the realisation of the micro-meshed membranes. We begin with the back-side deep-etching of the Si substrate (DeepRIE-ICP) followed by the etching of the BOX. The back SiN layer is also removed. This operation is illustrated by Figure 79.

6. Front RIE of the SiN to get the micro-meshed pattern (50 µm x 50 µm square pattern).

7. Dry etching of the 5 µm Si device layer using XeF₂. The Si device layer is completely removed after this step and we obtain the SiN meshed membrane.

8. Residual resist removal using Oxygen plasma treatment. Removal of the photolithography resist using solvents is prohibited at this stage because it will damage the membranes.
Figure 78: CAO of the 1024 array (left), of one pixel (top right) and of the TES with its interleaved electrodes (bottom right). On the bottom right, TES is in blue, the Aluminium interleaved electrodes in green and the Pd grid in red. SiN membrane is in black.

The overall fabrication process takes typically two weeks if there is no testing of the TES characteristics at low temperature. We are usually processing two wafers in parallel without considerably increasing the fabrication delays. The 256-pixel array is finally integrated within the focal plane holder and electrically connected to a printed circuit board (PCB) using ultrasonic bonding of Aluminium wires. The latest upgrade of the process allows very satisfying fabrication quality with a dead pixels yield as low as 5%. Pictures of TES in their final state are shown on Figure 80.

2.4.2 Cold electronics

The detection chain of the QUBIC instrument, shown on Figure 81, can be decomposed in 5 parts:

1. TES
   320 mK
2. TES voltage biasing and SQUID multiplexer
   1 K

Figure 79: Picture of the Deep etching of the Si to form the membrane of the pixels (left). Microscope image of the TES and the comb shaped electrodes (right).
Figure 80: Pictures of the 256 TES array being processed (left) and being integrated for the test (right).

Figure 81: Detection Chain including TES, TES biasing ($R_{sh}$), SQUID, ASIC (LNA) and Warm Digital Readout (ADC+FPGA). Feedback with DAC and $R_{fb}$ is also shown.

3. ASIC (LNA i.e. low noise amplification + Biasing + multiplexer clocking) 77 K

4. Warm LNA 300 K

5. Warm Digital ReadOut (ADC + FPGA) 300 K

Therefore, the cold readout described in this section refers to the TES voltage biasing, the SQUID multiplexers and the ASIC.

TES voltage biasing: This is the first part of the readout chain. Indeed, TES is wildly used when large number of detector is needed due to the strong Electro Thermal Feedback (ETF) which homogenize the detector responses even if unavoidable fabrications inhomogeneity’s exists. However, strong ETF is obtained only if TES are voltage biased. This means that the voltage across the TES must be fixed independently to the TES resistance (which varies with the noise, the scientific signal and the background). To passively ensured such fixed voltage across a TES (operating resistance about 100 mK) the TES voltage biasing sources must have a Thevenin’s resistance smaller than the TES operating resistance. To provide such extremely low output resistance voltage sources at deep cryogenic temperatures, a simple current biased $I_{bias}$ shunt (very low value) resistor is used. This shunt resistance is thus the Thevenin’s resistance of the obtained TES biasing and is chosen with a value = 10 mΩ (which is lower than the TES operating resistance, that amounts to a few hundreds of mΩ). The TES voltage is then roughly fixed to $V_{TES} = R_{sh} \times I_{bias}$. The 10 mΩ shunt resistors are placed in the SQUID PCB (Printed Circuit Board) at 1K. The $I_{bias}$ current is provided by the Warm Digital Readout adjusted by the FPGA trough a specific slow differential DAC.

SQUID stage: SQUIDs fabrication and testing is described in Sect. 2.4.3. We concentrate here on the current front-end readout of the TES that also provides the multiplexing.
Current front-end readout: We previously discussed the needed TES voltage biasing, so this voltage biasing leads to a current readout: The voltage is kept constant across the TES and we measure the fluctuation of the current induced by the TES’s resistance fluctuation as function of the scientific signal. Moreover, the input impedance of the SQUID must be smaller than the Rsh shunt resistor to avoid adding a significant resistance in the biasing circuit. We discuss the impedance because this requirement is needed in DC, but also over all the TES bandwidth to avoid instability (TES current biased is unstable). The input impedance of the SQUID corresponds to the impedance of the SQUID input loop Lin. That loop is made using superconducting material (Nb) and introduces 0 resistance in the TES biasing circuit. However, regarding to the frequency response, that loop introduces an impedance which increases with frequency as \( Z_{in} = L_{in} \times 2\pi f \). Therefore, we have to chose \( L_{in} < 10m\Omega/2\pi BW \) where \( BW \) is the bandwidth response of the TES. Apart these considerations, \( L_{in} \) is also used to convert the TES current in flux \( \phi_{in} \) into the SQUID, then the SQUID provides an output voltage: trans-impedance amplification (gain) of the order of 100 V/A. However, this gain is strongly non-linear as shown on Figure 82.

To linearize the SQUID transfer function, the operating point is maintained in a steeper part of the flux-to-voltage transfer function. To counteract the input flux (coming from TES current fluctuation) a feedback flux is applied through the feedback coil and the feedback resistance. Thanks to this feedback technique, a wide linear range is provided to readout TES as shown on Figure 83.

Multiplexing: More than a cryogenic amplifier, SQUIDs also enable the multiplexing thanks to their large bandwidth. Indeed, the SQUID stages of 32 TES are connected together to readout successively each of this 32 TES. In addition, a 4 to 1 multiplexed LNA readout sequentially 4 columns of 32 SQUID each. The multiplexing factor is at the end up to 128. This scheme is shown on Figure 86. The low noise amplification (LNA), the sequentially biasing of the SQUID and the overall clocking of this 128:1 sub multiplexer is obtained thanks to an ASIC (operated at cryogenic temperature).
ASIC: The ASIC is described in details in Sect. 2.4.4.

### 2.4.3 SQUIDs

#### 2.4.3.1 Providing the SQUIDs by StarCryo

The SQUIDs are based on the SQ600S commercial design provided by StarCryoelectronics (starcryo.com). However, this design has been modified to remove an input transformer (for “current-lock” CL operation) not used in the QUBIC readout chain (based on flux feedback). In addition, size of the pads has been reduced to 200µ side and all the design has finally be compacted to reduce the area of silicon need for each SQUID and put about 4000 SQUIDs on 2 custom wafers. Even taking into account a 80% yield and the realization of spare cards, these two wafers should be enough for one QUBIC module. Scheme and pictures of the SQUIDs and their wafer are shown on Figure 84.

#### 2.4.3.2 Room temperature test and cleaning

Before any use, any SQUID must be removed from an adhesive layer used to maintain them while sawing. After that a resin layer is removed chip by chip through first an acetone bath, and then a methanol bath, before drying the SQUID chip with a nitrogen flux. Visual inspection allows removing part of the SQUIDs that clearly show defects, especially from the side of the wafer. A test probe-station equipped with a multimeter allows to test the electrical characteristics of the SQUIDs, with the criteria listed in Table 25. During these room temperature tests, many precautions should be followed to prevent ESD damages on SQUID.

#### 2.4.3.3 Cryogenic test:

One or two SQUIDs per wafer are tested at cryogenic temperature to determined the critical current and the swing ($\Delta V_{\text{squid}}$) of each wafer, as illustrated on Figure 85. To do that, a SQUID chip is glued and wire bonded in ‘4 points’. A single $V(\phi)$ measurement allows to determine all the parameters. These measurements without filtering and cryogenic ASIC are very noisy and give significantly less precise measurements than those obtained later in the full QUBIC readout chain. Nevertheless, this test gives an order of magnitude of the critical current and of the swing of the output voltage which are important parameters for the use of the SQUID in the QUBIC readout chain.

#### 2.4.3.4 Integration

Schematic of the SQUID multiplexer is given in Figure 86. It is composed of 4 columns of 32 SQUIDs each. 32 SQUIDs are connected together using one PCB.

A SQUID is a very sensitive device and its input must be filtered to keep nominal critical current. So, capacitors are added in parallel to the SQUID, input loop and heater to avoid radio frequency parasitic signals close to the SQUID washer. A resistor is added in series to the capacitors in the input inductor to damp LC resonances. Moreover, a SQUID is composed of two Josephson junctions (nm insulators) that are very sensitive to electrostatic discharge. So a 220Ω resistor is put in parallel to the SQUID to deviate peak current. 220Ω value is chosen as it is much larger than the typical 2Ω SQUID fragile shunt resistors, in order to neglect the voltage division introduced by this resistor. The final circuit is outlined on Figure 87.

Finally, a 10Ω resistor is put in parallel with the feedback loop to ensure feedback signal even if one of the feedback connection is open. Indeed, in the multiplexing scheme, all the feedback loops are connected in series. Without this 10Ω resistor, only one open feedback loop would lead to the loss of 128 pixels.

As seen in Figure 86, SQUID columns (32 SQUIDs) are connected together with a PCB board. 4 of this PCB are needed to readout 128 pixels. So, 4 of this PCB are stacked in a “SQUID box” as shown in Figure 88 (left and center). Finally, 2 of this SQUID box are placed below the 256 TES array in the cryo-mechanical structure (Figure 88, right panel).

| Component | Symbol | Resistance range |
|-----------|--------|------------------|
| Heater    | $R_{h}$ | 300-500 $\Omega$ |
| SQUID     | $R_{\text{squid}}$ | 100-200 $\Omega$ |
| $R_{fb}$  | $R_{fb}$ | 300-500 $\Omega$ |
| $R_{in}$  | $R_{in}$ | 10-15 $k\Omega$ |
| Insulation $L_n$ | $R_{sq/in}$ | $> 10$ M$\Omega$ |
| Insulation $F_b$ | $R_{sq/fb}$ | $> 40$ M$\Omega$ |

Table 25: Requirements criteria for selection of SQUIDs
Figure 84: Layout (top) and photo (bottom) of the SQUID (left) and the full wafer (right). SQUID: input pads (left), Washer and flux loop (middle), heater (top right), SQUID access (middle right) and feedback pads (bottom right). A square of the grid is 100$\mu$m. The SQUID chip has thus a size slightly smaller than 2mm. Wafer: about 54 SQUIDs on the diameter $\rightarrow$ 2000 SQUIDs on the wafer.
Figure 85: \( I(\phi) \) measurement using a vector analyzer allows to obtain the SQUID \( V(\phi) \) transfer function (left and bottom right). From this measurement given for different SQUID biasing, the SQUID \( I(V) \) curve can be reconstructed as shown in the right: Y axes is \( V_{\text{squid}}[V] \), X bottom is \( I_{\text{in}}[A] \) equiv. to \( \phi \) and X top is the SQUID biasing \( I_{\text{squid}}[A] \).

Figure 86: Topology of the 128 to 1 multiplexer sub-system (4x32 SQUID + 1 ASIC). Integration of 32 SQUIDs (1 column) with bias capacitors and filter devices.
Figure 87: SQUID glued and wire bonded with filter devices. Values of the filter devices put close to SQUIDs.

Figure 88: Two SQUID boards stacked (left) to finally obtain a SQUID box composed of 4 PCBs, and thus 128 SQUIDs (center). TES thermo-mechanical structure showing the 2 SQUIDs boxes near the TES array.
Figure 89: (a) Microphotography of cryogenic ASIC designed to readout 4x32 TES/SQUID pixels; (b) ASIC module assembly used for QUBIC experiment: chips are assembled in CQFP144 packages, soldered on standard 6 layers FR-4 Printed Circuit Board (PCB) with the needed differential LEMO, SMB, Micro Sub-D and high density SAMTEC connectors. Each module consists of 2 back to back of these PCB which is able to readout 256 TES/SQUID pixels i.e. one quarter of a QUBIC telescope focal plan.

| Multiplexing factor | 128 :1 |
|---------------------|--------|
| Multiplexing frequency | 100 kHz |
| ASIC power dissipation @ 40K | 16 mW / ASIC |
| ASIC noise level | 0.3 nV/√Hz at 77 K |

Table 26: Main characteristics of the cold electronics

SQUID are thermalized to 1K whereas TESs are at 320 mK.

### 2.4.4 ASIC

#### 2.4.4.1 Technology and design approach

The ASIC is designed in full-custom using CADENCE CAD tools. The used technology is a standard 0.35µ BiCMOS SiGe from Austria MicroSystem (AMS). The access to this technology was made possible through the services of the "Circuits Multi Projects" (CMP) of Grenoble. This technology consists of p-substrate, 4-metal and 3.3 V process. It includes standards complementary MOS transistors and high speed vertical SiGe NPN Heterojunction Bipolar Transistors (HBT). Bipolar transistors are preferentially used for the design of analog parts because of their good performances at cryogenic temperature. Due to kink effect in MOS transistors resulting from carrier freeze-out phenomenon in semiconductors below 30 K, the use of these transistors is preferentially reserved for the design of digital blocks and limited to PMOS current mirrors almost exclusively for analog parts. The design of the ASIC is based on pre-experimental characterizations results, and its performance at cryogenic temperature is extrapolated from simulation results obtained at room temperature, using CAD tools.

#### 2.4.4.2 Implemented functions:

Our Time Domain Multiplexer (TDM) readout is based on 4 columns of 32 SQUID in series associated to a cryogenic ASIC. SQUID boards are thermalized on the 1K stage whereas the ASIC are on the 40K stage. This cryogenic ASIC, shown on Figure 89, integrates all parts needed to achieve the readout, the multiplexing and the control of an array up to 128 TES/SQUID. Its functions are outlined on Figure 90. It operates from room temperature down to 4.2K, thanks to a low power dissipation (16 mW per ASIC typically, whatever the number of columns to readout). It includes a differential switching current source to address sequentially 32 lines of SQUID, achieving a first level of multiplexing of 32:1. In this configuration, the SQUID are AC biased through capacitors which allows satisfying both, good isolation (low crosstalk between SQUID columns) and no power dissipation. A cryogenic SiGe low noise
amplifier (0.3 nV/√Hz), with 4 multiplexed inputs, performs a second multiplexing stage between each column.

This cryogenic ASIC includes also the digital synchronization circuit of the overall multiplexing switching (AC current sources and multiplexed low noise amplifier). A serial protocol allows to focus on sub-array as well as to adjust the amplifiers and current sources with a reduced number of control wires. This ASIC includes also an 8 bits analog-to-digital converter, register (memory) and digital-to-analog converter to measure and store the offsets during the slow control, and dynamically compensate offset during observation time. As the digital side takes a large part, we have developed a full custom CMOS digital library dedicated to cryogenic application and ionizing environments (rad-hard full custom digital library). The main strategy consists to enclose each MOS transistors, designed in edge-less transistors shape, by guard rings.

2.4.4.3 Characterization tests Low noise multiplexed amplifier characterizations have been investigated using a vector analyzer. A white noise level of 0.3 nV/√Hz with a differential voltage gain of 200 and a bandwidth of 6 MHz were measured at 77K, as shown on Figure 91.

The behavior of integrated DC biasing sources has been also investigated down to 4.2K, with the setup shown on Figure 92. Each of them is operational at cryogenic temperature with expected values except for the source involved into the AC SQUID biasing operation. To overcome this issue, the AC SQUID biasing circuit will be referenced to an
2.4.5 Warm electronics

The room temperature (RT) readout electronics is designed to control and adjust the operating biasing and feedback to TESs and their associated SQUIDs. Furthermore, it readouts the signal from the cold multiplexing ASIC, computes the scientific signal and sends it compressed to the data acquisition system. Finally the RT electronic readouts the thermometers needed to monitor the cold stages of the instrument. This electronic makes ample use of the FPGA (programmable logic circuits) listed below.

Each board is associated to the cold electronics (ASIC) to manage 128 pixels, so that an ensemble of 16 boards covers the full focal plane of 2048 pixels.

This board, called NetQuiC, and shown on Figure 96, is built around a XEM3005 board from Opal Kelly that includes a Xilinx Spartan 3E FPGA. This FPGA programmed in VHDL embeds:

- Asics control
Figure 94: Validation at 4.2K of the AC SQUID biasing operation through addressing capacitors (100nF) and dynamic offset compensation principle. The tests are performed on an array of 2 columns of 2 SQUIDs in series associated to the cryogenic ASIC which includes the needed switched current sources, multiplexed low noise amplifier and a digital sequencing circuit referenced to an external clock signal. The clock frequency is here set to 2 kHz. Signals 1 and 2 are synchronization signals of the SQUID switching current source and the multiplexed LNA respectively. Signal 3 is the measured multiplexed output signal, with and without dynamic offset compensation, corresponding to periodic sine like SQUID characteristics of each pixel obtained by applying a large ramp signal into their feedback coil.

Figure 95: Output signal measured at 100 kHz of multiplexing clock frequency. Each periodic sine signal corresponds to sampled SQUID characteristics of each pixel obtained by applying a large ramp signal with low frequency (20Hz) into the SQUID feedback coils.
• Management of the TCP/IP connection with the PC.
• Acquisition of scientific signal with the ADC
• Bias generation
• Digital Flux Locked Loop (FLL) control.

Figure 97 shows the architecture of the QUBIC experiment warm electronics. It includes 16 NetQuiC boards, one for each ASIC. The boards are connected to a PC via a network switch. The PC is in charge of the data storage.

2.4.6 QUBIC Studio, readout and control software

We have designed a single interface to deal with the readout, the control command software and the data storage (cf. section 2.4.7): the QUBIC Studio. We made the choice to use the generic EGSE tool, called “Dispatcher”, and developed at IRAP. This real-time-oriented generic tool is widely used on various experiments such as Solar Orbiter, SVOM/ECLAIRS, PILOT. It includes the tools described in the following sections.

This software includes a user-friendly interface to manage the connection with the readout electronics, the management of the control command and Housekeeping data:

• TES matrix thermometers
• blind TESs
• cryostat compressor, “He tubes” and “cold heads” thermometers
• calibration source control parameters
• mount’s motor control parameters

and the visualization of the scientific data. The QUBIC Studio also includes an internal scripting capability allowing us to build simple transfer functions acting on scientific or HK data, but also to develop calibration sequences associating...
Figure 97: Warm electronic overall architecture
control commands and acquisition functions. Users can connect to the QUBIC Studio as multiple clients to access HK/raw/scientific data or to set control-commands of different subsystems of the QUBIC instrument. The QUBIC Studio software also provides an efficient session-history capability, so that it is possible to store the global settings of the instrument at a given date, and re-launched directly from this setup. It is also possible to re-run any data sequence already observed and stored.

2.4.6.1 Architecture visualization tool  It allows to monitor data rates in the parts of the acquisition system, and check the connexion between the various subsystems: the readout electronics, the switches between boards, the user-clients, and the data storage disk. A typical screen capture is shown on Figure 98.

2.4.6.2 The focal plan visualization tool  This tool allows a global visualisation of the ASICs and associated scientific signals. It can display the scientific signal, i.e. integrated over the raw samples for each detector, the noise level of the scientific signal, or the raw signal of the current detectors. This can be used to detect bad pixels or check the sanity of the full readout chain very easily. The display can switch between an ASIC-centered view or a full focal plane overview, as shown on Figure 99.

2.4.6.3 Interface of the control command.  The control command interface, shown on Figure 100 allows us to initialize the following subsystems: ASICs, FLL (Flux Locked Loop) regulation, NetQuiC boards, DACs, raw Signal format, calibration and coefficients setting, horns switches, calibration facilities

Concerning the ASICs, we can set and control the polarization biases of the TES and the SQUIDS, as well as the digital FLL regulation parameters. These parameters may be automatically optimized by an internal script launched by the user. The scientific signal is processed in real time in the FPGA boards and sent to the QUBIC-Studio acquisition system. Starting from the multiplexed signal coming from the ASICs, the scientific signal is de-multiplexed in the FPGA and defined for each pixel as the sum of the raw signal over NSample, taking into account the rejection of data samples defined by a mask, which can be tuned by the user.

Because the raw signals represent a large amount of data (since they are defined at high sampling rate), and since they are not always needed, they are not always transmitted to the QUBIC Studio acquisition system. However
Figure 99: View of focal plane visualization tool
these raw signals can be useful to investigate the sanity of given pixels or of the multiplexing chain, or also to test the e.m. crosstalk between pixels. Hence we have defined three modes:

- **No Raw signal**: nothing is returned except the scientific signal for the 128 pixels
- **Cycle Mode**: One raw signal is returned for each packet of 128 scientific pixel data, cycling over a list of pixels provided by the user
- **Fixed Mode**: The raw signals of a fixed list of pixels are returned for each packet of 128 scientific pixel data. This mode can be used to return the full raw signals by selecting all 128 pixels.

The software includes much more features like: raw data analyzer, data storage, logbook, scripting capabilities, HK visualization (...).

### 2.4.7 Data storage

Concerning the data storage, the QUBIC Studio software presents two options. The first one consists in storing the binary data as received from the FPGA boards. These data are compressed and put less constraints on the disk space capacity. The second option consists in storing the data after interpretation by the software. These data are directly usable for the users, and already formatted to be looked at and analyzed. However, this format will require more disk space, which can be critical depending on the choice of the instrument setup. Indeed, the choice of the NSample parameter leads the total volume of the data, as shown in the tables 27 and 28. The smaller this parameter NSample, the larger the amount of data. Depending on the site of the instrument, this could be more or less critical. This is the reason why the NSample parameter is not fixed yet in the current setup of the instrument. It can be set in a reasonable range [10,1000] through the QUBIC Studio interface.

Data rate and storage of the scientific and raw data are respectively summarized in Table 27 and 28.

### 2.4.8 Detection chain: validation of a quarter of focal plane and readout system

#### 2.4.8.1 Description

The tests that aim to validate QUBIC’s focal plane are all performed on 256 TES sub-arrays at APC. The sub-array is placed on the coldest stage of a pulse-tube dilution cryostat that can cool the sample down to 100 mK. The next link in the readout chain is the SQUID. Each TES is inductively coupled to a SQUID, totalizing 256 SQUIDs cooled down to 1 K. Then, a SiGe ASIC at 40 K is used to control and amplify the signal from 128 SQUIDs in a TDM scheme. Two of them are thus used to characterize a quarter of focal plane.
### Table 27: Data rate and storage of scientific data.

| NSample | Data Rate | Data Storage |
|---------|-----------|--------------|
|         | fpack | Tpack | facq | Tacq | 1 ASIC | FFP | 1min | 1h | 1day | 1month | 12months |
|         | Hz     | ms    | kHz  | us   | ko/s   | Mo/s | Mo   | Go  | To   | To     | To       |
| 10      | 1560   | 0.64  | 200  | 5    | 782    | 12.2 | 732  | 42.9 | 1000 | 31     | 374      |
| 100     | 156    | 6.4   | 20   | 50   | 78.2   | 1.2  | 73   | 4.3  | 100  | 3.1    | 37.4     |
| 1000    | 15.6   | 64    | 2    | 500  | 8      | 0.122| 7.3  | 0.43 | 10   | 0.31   | 3.7      |

### Table 28: Data rate and storage of raw data.

| Raw Mode | Data Rate | Data Storage |
|----------|-----------|--------------|
| Fix / Cycle | Nraw | FFP | 1min | 1h | 1 day | 1 month | 12 months |
| 1        | 32 ko/s | 492 ko/s | 30 Mo | 1.7 Go | 42 Go | 1.3 To | 15.1 To |
| 5        | 160 ko/s | 2.5 Mo/s | 150 Mo | 9 Go | 207 Go | 6.3 To | 75.4 To |
| Full / Fixed | 128 | 61 Mo/s | 3.7 Go | 215 Go | 5.2 To | 156 To | 1.9 Po |

#### 2.4.8.2 Principle on a TES

Being voltage-biased, the TESs work at a stable and controlled temperature thanks to a strong electrothermal feedback: any fluctuation of power of thermal origin is compensated by an opposite contribution of power by electrical dissipation. The total power across the TES is therefore quasi-constant. A way to ascertain it is to proceed to I-V and corresponding $P - V$ measurements. Figure 101 displays these curves for a single pixel at different bath temperatures below its critical temperature $T_c$.

When regulated at a temperature lower than its $T_c$, a TES can be forced into its normal state by maintaining sufficiently high bias voltage (right part of the curves). While decreasing the voltage (from right to left), the TES is first in its normal state and shows a resistive metallic behaviour that follows Ohm’s law, thus the I-V curve is firstly a straight line. Then the TES tends to transit to its superconducting state and the electrothermal feedback starts to take place. This is when the I-V curve reaches its minimum. Once the feedback is operational, the TES is auto-regulated and works at quasi-constant power ($P_{\text{min}}$), which can be witnessed on the P-V plateaux. Meanwhile, the TES goes further on its transition and its resistance continues to drop, which leads to a portion of parabola on the left part of the I-V curve. One can also notice that the cooler the TES is regulated, the further it is from its transition and the higher the needed power has to be to bring the TES to its normal state ($P_{\text{min}}$ at 225 mK $>$ $P_{\text{min}}$ at 400 mK). The $I - V$ and $P - V$ curves of a bolometer provide a way to run through several of its stable states and therefore to recover some of its static parameters, such as its thermal conductance G and an evaluation of its theoretical NEP. To do so, the plateau power $P_{\text{min}}$ of the P-V curve is measured at different bath temperatures. These data are then fitted after $P_{\text{min}} = K(T_0^{n+1} - T_{\text{bath}}^{n+1})$ as seen in Figure 102.

The fitting returns the $K$, $n$ and $T_0$ quantities, assuming that $T_0$ is the critical temperature $T_c$, and $G(T_0)$ is calculated from them. It is then simple to deduce as an approximation from the $G$ term the theoretical NEP of the

![Figure 101: I-V (left) and P-V (right) curves of a TES (n=60, ASIC2, P41 array) at different Tbath < Tc.](image-url)
bolometer given that the phonon noise is prevailing, using \( \text{NEP}_G = (\gamma^4 k_B T_{0}^2 G)^{1/2} \).

2.4.8.3 Testing of an array. The same analysis has been performed on about twenty randomly distributed TESs on a 256-pixel array. Figure 103 is a graph summing up the I-V (upper curves, left axis) and P-V (lower curves, right axis) measurements of these pixels. For clarity purpose, the result for only one regulation temperature (\( T_{\text{bath}} = 350 \text{mK} \)) is displayed, combining two experiments (one with ASIC1 addressing the first half of the 256 pixels and one with ASIC2 for the second half).

The picture shows first that the TESs are working excellently (expected shape of the I-V and P-V curves) and that the strong electrothermal feedback is efficient: all the pixels reach a constant minimum power when they are on their transition to their superconducting state (left part of the P-V curves). In terms of homogeneity, all the pixels exhibit the same behaviour on their normal state. However, with the voltage decreasing and the TESs entering their transition, disparities can be noticed on the I-V curves showing that some pixels are getting superconducting while others are still at the beginning of their transition. But considering the P-V curves (that are a different manner to present the same data as the I-V curves), the disparities are less evident. In order to have a comparison criterion, the Pmin of all the tested pixels has been collected at \( T_{\text{bath}} = 350 \text{mK} \) and gathered in the histogram of Figure 104.

The figure shows that most of the pixels (75%) have a Pmin around \( 6.2 \pm 10\% \text{pW} \), which is a very good homogeneity. The small difference among the TESs may come from variations of the thickness of the suspending legs caused by anisotropies of etching during the manufacturing process. This would lead to disparities in the thermal conductivity \( G \). As in Figure 102, \( G \) is calculated for each pixel from the fitting of Pmin at different bath temperatures and gathered in a histogram with an average value of 106 pW/K. A first approximation of the NEP distribution, deduced from the values of \( G \) is also given with an average of \( 2.6 \times 10^{-17} \text{W}/\sqrt{\text{Hz}} \) at 350 mK. The value largely meets the QUBIC requirements of an electrical \( \text{NEP} < 5 \times 10^{-17} \text{W}/\sqrt{\text{Hz}} \), even for the few pixels whose NEP is a little scattered from the main distribution.

In order to be consistent with the saturation power for the 220GHz channel that is multimoded, the critical temperature will be increased for these TESs. Since the photon noise is higher in this channel, there will be no performance degradation.

2.5 Mount System and Baffling

2.5.1 Mount system

The QUBIC mount is a standard Alt-azimuthal astronomical mount. This will be able to support 1000kg and the total weight is expected to be 2000 kg with 2m x 2m x 2m approximate size. The mount will implement 3 rotational axis (Altitude, Azimuth and boresight) and is being designed under the responsibility of the Duch consortium NIKHEF, Leiden University, and TNO with collaborators in LAL/IN2P3 Orsay who could also be interested by contributing.

The mount, supporting the cryostat, will be installed on top of a platform (see Figure 105).
Figure 103: I-V (upper curves, left axis) and P-V (lower curves, right axis) curves of TESs on P41 array at \( T_{\text{bath}} = 350 \text{mK} \)

Figure 104: Histograms of \( P_{\text{min}} \), \( G \) and approximation of theoretical NEP of selected pixels of a 256 TES array obtained from I-V measurements at different bath temperatures.
2.5.2 External Baffling

2.5.2.1 Description The radiation shielding solution adopted for QUBIC instrument is composed by a Forebaffle (FB) and a Ground Shield (GS), see section 2.5.2.2 about their analysis and configurations. Both the shields will be manufactured by a selected external supplier. The final dimensions of FB are dictated by the cryostat window while for GS by the mount design and the expected instrument platform.

FB will be realised in a single conical structure with a dismountable flare, both manufactured with an aluminium alloy. The inner surface is covered with a 10 mm thick Eccosorb\(^4\) dielectric sheet, a material with high lossy absorptive properties suitable for the microwaves.

GS will be manufactured with several flat panels, petals, to fit a conical shape (see panel a) in Figure 106. The inner surface of each petal is a sheet of aluminium ensuring low emissivity and high reflectivity to point the beam spillovers to the cold sky instead of to the ground. The edge of the GS has a flare for the same reasons of FB.

Preliminary drawings of both shields are shown in Figure 106. There are no strict requirements on the two shields from an optical point of view while a certain rigidity must be ensured to meet the required geometry.

Similar solutions have been already adopted for FB and GS at BICEP instrument with severe ambient conditions near the South Pole Station\(^5\).

2.5.2.2 Simulations In order to reduce the possible contamination derived by the presence of unwanted sources, such as Sun, Moon and ground, a study of the shielding system for the first module of the QUBIC experiment has been realized in terms of geometry and employed materials for the shields manufacturing [44]. The study has been performed with the commercial softwares GRASP and CHAMP combining MultiGTD (Geometric Theory of Diffraction) and MoM (Method of Moments) approaches to infer the pattern of the instrument beam up to sidelobes at the lowest frequency, 150 GHz, where the impact is higher. In order to have a conservative approach in the estimation of the QUBIC instrument spillovers, we have investigated the impact of the shielding configuration on the beam pattern central feed horn of the feed-horn array. The shielding configuration is schematically shown on the left of Figure 107 while on the right a cut of the beam pattern of a Hybrid Conical Horn employed in the MultiGTD analysis.

The Forebaffle geometry has been optimized to minimize sidelobes varying its height in the range 0.5-2 meter and aperture angle from 7 up to 28 degrees. The different patterns are shown in Figure 108.

FB heights larger than 1 meter and an aperture angle larger than 14 degrees seem to be no advantageous, even from a mechanical manufacturing point of view.

In addition to a reflective solution, we studied an absorptive one to highlight the different impact on the pattern. Also a cylindrical shape has been considered for comparison.

The MultiGTD approach does not allow to analyze reflectors covered by dielectric materials with defined electrical properties. To overcome this restriction, we have performed our simulations with the help of the commercial software

\(^4\) http://www.eccosorb.com

\(^5\) The cylindrical FB and the GS of BICEP3 are shown in http://bicep.caltech.edu/~yuki/shield/
Figure 106: QUBIC Forebaffle (top) and Ground Shield (bottom) mechanical drawings.
Figure 107: Sketch of the QUBIC shielding configuration (left) and cut of the hybrid conical horn beam pattern used in MultiGTD simulations (right).

Figure 108: Cuts of the patterns (at 0 degrees) for the on-axis feedhorn varying: FB height, for an aperture angle equals to 14 degrees (left panel) and FB aperture angle, for the defined FB height (h=1m) (right panel). The colors code is specified in the legend.
Figure 109: Cuts of the beam pattern with and without a cylindrical shield (left panel) and with and without a conical shield (right panel). The colors are referring to: Feed beam pattern (black line), reflective (green line) and absorptive (red line) internal surface solutions.

Figure 110: Beam pattern cuts for the cylindrical forebaffle including the Flare: reflective inner surface (left panel) and absorptive inner surface (right panel). All the colored curves are defined in the legend.

CHAMP, which allows to analyze rotationally symmetric scatterer using the Method of Moment (MoM) approach. Regarding the absorptive solution, we have considered the possibility to cover the inner surface of the forebaffle with a 10 mm thick Eccosorb® dielectric sheet, a material with high lossy absorptive properties suitable for the microwaves. We assumed the following electrical parameters: electric permittivity 3.54, magnetic permeability 1 and tangent loss 0.057. The impact on the beam pattern of the central feedhorn with a conical or a cylindrical forebaffle, for the two different investigated solutions, is reported in Figure 109.

For both configurations the presence of an absorptive inner surface leads to increase the sidelobes rejection for angles larger than 20 degrees from boresight direction, respect to the nominal feed beam pattern and the reflective solution. This effect results to be more evident for the conical-shaped shield, as shown in the right panel of Figure 109.

Same analysis has been performed by adding a flared edge at the entrance aperture of the forebaffle, hereafter Flare, for both configurations, with the aim of increasing sidelobes rejection. Three values for the curvature radius, R = 25λ, 75λ and 150λ (λ=2 mm), have been analysed to study the impact on the beam pattern.

The insertion of a Flare in our configurations has allowed a further reduction of sidelobes at angles larger than 30 degrees from boresight, as shown in Figure 110 and Figure 111.

Similarly to the configuration without flare, both absorptive solutions seem to show better performance in terms of sidelobes amplitude. In the absorbing configuration, the flare’s dimension seems to have a small impact on sidelobes drop, this allows to choose a flare with the smallest curvature radius (R=50 mm), which implies a more simple mechanical fabrication.

http://www.eccosorb.com
The additional radiative loading on a single detector, given by the emission of the Eccosorb sheet in the inner surface of the forebaffle, has been evaluated, at 150 GHz, in the following way:

\[
P_{\text{FB}} = A_h t_{\text{tot}} \epsilon_{\text{opt}} N_{\text{pixels}} \Delta v B_{\text{sheet}}(\nu, T_{\text{sheet}}) \int_{D\theta} \int_{D\phi} AR(\theta, \phi) \sin \theta \cos \theta d\theta d\phi
\]  
(3)

where \(D\phi\) and \(D\theta\) are the ranges of angles within which the central feed horn subtends the FB.

The power collected by each pixel from the absorbing FB is \(\approx 0.07\) pW (blue line in Figure 112), lower than the expected saturation power of TES detectors, consequently it is not an issue in the total power budget of the QUBIC experiment.

This value has been compared with the equivalent radiative loading coming from the FB in the reflective configuration. For this case we have assumed that the loading reaching the focal plane is given by the emission of the atmosphere reflected by the forebaffle inside the instrument.

The numerical evaluation of the loading induced by the atmospheric emission \((T_{\text{atmo}}=240\) K) reflected on a single detector by the reflective FB, has been carried out in the following way:

\[
P_{\text{atmo}}(z) = A_h t_{\text{tot}} \epsilon_{\text{opt}} N_{\text{pixels}} \Delta v B_{\text{atmo}}(\nu, T_{\text{atmo}})\epsilon(z, \text{pwv}) \int_{D\theta} \int_{D\phi} AR(\theta, \phi) \sin \theta \cos \theta d\theta d\phi
\]  
(4)

where \(BB_{\text{atmo}}(\nu, T_{\text{atmo}})\epsilon(z, \text{pwv})\) is the assumed atmospheric brightness model where the zenith emissivity has been modelled assuming the simple model of stratified layers:

\[
\epsilon(z, \text{pwv}) = 1 - e^{[-\tau_0(\text{pwv}, \Delta\nu) \sec z]}
\]  
(5)

The zenith atmospheric opacity at 150 GHz, \(\tau_0\) is derived from pwv, as described in [51], including also a finite spectral bandwidth. The pwv values exploited in our analysis are plotted in Figure 113, as expected at Dome C.

The additional radiative loading collected by each pixel deriving by the atmospheric loading reflected on the forebaffle, by varying QUBIC zenith angle and pwv values, is shown in Figure 112.

The power collected by each pixel, by varying QUBIC elevation angle, defined as the sum between the atmospheric emission and the FB emission in reflecting and absorbing configuration, is shown in Figure 114. This plot shows as the atmospheric emission provides the main contribution in terms of radiative loading on each detector, about one order of magnitude, compared with the loading due to the emission of the FB in absorbing configurations.

For all these reasons, we selected the absorbing FB conical configuration with flare as the best solution in terms of sidelobes rejection of the feed beam pattern.

The whole instrument is oriented by an altazimuth mount and it is expected to be surrounded by a ground shield (GS) in order to minimize the brightness contrast between the sky and the ground.

We considered a reflective shield with a conical shape and a full aperture angle of 90 degrees (45 degrees from the vertical) with the base 3 m in diameter (see sketch on the left in Figure 115) and an aperture of 6 m in diameter with a flared edge. The final dimensions are expected to be tuned with the mount design and the geometry of the platform where the instrument will be installed.
Figure 112: Power collected by a single pixel on the focal plane: the blue line is referring to the emission from an absorbive forebaffle while the other colored lines (see color code in the legend) are referring to the atmospheric emission (for different pwv values) reflected by a reflective FB changing QUBIC zenithal angle. The expected maximum zenith angle is 55 degrees.

Figure 113: Zenith atmospheric opacity at 150 GHz as a function of the pwv content, from 0.1 mm up to a maximum value of 2 mm. According to atmospheric models for Chajnantor, to get the opacities at 220 GHz, these values should be scaled by $\sim 1.83$.

Figure 114: Power collected by a single detector due to atmospheric emission plus FB emission in reflecting and absorbing configurations, by varying QUBIC zenith angle. The colored lines are referring to 3 different pwv values as in Figure 113.
Figure 115: Left: QUBIC shielding components: a forebaffle (FB), fixed on the cryostat window, and a ground shield (GS), fixed on the ground. Right: Beam pattern cuts of the central feed with the forebaffle alone and including also the ground shield are shown. The FB is pointing towards the zenith. The color code is described in the legend.

The impact of to the reflective conical FB inside the GS on the central feed horn beam pattern, assuming the instrument pointing toward the zenith, is shown in the plot on the right of Figure 115. The cut-off experienced by the beam pattern at ±80° are given by the presence of the GS edge.

| @ z=0° | No Shields | With FB | FB+GS |
|--------|------------|---------|-------|
| Ground | 627 mK     | 117 mK  | 2 mK  |
| Sun    | 3 mK       | 328 μK  | 7 μK  |
| Moon   | 70 μK      | 7 μK    | 0.1 μK|

Table 29: spillover contributions.

In Table 29 the spillover contributions in terms of brightness temperature due to the main contaminants are listed with and without the presence of the shields.

2.6 Technological demonstrator

The development of the QUBIC instrument is a multi-step process (cf. section 5.3). Once the detection chain has been validated, the next step will be the fabrication, integration and test of the technological demonstrator, followed by the construction of the full first module of the instrument.

To meet this last challenge, taking into account the financial situation, technological advancement and schedule issues of each partner of the QUBIC collaboration, it was indeed decided after the June 2015 review to define the QUBIC technological demonstrator as the final instrument is, with only five downsizings: a reduced number of pixels, a reduced number of horns and switches, a reduced diameter of filters, a reduced number of pulse tubes, a reduced diameter of mirrors.

The decrease in the number of pixels is determined by the fact that we have no more funding to buy superconducting cables to connect them to the cold electronics and to fabricate the focal plane mechanics. Due to this fact we will re-use the 256 pixels array (and its mechanical support) already tested for the validation of the detection chain. For this former validation we had some spare cables, we are currently assessing the possibility to connect an additional 256 pixels (possibly at 220 GHz), supported by a replica of the mechanical support, fabricated in LAL and APC mechanical workshops.

The decrease in the number of horns and switches is due to the fact that the Milano laboratories anyway manufacture an 8x8 back-to-back array in order to fully validate their process of fabrication and test in view of the 20x20 final array. Using this 8x8 array for the demonstrator will save time and will reinforce the validation process for this sub-system. The switches of the 8x8 array will not be equipped of chokes, since chokes are usefull only for decreasing the return losses.
### Sub-systems

| Sub-system                        | Technological demonstrator | Final instrument |
|----------------------------------|----------------------------|-----------------|
| Cryostat                          | Nominal                   | Nominal         |
| Down to 4K cryo-coolers          | One pulse tube            | Two pulse tubes |
| Down to 320mK cryo-coolers       | Nominal                   | Nominal         |
| Mirrors                           | 400 mm diameter           | Nominal         |
| 1K box, cold stop                 | Nominal                   | Nominal         |
| Focal planes                      | 256 pixels at 150 GHz (option with 512 pixels). Option with 512 pixels. | 2 focal planes, 1024 pixels each (one at 150 GHz, one at 220 GHz) |
| Horns and switches back-to-back array | 8x8 without chokes       | 20x20 with dual band chokes |
| Filters, HWP, Dichroic            | 180 to 280 mm diameter    | Nominal         |
| Cold electronics                  | Nominal, but for just 256 or 512 pixels | Nominal |
| Warm electronics                  | Nominal, but just for 256 or 512 pixels | Nominal |
| Data storage                      | Nominal, but just for the volume of data produced by 256 or 512 pixels | Nominal |
| QUBIC-Studio (control and readout) | Nominal                   | Nominal         |
| Mount                             | Possibly a fake mount     | Nominal         |

Table 30: Respective definitions of the technological demonstrator and the final instrument.

In the final instrument two pulse tubes cryo-coolers will be used: one for the focal planes, the other one for the 1K box. Due to the reduced numbers of pixels and corresponding electronics and their related thermal loadings, the demonstrator could be equipped with only one pulse tube. This will delay also the financial burden on the Roma laboratory.

The decrease in the diameter of filters is due to the fact that as of November 2015, the Cardiff installations are not able to produce filters with a diameter bigger than 300 mm. Improvements of these equipment will be done in a near future but to save time and decrease risks the decision has been taken to install 300 mm filters in the technological demonstrator.

The decrease in the diameters of mirrors is due to the fact that Milano University has capabilities to manufacture mirrors with a diameter up to 400 mm. The mirrors of the QUBIC instrument have a diameter of 600 mm. So it was decided in order to save time, to use for the demonstrator 400 mm diameter mirrors, made in-house at Milano.

All these downsizings are optically compatible with each other, according to simulations.

A comparison of the characteristics of the technical demonstrator and of the first module is summarized on Table 30.

### 3 Calibration, Operation Modes and data processing

Before the installation of QUBIC on site (cf. section 4), the instrument will undergo a serie of measurements for its characterisation that are described in section 3.1.

Once on-site and besides the commissioning mode where the performances of the instrument will be assessed and tuned using calibration sources and sky data, QUBIC will be operated in two distinct modes: self-calibration and normal observation mode (cf. section 3.2).
3.1 Instrument testing and calibration operations

The objectives of the calibration is the determination of the main parameters of the instrument “in lab” (after its integration and before its shipment to the exploitation site), and the verification that the extracted values are in conformity with the requirements. The operations will be performed at APC and are divided in three steps:

1. First, the measurements will be achieved with the entrance window of the cryostat closed by a metal plate: this phase is here-after called “Blind cryostat” configuration.

2. Then, the metal plate will be removed. A density filter installed inside the cryostat will insure that there is no saturation of the detectors (from the 300K). This configuration is called “opened cryostat”

3. Finally, while the first two steps will be done inside the APC Hall, the instrument will be transported outside pointing at the calibration source placed on the roof of a building facing the Hall entrance.

The sub-system warm functional tests are supposed to have been performed successfully previously to the calibration start-up stage. The test plan is built keeping in mind that the number of cooling downs should be kept as low as possible. We estimate that we need fifteen days to cool down the instrument to 320mK.

3.1.1 Cryogenic measurements and functional tests

During the cooling downs (for both the blind and the opened configurations of the cryostat) successive tests with respect to the thermal behaviour of the instrument will be pursued. Beyond the follow up of the achieved temperatures on the different stages (40K, 4K, 1K and 320mK), we will measure the thermal conductance of each stage:

- 320mK: through regulation stage
- 1K: through heater
- 4K: through heater and switches
- 40K: through ASIC

We will also cross-check the thermal stability of the cryogenic chain. A comparison of the results with respect to the model of the thermal transfer within the cryostat will be assessed.

For different temperatures configurations, we will also measure the R(T) behaviour of the detectors.

In parallel functional tests on the use of the half wave plate and of the switch array will be performed. We will then be able to check the EMI/EMC their use induces in the instrument. Eventual repercussions on the cryostat temperature at the different stages, and the corresponding amount of time needed to come back to the optimal values will be extracted from the housekeeping data.

3.1.2 Detector characteristics determination

When the nominal values for the temperature of the different stages will be reached, the I(V) curves will be determined, as well as the working points of the detectors. A comparison of the measurements of the integrated instrument with respect to already existing ones on the response of the electronics, the SQUIDS and the TES will be assessed [46]. This procedure is already mastered by IRAP/APC and has been applied during the TES tests that have been performed at APC. The I(V) curves will be measured in parallel on all detectors.
Table 32: Characteristics of the QUBIC instrument that will be measured with the Carbon fiber source, the Calibration source and/or the FTS.

We will then measure their corresponding noise characteristics: their NEP, and the slope and knee values of the noise spectrum. Those characteristics will be determined for different V to better constrain the Instrument Model. Specific characteristics of the noise, such as the cross-talk will also be assessed using the blind detectors. Finally we will redo an EMI/EMC test while monitoring the detector response.

All the measurements described above can be done under different load configurations, which can be mimicked either by playing (within some extend) with the different cryogenic stages, and/or by the comparison between the two cryostat configurations (blind or opened). This would permit to further refine the Instrument Model. Depending on the availability of a temporary mounting system, the stability of the temperature stages and the noise on the detectors will be measured for different inclinations of the cryostat to check the elevation domain in which the instrument will work (in which the pulse tube is efficient enough).

3.1.3 With the calibration setup

Once we are sure that the previous measurements are within the requirements for the temperatures as well as for the noise parameters, the next step is to use internal and external sources:

- Carbon fiber sources, within the cryostat (see below)
- the Calibration source (cf. section 2.1)
- a Fourier Transform Spectrometer (FTS)

to further determine the detectors characteristics: the corresponding parameters are summarized in the Table 32.

The intercalibration of all detectors will be first tackled with Carbon fibers sources emitting in the IR [47]. A couple of such sources will be placed at the edge of the feedhorn array to monitor detectors response and also to check the alignment of the combiner along pointing directions (this can even be done in the blind cryostat configuration), and further determined with the Calibration source with the instrument installed outside.

At least an upper limit on the time constants will also be measured with the Carbon fiber sources (as it was done for the Planck-HFI calibration [49]). Since the time constant should not be an issue for QUBIC this test is rather a cross-check that a real measurement.

The absolute response will be measured with the Calibration source outside of the APC Hall. While proceeding with the HWP we will also be able to recover the polarisation angle of the source.

The percent level is expected on the spectral filter knowledge [ref]: band pass spectral measurements are therefore needed to make sure QUBIC is within the requirements. Inside the APC Hall a first validation of the spectral response will be tested with a vectorial analyser, and the measurements will be refined with the Calibration source by varying its frequency and correcting for its emission spectrum.

With the use of the mounting system, a complementary test on the eventual impact of gravity effects on the instrument will be checked by scanning the Calibration source and reconstructing the pointing of the focal plane. The synthetic beam (cf. Section 1.2.2), and the self calibration (cf. Section 1.2.3) procedures will finally be tested while pointing at the Calibration source outside the Hall.

The different parameters and the cryostat configuration in which they are supposed to be measured are illustrated in Figure 116. The blue dots are mandatory while the light blue ones are nice to have measurements.
3.2 Modes of operations

3.2.1 Self-calibration mode

The self-calibration mode consists in observing and scanning an artificial polarized source with QUBIC, opening and closing the horns switches in order to extract the fringe patterns for each of the interferometric baselines. We have shown in [36] [34] that such a procedure allows constraining tightly the instrumental systematics. This is the operation mode that is specific to QUBIC and cannot be performed with a usual imager. This mode is the one that we consider as the primary advantage of QUBIC in controlling better the instrumental systematics. The level of control on the instrumental systematics depends on the amount of time spent performing self-calibration. We therefore consider that up to 50% of the observation time could be invested in self-calibration if needed. The exact amount will be determined by analysing the self-calibration data in order to balance between systematics and statistical uncertainties. In [34], we have shown on rather simplistic simulations that we hope to reduce the level of systematics by more than an order of magnitude by spending 2.5% of the observation time performing self-calibration (see Section 1.2.3 and Figure 6 for more details).

3.2.2 Observation mode

QUBIC aims at observing regions of the sky that show the lowest amount of dust contamination possible. Two such regions are considered up to now:

- The well known and well observed « BICEP2 region » with equatorial coordinates (RA = 0 deg, DEC = -57 deg). This region is known to be contaminated by dust at a level $r \approx 0.2$ for which our simulations (based on power law assumption for the dust component) have shown that we can achieve a $\sigma(r) \sim 0.02$ from Argentina using our two bands 150 and 220 GHz and adding the Planck 353 GHz maps.

- The region with equatorial coordinates (RA = 8.7 deg, DEC = -41.7 deg) where the analysis of Planck data have shown an apparent lower level of dust contamination, although with significant uncertainties [37].

We prefer to delay the final decision of the observed field to the beginning of the operations for QUBIC as more precise information might be available by then on the relative advantages of both regions in terms of dust contamination. They can equivalently be observed by QUBIC in Argentina and Antarctica with the Azimuth and Elevation ranges (accounting for a lower limit of 30 degrees elevation for operations in order to avoid a too high atmospheric emission) given in Table 33.
Table 33: Azimuth and elevation ranges for the two considered fields for QUBIC, for Dome C (left) and Argentina (right).

| Field                  | Concordia (Antarctica) | San Antonio de los Cobres (Argentina) |
|------------------------|------------------------|---------------------------------------|
|                        | Azimuth | Elevation | Azimuth | Elevation |
| BICEP2 Field           | 0-360 deg. | 55 +/- 15 deg. | 140-220 deg. | 45 +/- 15 deg. |
| Planck Clean Field     | 0-360 deg. | 45 +/- 15 deg. | 130-250 deg. | 50 +/- 20 deg. |

The observations will be performed through the so-called “constant elevation scanning” that is done in the following manner:

1. Constant elevation sweeps in azimuth around the azimuth of the center of the observed field with an amplitude of $\Delta\text{az}$ (typically 30 degrees) at the angular speed $v_{az}$ (typically 1 deg/sec) for a given number of sweeps $N_{\text{sweeps}}$ (typically 300). During such a series of sweeps, the elevation of center of the field varies through the field of view of the instrument and eventually the instrument starts sweeping the outer regions of the field.

2. After $N_{\text{sweeps}}$, one recenters the elevation of the instrument to that of the observed field and starts the constant elevation azimuth sweeps again. In sky coordinates, these new sweeps now exhibit an angle with respect to the previous ones, so that after 24 hours, all the regions in the sky have been observed with all angles (see Figure 117).

3. At the end of each azimuth sweep, the Half-Wave-Plate is rotated by one position, corresponding to 11.25 degrees.

4. An additional continuous or stepped slow rotation around the optical axis is envisioned (so we require the instrument mount to be able to perform it) in order to further modulate the signal, but further simulations are required to optimize it, accounting for the atmospheric fluctuations.

We only take data when the elevation of the instrument is between $\approx 30$ and $\approx 70$ degrees, the lower bound is set by the air-mass that becomes too large, and induces too high photon noise below 30 degrees, while the upper bound is set by the inclination range allowed by the Pulse-Tube-Cooler (cf. section 2.2.1) $\pm \approx 20$ degrees around the central position with elevation 50 degrees (the exact range will be defined during commissioning). Such a scanning strategy allows to cover $\approx 1\%$ of the whole sky in 24 hours. This is exactly the sky coverage that is optimal for setting an upper limit (meaning including only noise variance, the signal being considered to be 0 therefore without sample variance) on the B-modes signal at multipoles around 100 (using the recombination bump).

In the eventuality where a B-mode signal is detected by another experiment before us, or by ourselves, one may want to increase the sky coverage in order to reduce the sample variance from the primordial B-modes. This is easily achievable by performing the same scanning strategy with slight shift in RA, DEC for the center of the field over a
few days. This can be seen in Figure 118 where 2.4% of the full sky is achieved with 10 days (whereas in 1 day, 0.9% are covered as shown in Figure 119).

The actual scanning strategy baseline is still evolving with the progress of the simulations and will be definitely frozen only when observations will start.

3.3 Self-calibration

The self-calibration system, which is introduced in section 3.3.1, is composed of millimetric wave sources (the self-calibration sources cf. section 3.3.2), placed on top of a calibration tower (cf. section 3.3.3) at ≈ 45m from the experiment. The sources will be observed by the QUBIC instrument with an elevation angle of ≈ 30°-45° from the horizon.

3.3.1 The self-calibration procedure

As discussed in section 1.2.3, the interferometric nature of QUBIC will allow to track down systematic effects such as a misalignment of horns, focal plane, mirrors, but also non-homogeneous temperature (...)

Theoretically, in case the instrument doesn’t have any systematics effect, all equivalent baselines (meaning any combination of a pair of back-to-back horns separated by an identical distance) would behave and transmit the signal
the same way (meaning giving the same fringes on the focal planes). It was shown in [36], that a comparison between the real fringes obtained with equivalent baselines allows to estimate the systematic effects of the instrument, and is called the self-calibration process.

In order to practically implement such a procedure, all back-to-back horns are equipped with RF switches located between input horn and output horn (cf. section 2.3.5). By closing horns two by two, the behavior of the instrument can be analyzed and systematics can be withdrawn from its transfer function.

In order to implement the self-calibration procedure, a well characterized signal emitting at 150 and 220 GHz and polarized, has to be received by the instrument.

### 3.3.2 Self-calibration sources

The main drivers that set the self-calibration sources specifications are the high polarization degree of the sources (practically 100% for a corrugated horn excited through a rectangular waveguide), and the available power at the output. During the self-calibration phase, we need to characterize the different realizations of the same Fourier mode (through different horn pairs), which at the end consist in mapping the corresponding interference fringes on the focal plane: the higher the S/N ratio of fringe detection, the higher the level of the accuracy of systematic effects retrieval. A study has been done to show that a high S/N can be achieved as a result of a good balance between the FWHM of the sources, sources power, and the fraction of saturated detectors in the focal plane.

More specifically, the self-calibration sources should emit in the two frequency bands observed by QUBIC with a bandwidth of 25%. For this purpose two different self-calibration sources are required, one for each frequency band. The signal which should be linearly polarized should induce a cross-polarisation smaller than -30dB. It is expected to be energetic enough to be detected and read-out by the instrument, but sufficiently tiny not to saturate the detectors. To assure the possibility of detecting an interference fringe with a S/N ratio > 20000, this leads to an expected emitted power between 1 and 5 mW on the whole frequency band, with a flatness of 3dB. In addition the signal should be very stable, with a power drift smaller than 1% per hour. The main characteristics are given in table 12.

The typical solution matches those of off-the-shelf mm-wave sources, which is to use a microwave synthesizer in a baseband up to 20 GHz, which feeds a cascade of amplifiers/multipliers up to the desired frequency band, with the desired power level. Gunn oscillators endowed with a PLL are another possible option. The same technology will be used for both 150 and 220 GHz bands. Standard corrugated horns can be manufactured with the desired beam (scalar horns with 10° beam are typically purchased off-the-shelf).

The sources will also be used for the Calibration operations (cf. section 3.1).

The self-calibration sources device must cope with the extreme weather conditions in the chosen exploitation site. They will be maintained within a 30cm x 30cm x 30cm and 10kg weight thermally insulated box that will be designed within the collaboration.

They must have a high reliability and availability, since the self-calibration will represent an important percentage of observation time (cf. section 3.2.1).

### 3.3.3 Self-calibration sources support

The sources location needs be chosen so that the instrument would receive the signal as if the source was in far field conditions. For this purpose it will be mounted on top of a mast able to maintain the source at least 45 meters high and 45 meters away from QUBIC.

The baseline (conservative) plan for the QUBIC calibration tower is an exact copy of the American Tower installed on Dome C, but we are also investigating the possibility to use a much lighter solution with much closer struts. A preliminary design was produced by the ITAS company with supporting struts limited to a distance of 10m from the tower (see Figure 120). ITAS company is working also on different solutions including one without struts.

### 3.3.4 Full beam calibration source

The principal axis of the polarimeter must be known with high accuracy. To this purpose we will use a full-beam calibrator, consisting of a dielectric sheet stretched across the beam, in the fore-baffle outside the cryostat window, at 45° incidence, and a room-temperature blackbody. The sheet transmits a large part of the atmospheric and CMB signals, and reflects (partially polarizing) a small fraction of the emission of a room-temperature blackbody (see Figure121).

The polarization properties of the calibration signal produced in this way can be computed with good accuracy. The assembly of the 45° dielectric sheet and room temperature blackbody can be rigidly rotated in controlled matter...
Figure 120: the “American tower” at Concordia Station, a guy-cable tower (left); a schematic of a tower with less footprint but with a basement loaded with concrete (right, courtesy of ITAS company).

Figure 121: Operating principle of the full-beam calibrator.
Figure 122: Stokes parameters I and Q of the radiation produced by the full beam calibrator in the 150 GHz band of QUBIC.

around the optical axis of QUBIC. For each position of the calibration assembly, QUBIC observes with all the detectors and for all the positions of the HWP, so that a position angle of the polarimeter can be estimated fitting the data. In Figure 122 we show that the polarized signal produced in the D-band by the calibrator does not depend significantly on atmospheric emission.

The mechanical design of this calibration system will be finalized together with the mechanical design of the forebaffle, to allow for mounting on the same holes, on the top flange of the QUBIC cryostat.

4 Operation site

Dome C was the initial foreseen site for the installation of the QUBIC first module. In view of the complexity of its logistics and cost, and of its requirements in term of the experiment reliability, we have however decided to deploy this first module from another site, Alto Chorillos in the Puna province of Argentina, which still offers excellent observation conditions while being much less demanding on logistics and reliability. To assess this choice, we have thoroughly compared the forecasted QUBIC sensitivity in both sites. This comparison is detailed in Section 4.1. More details on the Chorillos site are then given in Section 4.2.

4.1 Sites comparison

This section presents a detailed comparison of Dome C and Chorillos, in terms of sensitivity, in order to help assessing the advantages and drawbacks of each site. We compare the sensitivity that will be achieved by QUBIC using realistic meteorological conditions for both sites (obtained from measurements) and the scanning strategies optimized for each site.

Regarding the scanning strategy, the main difference between the two sites is that the target fields for QUBIC are visible above 30 degrees and below 70 degrees elevation 100% of the time in Concordia, Antarctica, while only 40% of the time in San Antonio de los Cobres, Argentina (see section 3.2.2 for details about the scanning strategy).

In order to calculate the sensitivity for both sites, one needs to have a detailed knowledge of the atmospheric water vapour content as emission from water is the main driver for the amount of photons QUBIC receives, hence the photon noise we measure. We have used the following data for this study:

- For Concordia, Antarctica:
  - Precipitable Water Vapour (PWV) data in Concordia are derived in [53], direct Radiosoundings data provided by the Routine Meteorological Observations Research Project at Concordia station, employed to feed Atmospheric Transmission at Microwaves (ATM) code to generate synthetic spectra as in [51] and balloon soundings as in [62].
  - When needed, conversion from PWV to atmospheric opacity (usually labeled $\tau$) at 150 GHz using the modeling performed for Concordia in [53] (eq. 5).
Figure 123: PWV data for Concordia from balloon soundings at Concordia [62].

Figure 124: Atmospheric spectrum from ATM with parameters optimized for Chajnantor Atmosphere
The atmospheric temperatures in Concordia were obtained along the year using the data published in [55].

When needed, conversion from $\tau(150 \text{ GHz})$ to $\tau(220 \text{ GHz})$ using an atmospheric emission spectrum from the ATM code. Precipitable Water Vapour (PWV) data directly and from direct analysis of Radiosoundings data provided by the Routine Meteorological Observations Research Project at Concordia station, corrected by temperature and humidity errors and dry biases and then employed to feed Atmospheric Transmission at Microwaves (ATM) code to generate synthetic spectra in the wide spectral range from 100 GHz to 2 THz as in [51].

• For San Antonio de los Cobres, Argentina:

  – $\tau(210 \text{ GHz})$ measurements performed for the LLAMA site testing over more than three years kindly transmitted by Marcello Arnal (PI of LLAMA, from IAR, La Plata).

  – Extrapolation to $\tau(150 \text{ GHz})$ from $\tau(220 \text{ GHz})$ using an atmospheric emission spectrum from the ATM code optimized for Chajnantor (see Figure 124). Final results are shown on Figure 125.

We combine all the results together to obtain a compared atmospheric emissivity along the year for the two sites, at both of our observations frequencies. This is shown in Figure 126.

The atmospheric emissivity, along with the temperature of the atmosphere along the year allows to forecast the background radiation arriving from the atmosphere on the QUBIC focal plane, it is straightforward to calculate the photon Noise Equivalent Power (NEP) on the detectors from this quantity. The actual noise of the detector is the quadratic sum of this photon noise and of the intrinsic noise of the detectors. Once the total NEP is calculated, it is straightforward to convert it into Noise Equivalent Temperature (NET) as shown in Figure 127.

Unsurprisingly, Concordia offers the highest sensitivity with an average polarized NET at 150 GHz of $278 \mu K\text{.sec}^{1/2}$ and $461 \mu K\text{.sec}^{1/2}$ at 220 GHz while the numbers are $305 \mu K\text{.sec}^{1/2}$ at 150 GHz and $552 \mu K\text{.sec}^{1/2}$ at 220 GHz in Argentina for the best nine months in the year. During the so-called Bolivian Summer, the atmospheric conditions are strongly degraded in Argentina.

In addition, atmospheric conditions in Dome C have been demonstrated to be more stable. This is not accounted in the present analysis.

In order to accurately assess the relative sensitivity of the two sites, one therefore needs to precisely account for the observation efficiency that is going to be rather different in the two sites:

• The target fields are only visible 40% of the time in Argentina, while 100% of the time in Antarctica. Note that self-calibration can be performed during the periods where the target field is not visible from Argentina.
Figure 126: Atmospheric emissivities compared for both Concordia and Argentinian sites.

Figure 127: Noise Equivalent Temperatures forecasted from our study at 150 and 220 GHz for QUBIC in both possible sites.
**Bad months** | Concordia | Chorillos
---|---|---
**Monthly Observation efficiency** | 92 % | 75 %
**Hours below 30 deg.** | 0 | 14.4
**Hours Fridge Cycling** | 4 | 4
**Hours Self Calibration** | 0 | 6 | 12
**Hours Field Observation** | 20 | 14 | 8 | 9.6 | 9.6 | 8
**Daily Observation Efficiency** | 83 % | 58 % | 33 % | 40 % | 40 % | 33 %
**Total Observation Efficiency** | 76 % | 53 % | 28 % | 31 % | 30 % | 25 %

Table 34: Relative observation efficiency for the two sites

- The fridge cooling the detectors to 320mK needs to be recycled for 4 hours every 24 hours wherever the instrument is located.

- During the Bolivian Summer (three months), it appears difficult to make useful observations, however these months will be chosen for doing upgrades and maintenance of the instrument. Similarly, but to a lesser extent, the strong activity in Concordia during at least one month in summer makes it hard to pursue useful observations, this time will be better used with upgrades and maintenance of the instrument.

These considerations on the observation efficiency are summarized in Table 34 with various hypotheses regarding the amount of time one will spend performing self-calibration. Assuming a negligible time spent self-calibration, the observation efficiency in Concordia is more than twice higher than in Argentina, while with a large amount of self-calibration, both sites achieve the same observation efficiency. This occurs because we manage to perform self-calibration when the target field is below the observation limit.

These results and the Noise Equivalent Temperatures from Figure 127 are then used to feed the sensitivity forecast program that was used to predict sensitivities for QUBIC (in section 1.1). We run this program for various values of the observation efficiency from 0 to 1 and obtain the corresponding minimum tensor-to-scalar ratio achievable in two years for the two different sites. The results are shown in Figure 128. We see that installing QUBIC in Argentina will lead to a reduction of sensitivity of a factor between 1.4 and 2.8 wrt Dome C, for 0h and 12h per day spent doing self-calibration.
4.2 San Antonio de los Cobres, Argentina

As mentioned earlier, we have chosen to install the QUBIC first module in Argentina, near the city of San Antonio de los Cobres, in the Salta Province. This site has coordinates (24° 11' 11.7" S; 66° 28' 40.8" W ) and an altitude of 4869m a.s.l. It is located in the plateau known as “La Puna” in Argentina, and “Atacama” in Chile. The site is located ~180km from the Chajnantor site where other millimeter-wave experiments are located (ALMA, ACTPol, PolarBear) and offers similar atmospheric properties (see Fig.129).

Figure 129: Alto Chorillos site in Argentina, near San Antonio de los Cobres, province of Salta. The position for other astronomical instruments location in Chile is also shown (red cross).

In Figure 130 we can see the position of the chosen site for QUBIC along with the LLAMA position. LLAMA is a project for the installation of an ALMA-like antenna lead by an Argentina-Brazilian collaboration. This project had conducted the site characterization studies, in particular related to atmospheric opacity shown in Section 4.1. In Figure 130 is posible to see the relative position of QUBIC and LLAMA. The magenta polygon is the 400 hectares area allocated by the government of the Salta province to CONICET for scientific use only. The corresponding decree can be found in the official web site of the government: http://boletinoficialsalta.gob.ar/NewDetalleDecreto.php?nro_decreto=824/14. In this figure we can also see the gas pipeline (green line) that will feed the gas generators for LLAMA and the Vega lagoon, from which the water needed for both instruments can be extracted. A high-speed internet connection to San Antonio de los Cobres will be available soon thanks to the installation of an optical fiber in the near future.

Figure 130: Views of the chosen QUBIC site in Argentina along with the LLAMA [64] location and logistic installations planned to be installed during 2017 and funded by MinCyT and the Province of Salta. In magenta the limits of the allocated area for scientific use from the Salta government.

7 http://www.iar.unlp.edu.ar/llama-web
Even if the chosen position for the instrument is outside the initially scientific allocated area, QUBIC could always benefit from the LLAMA installation associated logistics (i.e., access road, electrical power, water and internet network) already funded and expected to be constructed during 2017. The schedule for this infrastructure to be ready is the following:

- Electricity, connectivity — April 2017
- Access road — July 2017
- First Stage of Headquarters — December 2016.

The LLAMA project has also offered the possibility of using the headquarters they have planned in the city for installing the data storage and control center for QUBIC (50 m² granted), as well as bedrooms, access to the workshop and a clean room. Dr. Marcelo Arnal, Argentinian PI of the LLAMA project, has expressed his agreement to the installation of QUBIC on the same grounds.

The shipping of the instrument and the access to it will be clearly easier than in the original antarctic choice, as Chorillos site is only a 45 minutes drive away from San Antonio de los Cobres, and at a 3.5 hours drive from Salta, the capital of the province, where a large airport and university facilities are available. A smaller airport is also directly available in San Antonio de los Cobres. Access to the site is granted 365 days a year with less than 24 hours trip from Europe. In San Antonio de los Cobres are hotels and the basic services (i.e., hospital, bank, restaurants, gas station, shops).

Regarding the general atmospheric conditions, in addition to atmospheric opacity, already studied in section 4.1, temperature, humidity and wind speed have been monitored on site for several years. Except during the Bolivian Summer (December to March period) the values of these parameters are within the specifications for smooth operation (see Figure 131). In order to confirm the values taken in LLAMA site and to monitor the atmospheric conditions during at least one year, a weather station will be installed on QUBIC site in the next months.

The installation of QUBIC in Argentina is strongly supported by the National Ministry of Science and Technology (MINCyT), the government of Salta Province, the National Scientific and Technical Research Council (CONICET) and National Commission of Atomic Energy (CNEA). Researchers from different Argentinean institutions are involved in QUBIC now, participating not only on site development but also on instrumental aspects. The Qubic-Argentina Collaboration is formed by researchers from the Argentinean Institute of Radioastronomy (IAR), the Institute of Detection Technologies and Astroparticles (ITeDA), the Bariloche Atomic Center (CAB) and the Department of Aeronautics and the Faculty of Astronomy and Geophysics of the University of La Plata (FCAGLP, UNLP).

At this moment, 500,000 USD has been already allocated by MINCyT for the first stage of QUBIC installation and negotiations between the different Argentinean agencies supporting QUBIC in Argentina are carrying on in order to define the global structure of the collaboration and the contribution from each party to the project.

5 Organisation

5.1 Management

5.1.1 Management of the collaboration

The organization of the QUBIC collaboration is based on two main governing bodies: the QUBIC Steering Committee and the QUBIC Project Office. The Steering Committee is in charge of deciding crucial orientations and decisions; the Project Office is in charge of the implementation into the project of these decisions. The Steering Committee is composed according to the track record of the QUBIC project with representatives from participating countries (France, Italy, United Kingdom, Ireland, United States of America) and the managing executives of the project (the Project Scientist, Project Manager, Instrument Scientist and Logistic Coordinator). The Steering Committee is the governing body choosing between the most crucial options during the life of the project: funding, schedule, introduction or exit of new partners, Intellectual Property issues, release of general specification, general strategy, choice of key personnel, publication policy.

The Project Office is in charge of concretely executing the decisions of the Steering Committee. It is the executing governing body of the project. It is composed with the Project Scientist, the Project Manager, the Instrument Scientist, the System Scientist or Engineer, the Logistics Coordinator and the CAD and Mechanical Architect. The Project Office takes the day-to-day technical and managerial decisions and coordinates with the involved laboratories the implementation of its own decisions and of those decided by the Steering Committee.
The institutions participating to the QUBIC Collaboration, and their respective responsibilities (if any, besides scientific exploitation) are described in table 35.

5.1.2 Collaboration Agreement (CA) / Memorandum of Understanding (MoU)

In April 2015 a Collaboration Agreement has been signed between the members of the QUBIC Collaboration. This Collaboration Agreement is focused on the construction and implementation of the first module of the QUBIC experiment. It deals with the description of the collaboration, the detailed commitments of each stakeholders, the global view of the funding situation, the schedule, the organization of the consortium, the exploitation of the instrument, the access to scientific data, the publication policy.

A Memorandum of Understanding (MoU) more focused on commitments on funding and manpower will be written and signed as a second step in the formalization of the QUBIC collaboration.

5.1.3 Publication policy

Research Projects undertaken in the collaboration must be announced to the collaboration through the mailing list specifying the topic, project leader, and known collaborators. The list of Research Projects will be maintained by the Project Scientist and made available on the Collaboration internal website. Any member of the QUBIC collaboration is entitled to work on any of the Research Projects undertaken.

Publications are expected to be the result of these Research Projects and need to be reviewed within the collaboration at least a month before being submitted to a journal.

Authorship of the publications:
| Country | Organization | Responsibilities |
|---------|--------------|------------------|
| France  | CNRS / IN2P3 / APC | Leadership, technical coordination and management, Detection chain system, AIT activities, Calibration system, Instrument design, Science simulations, Mechanical design, assembly and test of RF switches, Sub-K control electronics, TES detectors |
|         | CNRS / IN2P3 / CSNSM | Calibration and test of the instrument |
|         | CNRS / IN2P3 / LAL | Carbon fiber sources |
|         | CNRS / INSU / IRAP | Slow control, Readout software, Data storage |
|         | CNRS / INSU / IAS | - |
| Italy   | Università di Roma La Sapienza | Optical group coordination, Cryostat, Cryostat control electronics, Cryogenics, Cryostat window, HWP rotation system, Full beam source, Baffling, Test of mirrors, Horns fabrication |
|         | Università degli Studi di Milano | Fabrication, slow control of RF switches |
|         | Università degli Studi di Milano-Bicocca | Test of horns, Fabrication of mirrors |
| U.K.    | Cardiff University | RF design of switches, Half Wave Plate, Polarizer, Dichroic, Filters |
|         | Manchester University / JB Technology Group | RF design of horns |
|         | Manchester University / Advanced Technology Team | 1K and Sub-K fridges, Heat-switches |
| Ireland | National University of Ireland, Maynooth | Optical simulations of the instrument |
| USA     | Wisconsin University | - |
|         | Brown University | - |
|         | Richmond University | - |
| Argentina | IAR La Plata | Logistics - Site Development |
|         | ITEDA Buenos Aires | Logistics - Site Development |
|         | ITEDA Mendoza | Logistics - Site Development |
|         | CNEA CAB (Bariloche) | Cryogenic maintenance |
|         | GEMA La Plata University | Mount design and fabrication |

Table 35: Main characteristics of Institutes in the QUBIC collaboration
• Any member of the QUBIC collaboration can request that his/her name be added to the list of author of an article. It is the responsibility of the Research Project leader to accept or not this request depending on his contribution to this specific research project. The ordering of the list of authors is left to the choice of the specific Research Project members.

• QUBIC members having the Architect status have the right to choose to be co-author of any of the publications. The Architect status is granted by the Steering Committee based on significant contributions to any stage of the experiment (design, construction, integration, operation or analysis).

• The default policy for signature of papers is: first the main authors, then other involved people in alphabetic order.

Any disagreement should be resolved through the Steering Committee whose decision would be final.

In addition to the Research Projects, The QUBIC Project Scientist, in agreement with the Steering Committee, may establish Key Projects and Working Groups whose work could also result in a publication. The authorship for such projects will be discussed in the Steering Committee and would by default be the whole QUBIC collaboration in alphabetical order.

5.2 Organization

5.2.1 Product Breakdown Structure (PBS)

The QUBIC system is structured as in Table 36.

5.2.2 Works Breakdown Structure / Works packages

The different tasks for design, fabrication, tests for each component of QUBIC are described in the chart shown on Figure 132.

Otherwise explicitly stated, a component is designed, fabricated and tested by the same laboratory.

Besides activities for providing the components parts of QUBIC, integration activities, under the responsibility of APC, have been integrated in the chart. The global management and coordination of the experiment is also under the responsibility of APC.

Each laboratory is represented by its own color code in the graph.

5.3 Development plan

The development of the QUBIC instrument is a multi-step process. After i) the first R&D works, it was decided in a review held in 2013 to ii) validate the detection chain. Now this validation is almost done. The next steps are iii) the validation of a technological demonstrator, and then iv) the construction of the full first module of the instrument. The final step will be v) the fabrication and implementation of the five additional modules.

5.3.1 Heritage and first R&D works

Since 2008, many Research and Development works on the following topics have path the way to the construction of QUBIC.

• Proof of principle concept of bolometric interferometry:

MBI-4 and BRAIN have been successful demonstrator of the concept of bolometric interferometry.

The merge of this two projects and their respective teams gave birth to the QUBIC project.

• Exploitation site:

BRAIN has been successfully installed and exploited in the Concordia Station in Antarctica in 2006. This implantation has been of great value with respect to the exploitation of such an instrument and its main sub-systems (such as the pulse tube cryo-coolers) in the harsh conditions of Antarctica.

Besides this installation measurements have been made on the quality of the sky at Concordia Station by Dr Alessandro Schillaci in 2010 and 2011.
| Sub-system               | Component        | Items                                                                 |
|-------------------------|------------------|----------------------------------------------------------------------|
| Detection chain         | Focal plane      | TES                                                                  |
|                         |                  | Mechanical support                                                   |
|                         | Cold electronics | ASIC, SQUID, Wiring                                                  |
|                         | Warm electronics | Amplifier, FPGA board                                                |
| Optical system          | Window           |                                                                     |
|                         | Horns / switches array | Horns, Switches, Mechanics, Slow control and readout               |
|                         | Filters          | Thermal filters, Band defining filters, Half wave plate, Dichroic  |
|                         | Mirrors          | Primary, Secondary, Hexapods                                         |
|                         | Cold stop box    | 1K Box, Optical covers                                              |
|                         | External baffling| Ground shield, Fore baffle                                         |
| Cryostat system         | Vacuum vessel    |                                                                     |
|                         | Thermal screens  |                                                                     |
|                         | Cryogenics       | 4K fridge, 1K fridge, 320mK fridges, Heat switches                  |
|                         | HWP rotator      |                                                                     |
|                         | Slow control     |                                                                     |
| Mount system            | Mechanics        |                                                                     |
|                         | Motors           |                                                                     |
|                         | Slow control     |                                                                     |
|                         | Cables guide     |                                                                     |
| Infrastructure          | Laboratory       |                                                                     |
|                         | Service shelter  |                                                                     |
|                         | Instrument shelter |                                                             |
| Control, readout, data storage | QUBIC-Studio software | Control computer                                                |
|                         | Data storage     | RAID system, Back-up system                                         |
|                         | External wiring  |                                                                     |
|                         | Science simulation software |                                                   |
|                         | Data treatment software |                                                       |
|                         | Self calibration software |                                                        |
|                         | Computing hardware system |                                                   |
| Calibration system      | Calibration sources |                                                             |
|                         | Calibration source support |                                                 |
|                         | Full beam source  |                                                                     |
|                         | Carbon fiber sources |                                                |
|                         | Slow control     |                                                                     |
| AIT system              | Electronics test system |                                                             |
|                         | Optical test system |                                                |
|                         | Thermal test system |                                                               |
|                         | Assembly system  |                                                                     |
| Logistics systems       | Handling system  |                                                                     |
|                         | Containers       |                                                                     |

Table 36: PBS of the QUBIC project. when present, comma separated lists in the **Items** column indicate separate products.
The validation of the detection chain was focused on the following issues:

- **Detectors:**
  
  The BSD collaboration, granted by an ANR, is a collaboration between the laboratories involved in QUBIC detectors development (APC, CSNSM). By establishing this collaboration, these laboratories have been able to procure equipment and materials for production or test of TES arrays.

  One of the first result of this collaboration and of first R&D was the production of a 23 pixels TES array in 2011.

- **Switches:**

  First tests were made in 2012 on a single switch. Integration of the electro-magnet with the blade that close the wave guide, good functionality in liquid nitrogen and in 4K cryostat of the unit, development of the electronic system able to perform the switches and detect their position, first measurements of the cut-off when the blade close the waveguide were the main results of this R&D.

- **Horns:**

  First developments were done on the RF design of the corrugated horns at Manchester in 2010. Parallel developments were undertaken in APC on the mechanical design and fabrication of such horns. Use of platelets (instead of electroforming) was investigated in order to decrease costs of fabrication. In 2012 Milano team of Marco Bersanelli, who provides the platelets horns for the Planck satellite joins the QUBIC collaboration. Their experience and industrial networking is of great value for that matter.

- **Read-out electronics:**

  The heritage from the control and read-out system of the PILOT experiment, designed by IRAP, has been fully integrated in QUBIC-Studio.

5.3.2 **Validation of the detection chain**

The QUBIC project was reviewed in summer 2013 by IN2P3, INSU and IPEV. The main conclusion of the review group was that the detection has to be validated before giving the project a formal go-ahead.

The validation of the detection chain was focused on the following issues:
• Definition of the numerous steps of fabrication for the production of an array of 256 TES,
• Production and test of this array (checking short-circuit or cut in the routing, control of superconducting transition temperature, decrease of the percentage of damaged pixels),
• Finalization of the cold and warm electronic read-out (definition, purchase, fabrication and tests of SQUIDs, ASICs, PCBs, superconducting and cryogenics cables and connectors, warm amplifier, warm electronic PCB with embedded FPGA, software system QUBIC-Studio for control and read-out),
• Mechanical, thermal and electrical integration of all these elements into a dilution-cooled test cryostat at APC,
• Functional tests of this detection chain (measurement of Tc, ability of reading transition on the system),
• Characterization of the TES (measurement of V(I) curves)
• Measurement of the noise level of the system.

All of these steps have been successfully performed. The noise level measurement has been done in spring 2016 by increasing the sampling rate, integrating a numerical FLL in the FPGA using a updated version of the read-out PCB. However, the noise level measured $10^{-16} \text{W}/\sqrt{\text{Hz}}$ is a factor two above the $5 \times 10^{-17} \text{W}/\sqrt{\text{Hz}}$ requirement. This is now understood and is due to noise aliasing. This explanation has been demonstrated by increasing the read-out rate yielding to a reduced noise level. The natural solution is to add superconducting inductances in front of the SQUIDs which is currently being implemented on a new test TES array. The expected noise reduction is at least a factor of two (therefore reaching the requirement) or even better. The detection chain of QUBIC is therefore technically validated although the ultimate noise will only be reached after the test of the new TES array incorporating the inductances to limit the noise aliasing.

We can already say that this validation process allows us to have a far better understanding of the QUBIC detection chain. Procurement of parts, efficiency of potential suppliers, cost issues, technical difficulties and incompatibilities into the industrial process of fabrication, thermal issues are matters that have been greatly clarified.

5.3.3 Validation of a technological demonstrator

In June 2015, a new review assessed the progress in the QUBIC project and especially the status of the detection chain validation.

A major conclusion of this review was to encourage the fabrication of a demonstrator of the final QUBIC instrument with the already available funding, before end of 2016. Details on the configuration of this demonstrator are given in Section 2.6. The QUBIC technological demonstrator, when assembled and tested will validate the full instrument design and test it electrically, thermally and optically.

The test plan of the technological demonstrator is similar to that of the first module, which is described in Section 3.1.

5.3.4 Construction and implementation of the first module

The final results of the detection chain will be available in 2016 and the technological demonstrator of the instrument will be assembled in early 2017 and will undergo first tests during this same year. This way, it is expected that funding agencies and authorities of each partners will give the go-ahead and funding and manpower for the fabrication of the final first module (i.e instrument, mount and logistics).

With the additional funding for superconducting and cryogenics electrical cables, for mechanics of focal planes, final filters and additional pulse-tube, the assembly and tests of the first module are expected to take place during the second half of 2017 in the assembly hall of APC.

When assembled, the instrument will be tested following the plan described in Section 3.1.

After all these steps an important milestone will be the acceptance review of the QUBIC first module in order to get the approval from authorities before shipping it to the exploitation site.

Shipping the first module, the mount and all ancillary materials to the exploitation site will take a few months.

Once arrived on site the instrument will be visually inspected in order to check that its integrity has been kept during the shipping. Then the mount will be installed on its platform. Afterwards the instrument is put on the mount. Once done, the commissioning phase begins.

When the instrument is fully checked in its good health and performances, the scientific operations begin. They are expected to take two years.
5.4 Schedule

5.4.1 Construction and test of the technological demonstrator

The fabrication, procurement and test of each sub-systems of the technological demonstrator is expected to be done between October 2016 and the beginning of 2017. Tests are expected to start soon afterwards.

5.4.2 Construction of and test the first module instrument

The construction of the first module will start as soon as the tests on the technological demonstrator will be finished and that requested funding to achieve the instrument (cabling, mechanics for focal plane, additional pulse tube) are delivered in due time by the authorities. The goal is to finish assembly and tests by end 2017.

5.5 Costs and funding

5.5.1 Costs an funding for R&D and validation of the detection chain

Main R&D and cost for construction and test of a prototype detection chain have been funded by the main contributions listed in Table 37.

5.5.2 Costs and funding for construction and test of the technological demonstrator

The construction of the technological demonstrator is expected to be constructed without any additional funding (at least for the French contribution).

5.5.3 Cost and funding for the construction of the first module

The cost for construction of the first module is likely to be shared between the agencies listed in Table 38.

5.5.4 Cost and funding for the implementation on site of the first module

Regarding implementation on site and logistics (buildings and shelters, manpower for installation of infrastructure, shipping of goods, consumed power, etc.) the agencies in charge of the sites are expected to take these costs as their participation to the project. A rough estimate of these logistics costs can be read in section 4.2. Regarding scientific exploitation, an application has been sent to the ANR 2016 call for that purpose.

5.6 QUBIC Evolution to a CMB Stage IV experiment

The technology proposed by QUBIC is innovative and therefore includes a balance of risk (novel technology) and virtues (high sensitivity, higher immunity to systematic effects, one of the main concerns in deep microwave background polarimetry). Therefore, definitive statements on what we envision beyond the first module can only occur after a precise assessment of its results after at least few months of observations. We can however depict a roadmap...
| Agency(ies) | Grant  | Funded sub-system (hardware, software or temporary manpower) |
|------------|--------|---------------------------------------------------------------|
| TBD        | 806 k€ | Science exploitation: 8 year of post-doc and manpower, calibration, RAID system, missions for exploitation. |

Table 39: Estimation of costs for scientific exploitation.

under the assumption that the first modules gives results as predicted and demonstrates the interest of bolometric interferometry.

For such a roadmap, various options can be considered:

1. Evolving the technology of QUBIC with modules comprising more horns and detectors in order to significantly increase the sensitivity and angular resolution (set by the size of the primary horn array). The final sensitivity would deserve a detailed study that can only be done when the results of the first module will be known.

2. Keeping the size of the first module for future modules operating at a total of three different frequencies (90, 150 and 220 GHz). In such a scenario, the achieved sensitivity is easier to estimate. One could imagine than the installation of the second module could start two years after the installation of the first one and then, one additional module could be added each year until we reach six modules and operate until 2025 following the example scheme in Table 40. The resulting number of (focal planes).(year) is 9 at 90 GHz, 21 at 150 GHz and 20 at 220 GHz. Keeping the same number of focal planes at 150 and 220 GHz allows us to extrapolate the achieved sensitivity from the one that was calculated for a single module while the 9 modules at 90 GHz are supposed to handle the contamination from synchrotron B-polarization. In such a scenario, we could achieve a sensitivity increase of a factor 10 with respect to the 2 (focal planes).(year) we have with the first module, and therefore reach $r=0.002$

Of course the numbers given above are just for the sake of illustration and definitive decisions will be based on the results of the first module. We will certainly learn a lot from it and may want to upgrade or modify some of its hardware. For instance, the TES bolometers could be replaced by MKIDs if these turn out to become more competitive in the next few years. Various teams in QUBIC are already involved in R&D on MKIDs.
| Module               | Start | End   |
|---------------------|-------|-------|
| Module 1: 150/220 GHz | 2018  | 2025  |
| Module 2: 150/220 GHz | 2019  | 2025  |
| Module 3: 90 GHz    | 2020  | 2025  |
| Module 4: 150 GHz   | 2021  | 2025  |
| Module 5: 220 GHz   | 2022  | 2025  |
| Module 6: 90 GHz    | 2023  | 2025  |

Table 40: Possible deployment schedule for future modules (just an example). This would result in 2025 into a number of (focal plane).(year) distributed as follows: 9 at 90 GHz, 21 at 150 GHz and 20 at 220 GHz.

Figure 133: One sigma sensitivities for QUBIC (red dots) compared with the anticipated sensitivities of Stage III and Stage IV experiments.
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6 References

[1] N. Krachmalnicoff, C. Baccigalupi, J. Aumont, M. Bersanelli and A. Mennella, Astron. Astrophys. 588, A65 (2016) doi:10.1051/0004-6361/201527678 [arXiv:1511.00532 [astro-ph.CO]].

[2] P.T. Timbie and G.S. Tucker, Adding interferometry for CMBpol, Journal of Physics: Conference Series 155, 012003 (2009)

[3] D. Baumann, CMBPol Mission Concept Study. AIP Conference Proceedings, Volume 1141, pp. 10-120 (2009) arXiv:0811.3919

[4] Smith, K. M. 2006, Phys. Rev. D, 74, 083002

[5] Smith, K. M., & Zaldarriaga, M. 2007, Phys. Rev. D, 76, 043001

[6] Zemax-EE, ZEMAX Development Corporation. Online at http://www.zemax.com/ (as of August 2015).

[7] O’Sullivan, C., et al., (2002), Far Infra-red Optics Design & Verification. International Journal of Infrared and Millimeter Waves 23,(7), 1029-1045.

[8] Goldsmith, P.F., (1998). Quasioptical Systems: Gaussian Beam Quasioptical Propagation and Applications, IEEE Press series on microwave technology and techniques.

[9] Gradziel, M. Ł, et al., (2007). Modelling of the optical performance of millimeter-wave instruments in MODAL, in Proc. SPIE 6472, 64720D.

[10] Murphy, J. A., et al., (2001). Radiation patterns of multi-moded corrugated horns for far-IR space applications. Infrared Phys. and Tech. 42, 515-528.

[11] Scully, S., PhD Thesis, National University of Ireland, Maynooth (submitted October 2015).

[12] Gayer, D., PhD Thesis, National University of Ireland, Maynooth (in preparation).

[13] Hamilton, J.-C., Charlassier, R., Cressiot, C., et al. 2008, A&A, 491, 923

[14] Bicep Planck, Phys. Rev. Lett. 114, 101301 (2015)

[15] Ade, P. A. R., Akiba, Y., Anthony, A. E., et al. 2014, Physical Review Letters, 113, 021301

[16] S. Naess et al. [ACTPol Collaboration], JCAP 1410, no. 10, 007 (2014) doi:10.1088/1475-7516/2014/10/007 [arXiv:1405.5524 [astro-ph.CO]].

[17] Keisler, R., Hoover, S., Harrington, N., et al. 2015, ApJ, 807, 151

[18] http://moriond.in2p3.fr/2016/transparencies/1_sunday/1_morning/7_bischoff.pdf

[19] http://moriond.in2p3.fr/2016/transparencies/3_tuesday/1_morning/1_bender.pdf

[20] http://moriond.in2p3.fr/2016/transparencies/3_tuesday/1_morning/5_niemack.pdf

[21] http://max.ifca.unican.es/EWASS2015/TalksOnTheWeb/Number09_Borrill.pdf

[22] http://moriond.in2p3.fr/2016/transparencies/3_tuesday/1_morning/6_moncelsi.pdf

[23] Lazear, J., Ade, P. A. R., Benford, D., et al. 2014, Proc. SPIE, 9153, 91531L
[28] EBEX 10K proposal to NASA, 2015
[29] Essinger-Hileman, T., Ali, A., Amiri, M., et al. 2014, Proc. SPIE, 9153, 91531I
[30] The LSPE collaboration, Aiola, S., Amico, G., et al. 2012, arXiv:1208.0281
[31] Errard, J., Feeney, S. M., Peiris, H. V., & Jaffe, A. H. 2016, J. Cosmology Astropart. Phys., 3, 052
[32] Chanial et al., in preparation
[33] Salatino, M., & de Bernardis, P. 2010, arXiv:1006.3225 Salatino et al., 2010, http://pilot.irap.omp.eu/PAGE_PILOT/index.html
[34] M.-A. Bigot-Sazy, R. Charlassier, J.-C. Hamilton, J. Kaplan and G. Zahariade, Astron. Astrophys. 550 (2013) A59 doi:10.1051/0004-6361/201220429 [arXiv:1209.4905 [astro-ph.IM]].
[35] Errard, J., Ade, P. A. R., Akiba, Y., et al. 2015, ApJ, 809, 63
[36] Marie-Anne Bigot-Sazy, M.-A., (2013). PhD Thesis, Université Paris Diderot, Paris 7.
[37] R. Adam et al. [Planck Collaboration], arXiv:1409.5738 [astro-ph.CO].
[38] Scott, P. F.; et al. (2003). "First results from the Very Small Array III: The CMB Power Spectrum". MNRAS 341 (4): 1076-1083. arXiv:astro-ph/0205380
[39] Kovac, J. M., Leitch, E. M., Pryke, C., et al. 2002, Nature, 420, 772
[40] Readhead, A. C. S., Myers, S. T., Pearson, T. J., et al. 2004, Science, 306, 836
[41] Fuskeland, U., Wehus, I. K., Eriksen, H. K., & Næss, S. K. 2014, ApJ, 790, 104
[42] Bennett, D. G., (2014) PhD Thesis, National University of Ireland, Maynooth
[43] Rusch, W. V. T., et al., (1990). Derivation and application of the equivalent paraboloid for classical offset Cassegrain and Gregorian antennas, IEEE Trans. Antennas and Propagat. 38, (8), 1141.
[44] Buzi, D., PhD Thesis, University La Sapienza, Rome (submitted October 2015).
[45] Franceschet, Cristian, (2013) Analysis of non idealities on the D-band QUBIC feed horn performance.
[46] Martino, J. Characterization of a detection chain using superconducting bolometers for polarization measurement of the Cosmic Microwave Background https://tel.archives-ouvertes.fr/tel-00794700 + Perbost C. to come
[47] Henrot-Versillé, S., et al., Pulsed Carbon fiber illuminators for FIR instrument characterization. Infrared Physics &Technology 2009 52 159–165
[48] P. Battaglia, F. Cavaliere, C. Franceschet, E. Pagana, A. Simonetto, M. Zannoni "D Band Antenna Technological Demonstrator Test Report", QUBIC Internal Report, University of Milano 2014
[49] Planck Collaboration, A&A Volume 520, September-October 2010 “Pre-launch status of the Planck mission HFI ground calibration”, A10
[50] P. A. R. Ade et al. [BICEP2 Collaboration], Submitted to PRL, arXiv:1510.09217
[51] De Gregori et al. (MNRAS, 425, 222-230, 2012.) De Gregori et al.
[52] Polenta et al. NA 51, 3-4, 2007
[53] Battistelli et al. MNRAS 423, 1293, 2012 Battistelli et al. 2012
[54] De Petris et al. in preparation
[55] Aristidi et al. A&A 444, 651-659 (2005)
[56] Tristram, M., Patanchon, G., Macías-Pérez, J. F., et al. 2005, A&A, 436, 785
[57] Ferté, A., Grain, J., Tristram, M., & Stompor, R. 2013, Phys. Rev. D, 88, 023524, Ferté, PhD Thesis 2014
[58] Grain, J., Tristram, M., & Stompor, R. 2009, Phys. Rev. D, 79, 123515
[59] Fraisse et al., JCAP04 (2013) 047 arXiv:1106.3087.
[60] Tomasi, C., Petkov, B., Maria Dinelli, B., et al. 2011, Journal of Atmospheric and Solar-Terrestrial Physics, 73, 2237
[61] Salatino M., et al., Astron. & Astrophys. 528, A138 (2011)
[62] R. Puddu, PhD thesis, University of Siena (2016)
[63] Clarricoats, P.J.B., and Olver, A.D., Corrugated Horns for Microwave Antennas, IEE Electromagnetic waves series, Vol. 18, Peter Peregrinus Ltd., London, (1984)
[64] http://www.iar.unlp.edu.ar/llama-web/project.htm
[65] “Project QUBIC: Estimation des dépenses pour le 1er module” IPEV Document dated 13/11/2012.
A Annexe: Experiment location in Dome C

A.1 Studies of the deployment of a QUBIC module at Dome C, Antarctica

This annex details the implementation studies that have been performed to install a QUBIC module at Dome C, which offers exquisite atmospheric characteristics.

A QUBIC module may be hosted in the Concordia base, at Dome C, which is run jointly by French IPEV and Italian PNRA. The site is located at an altitude of 3233 m a.s.l. with coordinates (75° 06′ 00″ S 123° 19′ 58″ E). The base was created in 1995 and started winterovering in 2005. It is now one of the three inland Antarctica stations operating all year through. In summer, Concordia can host around 60 people, while around 15 persons are present during winter. The Meteorological conditions in Concordia can be very hard, with temperatures as low as -80°C in winter. This limits the access to the site to only three months per year during Antarctic summer and thus the implementation of an experiment in Dome C has to be carefully planned in advance (see section A.1.1). Views from the station are shown in Figure 134.

The QUBIC collaboration has started logistic and site testing operations in Dome C as early as in 2006 with the BRAIN-pathfinder experiment [52]. Since then we have demonstrated the possibility to use a dry (cryocooler based) cryogenic system in such environmental conditions. We also carried out detailed site atmospheric testing demonstrating the stability of the atmospheric emission, the low level of opacity and water vapour content, and the lack of polarized emission from the atmosphere itself [53]. During summer 2014-2015 further site testing has been performed with the CASPER experiment [54]. Thanks to this experiment, we now have information about the short timescale atmospheric fluctuations (sampling time 10s) that are useful to complement the daily radiosounding data.

The study of the location of a QUBIC module within the Concordia station has been the subject of the 2015-2016 summer campaign. During this campaign a detailed analysis based on the needs of the QUBIC experiment, on the easiness of access for winter-overers during winter, on the interference with other experiments and logistic considerations for IPEV and PNRA has been performed. The discussion is still ongoing but a preferential location has been selected (cf. Section A.2). The most favored solution appears to be the one labeled as “QUBIC 3bis” where a QUBIC module would be installed at 50-70m North-East from the so-called American Tower which would then be usable for hosting our calibration source and would prevent us from reinstalling such a tower in Concordia. The distance from the scientific module to the Concordia base would be 950m, a rather large distance for winter-overers, but this issue would be mitigated by the use of the Astronomy laboratory, located at a reasonable distance between the module and the station, for data acquisition, storage and control of the experiment. This location also has the advantage of leaving plenty of freedom for the possible installation of more QUBIC modules in the future. Flags were installed on this location during the summer campaign 2015-2016 (in Dec. 2015) by the QUBIC Logistic Coordinator. The “QUBIC 3bis” site is shown in Figure 135.
A.1.1 Implementation issues at Dome C

In this section we describe our default implementation plan for a QUBIC module in Dome C. Any modification is possible in coordination between PNRA, IPEV and the QUBIC collaboration.

The envisaged location for the first module presented in this document has to be suitable to sustain from one side the full development of QUBIC and from the other side to ensure the minimum impact of the full implemented project with respect to the other ongoing projects.

A.1.2 Milestones

A preliminary installation timetable is shown in Table 41. The logistic should evaluate if there are additional costs to ensure as much as possible that these milestones can be respected.

A.1.3 Materials transportation

Our plan for materials transportation has been designed assuming the typical time schedule for delivery of Cargo at Concordia as in Figure 136. It is outlined in Table 42, and its cost is estimated in Table 43. We have assumed a shipping cost of 6 €/kg for ship+traverse shipment and 25 €/kg for ship+Basler plane shipment.

A.1.4 Resume of logistics costs

In case of the installation of a QUBIC module in location option 3, we estimate the logistic costs to $\sim$154,000€.

In the following we have performed an attempt to resume the total logistic costs of a QUBIC module shipped and installed at Dome C. This is intended to be a preliminary estimation to be detailed, validated and recalculated by PNRA and IPEV.

Costs assumptions:

- Shipping cost of 6 €/kg for ship+traverse and 25 €/kg for ship+Basler plane;
- kWh cost assumed to be 1.52 € per kWh in Concordia;
- Summer logistic and scientific personnel salary in Concordia 9000 € gross/month (i.e. 300 € per Man-Day/MD);
- Winter Over personnel salary in Concordia 12,500 € gross/month;
- Part of the costs and manpower assumptions have been derived from [65].

For the mount and construction of a QUBIC module we have done the following assumptions:

- Preliminary study: 45 MD on 09/2015-11/2015;
- Preparation of the surface (hill) for the instrument: 10 MD on summer 2015-2016;
**MILESTONES/TIMETABLE**

| ITEM                                                   | TIME                      |
|--------------------------------------------------------|---------------------------|
| Definition of the experiment site                      | 09/12/2015                |
| Prep. of the hill for the instrument and cal. tower    | 11/2015-01/2016           |
| Construction of the experiment module pillars          | 12/YY-02/(YY+1)           |
| Routing for the cables (exp. + cal. tower)             | 12/YY-02/(YY+1)           |
| Insertion of the mount concrete pillars                 | 12/YY-02/(YY+1)           |
| Transportation of the experiment module                 | 08/YY-02/(YY+1) (R0 or R1 + T2 or T3) |
| Transportation of the calibration tower                 | 08/YY-02/(YY+1) (R0 or R1 + T3 or T1 (YY+1)-(YY+2)) |
| Building the experiment module                          | 11-12/(YY+1)              |
| Building the calibration tower                          | 11/(YY+1)-01/(YY+2)       |
| Transportation of the Mount                             | 08/(YY+1)-12/(YY+1) (Basler) |
| Transportation of the cryostat                           | 08/(YY+1)-12/(YY+1) (Basler) |
| Mounting of the mount+cryostat                           | 01/(YY+2)                 |
| Commissioning and beginning of observations             | 01-02/(YY+2)              |

Table 41: Milestones for the implementation of QUBIC in Concordia Station, YY stands for the year for which the experiment module would be available for shipping.

Figure 136: Materials delivery: typical time schedule for cargo delivery at Concordia.
## TRANSPORTATION OF MATERIALS

| ITEM             | CRATES AND WEIGHT                              | WAY OF TRANSPORTATION*                                                                 | COSTS**  |
|------------------|-----------------------------------------------|---------------------------------------------------------------------------------------|----------|
| CALIBRATION TOWER | 5 crates 2.7m x 1.4m x 1.7m each, 600kg each | • commercial vessel from Le Havre on August 20th 2016                                   | 18,000€  |
|                  | IMPORTANT: note needed in case the QUBIC 3 location is selected | • Astrolabe R0, R1 2016-2017                                                          |          |
|                  |                                               | • Traverse T3 2016-2017 (in case of use helicopters to traverse the see) or T1 2017-2018; |          |
|                  |                                               |                                                                                       |          |
| EXPERIMENT MODULE| total weight ~ 7500kg                         | • commercial vessel from Le Havre on August 20th 2016                                   | 45,000€  |
|                  |                                               | • Astrolabe R0, R1 2016-2017                                                          |          |
|                  |                                               | • Traverse T2 or T3 2016-2017 (crucial to have the material ready at the beginning of 2017-2018); |          |
| 1/2 EQUIPMENT    | ~10 crates of 0.6m x 0.7m x 0.7m and 50kg each| • commercial vessel from Le Havre on August 20th 2016                                   | 3,000€   |
|                  |                                               | • Astrolabe R0, R1 2016-2017                                                          |          |
|                  |                                               | • Traverse T3 2016-2017 (in case of use helicopters to traverse the see) or T1 2017-2018; |          |
| 2/2 EQUIPMENT    | ~10 crates of 0.6m x 0.7m x 0.7m and 50kg each| • Commercial Vessel on August 2017                                                    | 12,500€  |
|                  |                                               | • C130 (New Zealand-MZS) + Basler plane MZS-Dome C on November 2017                     |          |
| CRYOSTAT         | 1 crate 1.7m x 1.7m x 1.42m; 600kg            | • Commercial Vessel on August 2017                                                    | 15,000€  |
|                  |                                               | • C130 (New Zealand-MZS) + Basler plane MZS-Dome C on November 2017                     |          |
| MOUNT            | 2 crates 1.7m x 1.7m x 1.42m; 1000kg each (2 separate flights) | • Commercial Vessel on August 2017                                                    | 50,000€  |
|                  |                                               | • C130 (New Zealand-MZS) + Basler plane MZS-Dome C on November 2017                     |          |
| TOTAL            |                                               |                                                                                        | 143,500€ |
• Construction of the experiment module piles and concrete pillars: 20 MD on summer (YY-YY+1);
• Routing for the cables and service (exp. + cal. tower): 40 MD on summer (YY-YY+1);
• Building the experiment module: 40 MD on summer (YY+1-YY+2);
• Building the calibration tower: 20 MD on summer (YY+1-YY+2);
• Mounting the mount and cryostat: 10 MD on summer (YY+1-YY+2);

For the scientific personnel we have assumed the presence in Dome C of the following people:

• 1 scientific person on summer 2015-2016 (1 x 30 MD);
• 2 scientific people on summer (YY/YY+1) (2 x 30 MD);
• 6 scientific people on summer (YY+1/YY+2) (6 x 60 MD);
• 1 winter-over during year (YY+2);
• 1 winter-over during year (YY+3).

In Table 43 we have listed approximate logistic costs deriving from:

• isolated experiment module design and procurement;
• transportation as detailed above in section 4;
• mounting and construction of the 1st module as detailed above;
• calibration tower construction;
• scientific personnel;
• power and service connections;
• running costs for 2 years including winterovers.

A.2 Possible implementation at Dome C

For a module location in Dome C three options are envisaged, the most advisable of which is by the American Tower, 57m toward east (QUBIC 3bis option). Exact position has to be defined by IPEV, PNRA and QUBIC collaboration considering needs of other experiments in the surrounding. See Figure 137 for a detailed map of the area.

During 2012-2013 summer campaign, the QUBIC collaboration has started a detailed and fruitful scouting activity in Concordia for the definition of the QUBIC experiment localization. During the 2015-2016 summer campaign, the QUBIC collaboration was represented, in Dome C by its logistic coordinator, and this campaign aimed at finalizing this activity in the most coordinated and agreed way between the QUBIC collaboration, IPEV, PNRA as well as the other experiments and collaborations present or planned in Concordia station.

The conclusion of this study is that the QUBIC 3bis location seems to us the best trade-off of all possible solutions from the point of view of the interference problems, quality of the QUBIC observations, and for timing and economic reasons.

• QUBIC 1 option is located approximately 450m from the Dome C base toward the west direction. The 45m calibration tower needs to be located ~50m from the experiment, at its west. The idea behind this solution, is to position a QUBIC module at 100m from the Astronomy lab toward west, and use the Astronomy lab itself as data acquisition/storage with minimal continuous occupation. The possible interference between QUBIC, IRAIT, BSRN and the experiments located in the shelter Physics, shelter Atmo, and shelter Astronomy have been investigated and have driven the site localization in that area. Despite most of the experiments have minimal or null impact for QUBIC, there is some visual impact, especially for IRAIT, which could however be minimized with a distance of the calibration tower ~150m and with BSRN which may need to be repositioned. The QUBIC 1bis solution is very similar and relies on the fact to reuse an existing facility, the Star-Photomer/German Dome,
| ITEM | Timing | 2015-16 | YY-YY+2 | YY+1-YY+2 | YY+2-YY+3 | YY+3-YY+4 | Total cost  |
|------|--------|---------|---------|-----------|-----------|-----------|-------------|
| **Experiment module:** | | | | | | | | 130.000€ |
| Structure on pillars | 1-7/2016 | 65.000€ | | | | | |
| Isolated module | 1-7/2016 | 45.000€ | | | | | |
| Service (electricity,...) | 1-7/2016 | 10.000€ | | | | | |
| Flexible cover (Boot) | 1-7/2016 | 10.000€ | | | | | |
| **Transportation:** | | | | | | | 143.500€ |
| Calibration tower (traverse) | sum (YY/YY+1) | 18.000€ | | | | | |
| Exp. module (traverse) | sum (YY/YY+1) | 45.000€ | | | | | |
| 1/2 Equipment (traverse) | sum (YY/YY+1) | 3.000€ | | | | | |
| 2/2 Equipment (Basler) | sum (YY+1/YY+2) | 12.500€ | | | | | |
| Cryostat (Basler) | sum (YY+1/YY+2) | 15.000€ | | | | | |
| Mount (Basler) | sum (YY+1/YY+2) | 50.000€ | | | | | |
| **1st module construction:** | | | | | | | 39.900€ |
| Preliminary study (45 MD) | 9-12/2015 | 13.500€ | | | | | |
| Surface preparation (10 MD) | sum 15-16 | 3.000€ | | | | | |
| Platform n pillars (20 MD) | sum (YY/YY+1) | 6.000€ | | | | | |
| Exp. mod. construction (40 MD) | sum (YY+1/YY+2) | 10.800€ | | | | | |
| Connections (12 MD) | sum (YY+1/YY+2) | 3.600€ | | | | | |
| Experiment mounting (10 MD) | sum (YY+1/YY+2) | 3.000€ | | | | | |
| Cal. tower construction (20MD) | sum (YY+1/YY+2) | 6.000€ | | | | | |
| **Scientific personnel (except wo):** | | | | | | | 135.000€ |
| 1 scientific (1 x 30MD) | sum (YY/YY+1) | 9.000€ | | | | | |
| 2 scientific (2 x 30MD) | sum (YY+1/YY+2) | 18.000€ | | | | | |
| 6 scientific (6 x 60MD) | sum (YY+2/YY+3) | 108.000€ | | | | | |
| **Service connections:** | | | | | | | 13.800€ |
| power (20 MD) | sum (YY/YY+1) | 6.000€ | | | | | |
| other connections (20 MD) | sum (YY/YY+1) | 6.000€ | | | | | |
| organization (6 MD) | sum (YY/YY+1) | 1.800€ | | | | | |
| **Running costs (2 years):** | | | | | | | 699.456€ |
| winter-over (1st season) | win YY+2 | | | | | | 150.000€ |
| power cons. (15kW x 365 days) | win YY+2 | | | | | | 199.729€ |
| winter-over (2nd season) | win YY+3 | | | | | | 150.000€ |
| power cons. (15kW x 365 days) | win YY+3 | | | | | | 199.729€ |
| **TOTAL COSTS:** | | | | | | | 1.167.656€ |

| | 155.500€ | 103.800€ | 208.900€ | 349.728€ | 349.728€ | 1.167.656€ |

Table 43: Logistic costs: Logistic costs foreseen for the QUBIC experiment. We have divided the costs within the years.
sited approximately 9m west of IRAIT, whose shelter does not fit the QUBIC requirements but the platform sits on a structure of three lightened concrete pillars identical to the one designed for the QUBIC platform. The main draw-back of the QUBIC 1bis solution is the optical pollution produced by QUBIC to IRAIT and vice-versa. This has been simulated and found to be minimized (although not cancelled) if ground shields are placed and the relative position between QUBIC and IRAIT allows each experiment to keep the other below 15° elevation. Both these solutions (QUBIC1 and 1bis) are technically feasible and the QUBIC collaboration foresees them as positive. We should however bear in mind that they result in a compromise which would reduce the scientific capabilities both of QUBIC and of IRAIT and may require the repositioning of BSRN.

- **QUBIC 2 option** was already selected during 2012-2013 summer campaign. In this option the experiment would be located 650m south form the Dome C base and the calibration tower either toward east or toward west, 50m from the experiment itself. The interference between geo-magnetic and seismology activities have been studied and an agreement has been found implying the construction of a new road going around the magnetic quite area and the necessity to build the QUBIC calibration tower in aluminium in order to reduce magnetic interference. This region is unfortunately currently not well served by infrastructure and, in addition, QUBIC implementation would require the construction of two shelters, one for the experiment, and one as
| Advantages / Gain                                      | Disadvantages / Mitigation                                                                 |
|-------------------------------------------------------|-------------------------------------------------------------------------------------------|
| Short distance from the base / Easier operations for winter-over | Less immune from Dome C base optical pollution due to its vicinity to the Base              |
| Only one shelter to build (i.e. the data acquisition module would be the Astronomy lab.) | Interaction with BSRN: possible need to reposition the experiment                         |
| Large bandwidth connection between experiment module and Astronomy lab | Interaction with IRAIT: reduce the sky area directly accessible to IRAIT                     |
| For QUBIC 1bis: reuse the existing concrete pillars structure | For QUBIC 1bis: direct air pollution on and from IRAIT                                       |
|                                                        | Need to build the calibration tower                                                        |
|                                                        | Not straight-forward to have a plan for the hypothetical QUBIC next generation formed by 6 identical modules |

Table 44: Pro and cons of QUBIC 1 option

| Advantages / Gain                                  | Disadvantages / Mitigation                                                                 |
|----------------------------------------------------|-------------------------------------------------------------------------------------------|
| quite and free-from-interference observational site | need to build a new road going around the Amagnetic area                                  |
| straight-forward to implement the hypothetical next generation 6-modules experiment | expensive and difficult operation due to the constraints created by the interference with geomagnetic operations |
|                                                    | need to build a calibration tower                                                         |
|                                                    | need to build 2 brand new shelters                                                        |

Table 45: Pro and cons of QUBIC 2 option

data acquisition/storage. This service would be expensive and time consuming especially in the light of the constraints set by other impacted activities. Unless there are no other choices, at the present status we consider this option not viable because it would be too expensive.

- **QUBIC 3 option** (see Figure QUBIC 3) foresees a QUBIC module installation at 950m west from the Dome C base, by the existing American Tower. The idea behind this solution, is to position the QUBIC experiment shelter as close as possible to the American tower (60m from it) at its east, clearly outside the clean area, in order to use the American Tower as Calibration Tower and being able to observe the calibration source with as high as possible elevation angle. The use of the American Tower as calibration tower would result in no need to build an additional tower with clear economic and time advantages. The impact of our calibration source on the tower would be minimal. Also, we foresee the possibility to use the Astronomy lab as data acquisition/storage with minimal continuous occupation. Within this solution we selected two possible locations: QUBIC 3 location would result at 60/70 m from the American Tower, south-east of it, while QUBIC 3bis location would be at 50/60m from the Tower, north-east from it. From a recognition performed in order to establish the possible interference between QUBIC and other experiments mounted on the American Tower, it seems clear that, despite most of the experiments have no impact to and from QUBIC, the positioning of QUBIC toward south (main wind direction in Dome C, QUBIC 3 option) would have an impact due to the change of the snow accumulation in the surrounding area (although QUBIC would anyway be outside the clean area). On the other hand, positioning a QUBIC module on the north(-east) side of the tower (QUBIC 3bis option), designing the experiment module in such a way that the snow accumulation would be kept under control, and keeping the experiment module as low as possible, would result in negligible effect on the activities on-going from the
American Tower. There are several other advantages of this solution including the immunity from air pollution due to the Dome C base. The main drawback of this solution is the distance from the base. For this reason, the instrument operations will be totally remotized and the winterover operations will be limited to three-times-a-week visits to the experiment besides the hypothesis of instrumental emergencies.

This solution (QUBIC 3bis) seems to us the best trade-off of all possible solutions from the point of view of the interference problems, quality of the QUBIC observations, and for timing and economic reasons.

| Advantages / Gain                                                                 | Disadvantages / Mitigation                                                                 |
|---------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|
| Use the American Tower as Calibration tower / no need to build another 45m tower | Distance from the base ∼ 950m with more complicated winterover procedures / fully remote experiment + dedicated winterover |
| Free from optical pollution due to the Dome C base                              | Dedicated/redundant network connection needed                                               |
| Use of the Astronomy lab and data acquisition-storage unit / no need to build another data acquisition shelter | Interference with experiment on the American Tower / place the experiment on the north-east side (QUBIC 3bis) at ∼ 60m from the tower + build the experiment shelter as low as possible taking care of the snow accumulation |
| Freedom in the planning of the hypothetical next generation 6-modules QUBIC      |                                                                                           |

Table 46: Pro and cons of QUBIC 3 option
| LOCATION                  | Lat.       | Lon.       | Notes                                           |
|---------------------------|------------|------------|------------------------------------------------|
| BASE                      | S 75° 06' 00.1'' | E 123° 19' 57.4'' |                                                |
| ASTRONOMY LAB             | S 75° 05' 59.3'' | E 123° 19' 13.4'' | ~350m from the base                             |
| AMERICAN TOWER            | S 75° 05' 50.7'' | E 123° 17' 58.4'' | ~970m from the base                             |
| QUBIC 1                   | S 75° 05' 58.2'' | E 123° 18' 59.7'' | at ~100m from Astronomy Lab                     |
| CALIBRATION TOWER 1       | S 75° 05' 57.4'' | E 123° 18' 53.0'' | ~50m from the experiment                        |
| QUBIC 1bis                | S 75° 06' 01.5'' | E 123° 19' 09.5'' | reuse German-Dome platform                      |
| CALIBRATION TOWER 1bis    | S 75° 06' 01.5'' | E 123° 19' 03.3'' | ~50m from the experiment                        |
| QUBIC 2                   | S 75° 06' 22.6'' | E 123° 19' 48.7'' | ~650m from the base                             |
| CALIBRATION TOWER 2       | S 75° 06' 22.6'' | E 123° 19' 42.5'' | ~ 50m from the experiment                       |
| QUBIC 3                   | S 75° 05' 51.9'' | E 123° 18' 07.1'' | ~950m form the base                             |
| QUBIC 3bis                | S 75° 05' 50.3'' | E 123° 18' 05.5'' | reduce interference                             |
| QUBIC 3bis corner 1       | S 75° 05' 50.5'' | E 123° 18' 05.1'' | SW corner of the shelter                        |
| QUBIC 3bis corner 2       | S 75° 05' 50.5'' | E 123° 18' 06.2'' | SE corner of the shelter                        |
| QUBIC 3bis corner 3       | S 75° 05' 50.0'' | E 123° 18' 06.1'' | NE corner of the shelter                        |
| QUBIC 3bis corner 4       | S 75° 05' 50.0'' | E 123° 18' 05.2'' | NW corner of the shelter                        |
| CALIBRATION TOWER 3/      | S 75° 05' 50.7'' | E 123° 17' 58.4'' | no need to build another 45m tower              |
| AMERICAN TOWER            |            |            |                                                |

Table 47: Possible locations of a QUBIC module with coordinates. In red we highlight not viable solutions (unless no other options are possible), in orange we highlight possible solutions with some limitations and loss on efficiency, in green we highlight our preferred solution which, from our point of view, is the best trade-off solution with minimal interference.
B  ATRIUM-77335
# Requirements for implantation of first module of QUBIC in San Antonio de los Cobres

## General Specifications

| Item              | Requirement                          | Comment                                                                 |
|-------------------|--------------------------------------|-------------------------------------------------------------------------|
| Site Altitude     | 4969m a.s.l.                         |                                                                         |
| Site location     | S : 24 deg 11’ 11.71 ‘’ O : 66 deg 28’ 40.79’’ | Plateau visited on Sept 22nd above LLAMA site                         |
| Electrical Power  | 25 kW                                 | Pulse Tube Cooler : 10 kW Electronics/Computer : 5 kW Mount (estimation) : 10 kW |
| Internet Bandwidth| 5 MB/sec                              | To San Antonio de los Cobres and to the rest of the world               |

## Infrastructure on the mountain

| Item              | Requirement                                           | Comment                                                                 |
|-------------------|-------------------------------------------------------|-------------------------------------------------------------------------|
| Road              | Road to access the QUBIC site from the LLAMA one : a few hundred meters to be added (To be specified by experts) | Concrete ground or not depends on soil quality. To be assessed by experts accounting for Instrument + mount weight |
| Planar area       | 100m in the EW direction 20m in the NS direction     |                                                                         |
| Shelter for Instrument | • 8m in the EW direction  
• 5.5m in the NS direction  
• Basement supports the cryostat + mount ~ 3 tons  
• Window in the ceiling to point the cryostat window outwards  
• Circular ground shield installed on the roof to prevent straylight from the ground on the cryostat window. | • Large width is chosen to have the ability to add more modules later  
• Hole in the window needs an « insulation coat » making it thermally/water/sand insulated (à la BICEP2 – see images below)  
• detailed specifications of the ground shield being finalized by Marco de Petris, Roma- see pictures for an example  
• May also be used as a temporary shelter for people working on the site. |
| Compressor Shelter| 3x3m ~ 15-20m from the Instrument Shelter            | Will host the compressors and noisy equipment. May also be used as a temporary shelter for people working on the site. |
| Calibration Tower | 45 m height 45 meters North from Module              | Hardware Funded by France DIM-ACAV. Manpower for installation needed.  |
### Infrastructure in San Antonio de los Cobres (inside LLAMA building)

| Item                      | Requirement                                           | Comment                                      |
|---------------------------|-------------------------------------------------------|----------------------------------------------|
| Offices and labs          | 50 sqm permanently allocated to QUBIC                   |                                              |
| Clean Room                | Access when needed for instrument upgrade              |                                              |
| Bedrooms                  | Two bedrooms permanently                              |                                              |
| Kitchen / Restrooms / common facilities | Shared access with LLAMA               |                                              |

### Integration / Operations

| Item               | Requirement                                                                 | Comment                                                                 |
|--------------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------|
| Integration        | • Personal from Argentina and their QUBIC partners to perform integration  | • Cranes, trucks, transportation in Argentina to be funded by Argentina |
|                    | • Integration hangar (around 50 sqm) in Salta (or San Antonio de los Cobres) to integrate and test Mount + Instrument prior installation on site. |                                                                 |
| Operation          | Two trained technicians permanently in San Antonio de los Cobres with regular visits to the instrument (frequency and duties to be detailed later) |                                                                 |
| Cryogenic Maintenance | Under the responsibility of San Carlos de Bariloche Team |                                                                 |

Important questions to be answered:
- Assess cost of the above infrastructure
- Assess date at which it could be available for QUBIC installation
- Precise various aspects of the above table by interaction with experts (especially J. Viramonte).

**Illustrations:**

![Figure 1: BICEP2 Insulating coat, forebaffle (black) and ground shield (metal)](image-url)
Figure 2: BICEP2 Shelter + mount sketch

Figure 3: BICEP2 inside of the shelter with view of the ceiling hole, mount and instrument
Figure 4: QUBIC implantation map at Alto Chorillo

Figure 5: schematic front view of the instrument module
Figure 6: schematic top view of the instrument module