QUBIC VII: The feedhorn-switch system of the technological demonstrator

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Abstract. We present the design, manufacturing and performance of the horn-switch system developed for the technological demonstrator of QUBIC (the $Q&U$ Bolometric Interferometer for Cosmology). This system is constituted of 64 back-to-back dual-band (150 GHz and
220 GHz) corrugated feed-horns interspersed with mechanical switches used to select desired baselines during the instrument self-calibration. We manufactured the horns in aluminum platelets milled by photo-chemical etching and mechanically tightened with screws. The switches are based on steel blades that open and close the wave-guide between the back-to-back horns and are operated by miniaturized electromagnets. We also show the current development status of the feedhorn-switch system for the QUBIC full instrument, based on an array of 400 horn-switch assemblies.

**Keywords:** Cosmic microwave background polarization, cosmology, bolometers, polarimetry, interferometry
1 Introduction

This paper is part of a set describing the current status of QUBIC (Q and U Bolometric Instrument for Cosmology), an experiment based on the concept of bolometric interferometry [1, 2] and designed to constrain tightly the B-mode polarization anisotropies of the Cosmic Microwave Background (CMB). The QUBIC science case in the framework of the current state-of-the-art is described in [3]. Here we describe the design, manufacturing and testing of the horn-switch system developed for the QUBIC technological demonstrator (TD), that will observe the sky at 150 GHz from the Argentinean Alto Chorrillo site.

The horn-switch system is based on an array of back-to-back corrugated feedhorns that allow the signals coming from different directions in the sky to combine additively on the instrument focal plane, thus generating an interference pattern. The horns are interspersed with an array of mechanical switches that allow us to select any subset of baselines during calibration.
In this paper we describe in detail the manufacturing and testing of the 64-elements horn-switch system of the QUBIC TD and present briefly the advances of the development of the complete 400-elements array that will be installed in the QUBIC Full Instrument (FI).

We start with a top-level description of the system in section 2, then we present the back-to-back horn system in section 3 and the switch array in section 4. In each section we review the main requirements, discuss the manufacturing and testing techniques, present the testing results and provide an overview of the development of the arrays for the QUBIC FI. Finally, section 5 summarizes the conclusions and future prospects of our work.

2 The horn-switch system

In the left panel of Figure 1 we show a schematic of the QUBIC working principle. The sky signal enters the cryostat propagating through a high-density polyethylene (HDPE) window. Then, a rotating half-wave plate modulates the polarization and a polarizing grid selects one of the two linear polarization components. An array of 400 back-to-back corrugated horns collects the radiation and re-images it onto a dual-mirror optical combiner that focuses the signal onto two orthogonal TES detectors focal planes. The output of each detector contains interference fringes that are the so-called “visibilities” of the selected Fourier modes. A dichroic filter placed between the optical combiner and the focal planes selects the two frequency bands, centered at 150 GHz and 220 GHz.

The right panel of Figure 1 shows a single element of the horn-switch array, constituted of a pair of back-to-back corrugated horns interspersed with a mechanical switch that opens and closes the connecting circular waveguide.

A shutter is placed in the middle of the waveguide connecting each back-to-back horn pair. Each shutter is used to exclude particular baselines when the instrument operates in calibrating mode. We call this particular calibration strategy self-calibration, which is a key feature of the QUBIC systematic effects control. The interested reader can find details about self-calibration in [4].

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Figure 1. Left: schematic of the QUBIC instrument. Right: details of one element in the feedhorn-switch array.
3 Back-to-back feed horns

3.1 Feed horns requirements and design

3.1.1 Requirements

The back-to-back horn array has two objectives: the front (sky) horns define the field of view (FoV) of the instrument, while the back horns illuminate the beam combiner with the desired edge taper. In table 1 we list the main requirements of the back-to-back horn array with notes detailing their relevance. Notice that we do not have a requirement for cross-polarization, because the horn array is placed behind the polarization modulation/separation stage, so that the cross-polarization does not introduce systematic effects.

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<th>Value</th>
<th>Notes</th>
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<td>Inter-axis distance ......</td>
<td>14 mm</td>
<td>Driven by sampling of the angular power spectrum</td>
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<tr>
<td>Aperture</td>
<td>12 mm</td>
<td>Driven by the FoV</td>
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<td>Return loss ..............</td>
<td>&lt; −25 dB</td>
<td>Over the 130–240 GHz bandwidth</td>
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<tr>
<td>Insertion loss ...........</td>
<td>&lt; 0.1 dB</td>
<td>To ensure overall transmission of ∼ 95%</td>
</tr>
<tr>
<td>Mass .....................</td>
<td>30 g/horn</td>
<td>Must be suspended on the top of the optical combiner</td>
</tr>
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For simplicity we built identical front and back horns. The design was based on a previous geometry [5] modified to accept the propagation of the 220 GHz frequency band. In Figure 2 we show the corrugations profile: the depth of the corrugations at the aperture is 0.5 mm and at the throat is 0.7 mm. This choice allowed us to obtain antennas which are sensitive to both the 150 GHz and 220 GHz bands.

Figure 2. The corrugations profile of the QUBIC horns.
3.1.2 Electromagnetic simulations technique

We have simulated the field produced at the mouth of the QUBIC corrugated horn using an electromagnetic mode-matching technique [6], depicted schematically in Figure 3. This technique regards the corrugated structure as a sequence of smooth walled cylindrical waveguide sections, each of which can support a set of propagating TE and TM modes. At each corrugation the sudden change in the radius results in a scattering of power into backward propagating reflected modes in the left-hand side guide segment and forward propagating transmitted modes in the right-hand segment.

The power coupling between modes is given by the overlap integral \( \int e_{n,l} h_{m,r} \, dA \), where \( e_{n,l} \) is the transverse electric field of mode \( n \) on the left-hand side of the junction, \( h_{m,r} \) is the magnetic field of mode \( m \) on the right-hand side of the junction and \( dA \) is a surface element on the transverse plane. The modes are then propagated through the length of waveguide section to the next scattering junction where the overlap integral between the modal components is computed again.

\[
\begin{bmatrix}
\vec{B} \\
\vec{D}
\end{bmatrix} = \mathbf{S} \cdot 
\begin{bmatrix}
\vec{A} \\
\vec{C}
\end{bmatrix} = 
\begin{bmatrix}
S_{1,1} & S_{1,2} \\
S_{2,1} & S_{2,2}
\end{bmatrix} \cdot 
\begin{bmatrix}
\vec{A} \\
\vec{C}
\end{bmatrix}
\] (3.1)

whose elements are calculated using overlap integrals as described in [7]. The columns of the scattering matrix describe the amplitude of each output mode generated by a unit-amplitude input mode. The scattering matrix for the horn as a whole, is computed by cascading the matrices for each uniform section and junction. We assume no scattering at the horn aperture so \( \vec{C} = 0 \).

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**Figure 3.** Schematic of the mode-matching model implemented in the electromagnetic simulations.

If \( \vec{A} \) and \( \vec{C} \) are column vectors of the mode coefficients of the fields incident from the left and the right, and \( \vec{B} \) and \( \vec{D} \) are the mode coefficients of the resulting reflected fields, then their relationship is described using a scattering matrix, \( \mathbf{S} \):
The field at the mouth of the corrugated horn is then determined from $\vec{D} = S_{2,1} \cdot \vec{A}$, where $S_{2,1}$ is the sub-matrix that deals with the forward-propagating modes, and the reflected field is determined from $\vec{B} = S_{1,1} \cdot \vec{A}$. The transmitted and reflected power are found by multiplying the complex elements of the relevant column vector by their complex conjugate and summing them.

In our analysis we used 60 waveguide modes (30 TE and 30 TM), but most of these modes carry no power to the mouth of the horn at 150 GHz. The TE and TM modes with power have a coherent phase relationship and in this case correspond to the single hybrid HE$_{1,1}$ mode.

In the 220 GHz band more than one column of the scattering matrices is non-zero and these represent possible independent modes of power transmission. We excite all modes equally at the input, $\vec{A} = [1, 1, 1, \ldots]^T$, and add the individual output fields incoherently. The reflected power is calculated as a percentage of the power that could be transmitted by the number of propagating modes and this can result in spikes at frequencies where a mode is just switching on but not carrying much power.

### 3.1.3 Simulations results

In Figure 4 we show the return loss (left panel) and maximum cross-polarization (right panel) in the two QUBIC bands. We can see at a glance that the performance in the 150 GHz band is superior compared to the 220 GHz band. In fact the design was initially tailored in the D-band and subsequently modified to accept also the higher band that could not be optimized in terms of performance like the lower frequency range.

The return loss at 150 GHz is, on average, around $-25$ dB, while in the higher frequency band it is compatible with $-20$ dB up to 230 GHz, and degrades to $\sim -10$ dB on the right hand side of the frequency interval. We assessed the potential impact of the poor return loss in the highest part of the 220 GHz band: a degradation of the return loss will induce a reduction of the horn transmission and therefore an overall decrease of the sensitivity. With a pessimistic $-10$ dB return loss over the whole 220 GHz, we estimate a degradation in the sensitivity of less than 2%, which makes this out-of-spec a negligible issue.

The cross-polarization is very good ($\sim -35$ dB) at 150 GHz, while it is around $-5$ dB at 220 GHz. This is coherent with the design: at 150 GHz we have a single-mode corrugated horn, for which we expect excellent polarization purity, while at 220 GHz we have propagation of higher modes that do not preserve the polarization state. But this is not a problem for QUBIC, as already mentioned, because the polarization is selected before the radiation enters the horns. For this reason we show here the expected cross-polarization performance but we will not discuss it further in the rest of the paper.

In Figure 5 we show the simulated beam patterns at 150 and 220 GHz for the three main co-polar planes (E-plane, H-plane and 45$^\circ$ plane). At 150 GHz we can appreciate the typical Gaussian profile of single-mode corrugated horns, while at 220 GHz the main beam shape is a flat-top resulting from multi-mode propagation. The sidelobes are low, less than $\sim -30$ dB at angles larger than $\sim 30^\circ$.

### 3.2 The technological demonstrator feed horn array

We have developed the horns array using the platelet technique, which requires drilling circular holes into metal plates that are subsequently stacked and mechanically clamped [8]. We have used two methods to drill the holes: chemical etching of 0.3 mm aluminum plates and CNC milling of top and bottom plates (3 mm and 6 mm thick, respectively).
Figure 4. Simulated return loss (left) and maximum cross-polarization (right) in the two QUBIC frequency bands.

Figure 5. Co-polar simulated beam patterns (E, H, and 45° planes) at 150 GHz (top row) and 220 GHz (bottom row).
On the one end, chemical etching allowed us a fast and cheap process, potentially scalable to a large number of elements. On the other hand, this method could not be applied to the external plates that required a more substantial thickness for mechanical clamping. To simplify the manufacturing we did not realize corrugations in the top plate, so that the feed apertures terminate with a smooth, 3 mm thick cylindrical aperture (see panel (c) of Figure 6). This impacts mainly the horn cross-polarization, which we know is not an issue for QUBIC.

Each of the two 64-horns arrays is composed of 175 plates enclosed between a bottom and a top flange (panels (a), (b), and (c) of Figure 6). We have silver-plated each plate and both flanges to improve electrical conductivity along the horns profile. Each metal plate has an overall size of $112 \times 112$ mm, with a thickness of 0.3 mm. The plates also include four 3 mm diameter holes for alignment pins and 77 holes for the Ergal (7075 aluminum alloy) M3 screws that pack the array between the two flanges.

The top flange has an overall size of $120 \times 120$ mm with a thickness of 3 mm and it contains the 64 horn apertures with a diameter of 12.33 mm. It also contains countersink holes for the tightening screws so that the screw heads lie flush with the array planar surface. The bottom flange has an overall size of $133 \times 133$ mm with a thickness of 6 mm and it contains circular waveguide segments with a diameter of 1.91 mm for each of the 64 horns. The bottom flange couples to the switch array and is machined to obtain anti-cocking interfaces between each waveguide pair. It also includes holes for the module tightening screws. Half of the screws run from the top to the bottom flange and hold each of the two arrays together (therefore allowing us to handle and test the arrays separately), the remaining group extends further to hold the horn and switch modules together (see panel (d) of Figure 6).

3.3 Mechanical measurements and achieved tolerance

3.3.1 Experimental procedures

We tested the mechanical tolerance according to two different procedures. First we visually inspected the inner profile of a sacrificial brass sample that was cut to allow us to magnify the shape of the antenna teeth and grooves. Then we used a metrological machine (Werth ScopeCheck 200) to measure the position, diameter and deviation from circularity of each hole in the platelets of the final array.

**Visual inspection.** The left panel in Figure 7 shows a section of the brass prototype. The enlargement in the right panel highlights the presence of cusps ($\lesssim 0.06$ mm high) on the profile of all the corrugations that are the effect of a non uniform erosion of the metal during the etching process.

This non uniformity is a limitation which is inherent in the chemical etching process, so that we can expect that the antennas produced with this method present imperfections in their corrugated profile. In Section 3.3.2 we discuss the impact of these defects on the feedhorn performance for QUBIC.

**Metrology.** Figure 8 shows the Werth ScopeCheck 200 that performs precision measurements using either an optical or a tactile device. In our setup we used the optical sensor, which can be moved in three dimensions over a glass work plane where we laid our platelets.

In the picture we see the two monitors (one to observe the hole profiles and the second to control the machine), and the control console in front of the computer keyboard. On the right part of the picture, in the background, we see the glass plane with the optical sensor. In Section 3.3.3 we discuss the results of the metrological measurements.
Figure 6. The QUBIC TD feedhorns array: (a) chemically etched aluminum platelets during the stacking process; (b) 3-D CAD model of the antenna array; (c) one of the two antenna modules after integration; (d) the complete integrated feedhorn-switch system.

3.3.2 Impact of mechanical imperfections on electromagnetic performance

We assessed the impact of the imperfections in the feedhorn profile caused by the etching process by computing the return loss and the co-polar radiation patterns on the $E$ and $H$ planes considering two cases: (i) the nominal profile, and (ii) a profile modified inserting a step-like defect on teeth and grooves of all the corrugations (see Figure 9).

**Return loss.** Figure 10 shows the effects of the defects on the return loss. We see that they do not change significantly the overall level, but shifts some of the resonances in frequency. In general, however, we can consider the impact on the return loss negligible.
Figure 7. Left. A section of the first feedhorn prototype. Right. Detail of the cusps on teeth and grooves resulting from non uniform chemical erosion.

Figure 8. Werth ScopeCheck 200 metrology machine.

Radiation pattern at the center frequency. Figure 11 shows the simulated radiation patterns (E-plane, H-plane, and 45° plane) at 150 GHz (top two rows) and 220 GHz (bottom two rows) for the two cases studied. The bottom plot in each figure shows the difference in dB of the beam patterns for the two cases. In the main beam region (−15° < \( \theta \) < 15°) the difference is less than 0.05 dB, and over all the −90° ≤ \( \theta \) ≤ 90° range the difference is within
3.3.3 Results of metrological measurements

We have carried out metrological measurements of both feedhorn arrays and compared the manufacturing precision with the maximum achievable tolerance of the chemical etching process, which is $\pm 0.05\, \text{mm}$. In this section we will refer to the two arrays as array-1 and array-2.

We measured the holes of each antenna and alignment pin for all the aluminum plates, compared the measured positions and diameters with their nominal values and calculated the form tolerance (FT) of each hole (see the sketch in Figure 12 for a definition of this parameter). This rich set of measurements allowed us to obtain the actual mechanical profiles of all the feeds in the array that we used to simulate their actual electromagnetic behavior. We then

$\pm 2\, \text{dB}$.

Figure 9. Sketch of the model used to simulate the imperfections in the feedhorn profile.

Figure 10. Impact of defects on the feedhorn return loss.
Figure 11. Impact of defects on the co-polar radiation patterns. The black line in the bottom panel shows the difference between the two beam patterns. The top plots refer to 150 GHz simulations, the bottom plots refer to 220 GHz simulations.

compared this family of simulations with the electromagnetic parameters measured in the laboratory, as explained at the beginning of Section 3.4.

The boxplots of Figure 13 show the deviation of the measured Cartesian center coordinates of the antenna holes from their nominal value ($\Delta x$, top-left, and $\Delta y$, top-right), the deviation between the measured and nominal hole diameters (bottom-left), and the corresponding distribution of FT values (bottom-right). The red line corresponds to the expected deviation, while the green area highlights the expected manufacturing tolerance. The measurements are related to the array-1.

As one can see, all the antenna positions comply with the manufacturing tolerance, while more than 90% of the antenna diameters are out of specification, generally larger than expected and distributed around two peaks: $\Delta d_1 = 0.07$ mm and $\Delta d_2 = 0.15$ mm, with a maximum deviation of 0.25 mm. The measured shape tolerances show no significant deviation.
from circularity.

We obtained similar results for the alignment pins of array-1 and for both antenna holes and pins of array-2, but they are not reported here for simplicity. We measured also the top and bottom plates of the arrays and they are in compliance with the milling precision tolerance of 0.03 mm.

The out-of-spec was due to a loose control of the chemical etching time. Indeed, one can see that the measurements are grouped in blocks of plates and the average deviations from the nominal diameters follow a bi-modal distribution. Discussing with the company that performed the etching we understood that the plates were treated in batches, and the time was dependent also on other items (independent of QUBIC) in their production line. These problems were solved in the production of the horns for the final instrument (see Section 3.5) by strictly controlling the etching time.

In Section 3.4 we discuss the effect of this out-of-spec on the TD horns electromagnetic performance, where we compare the measured return loss and beam patterns with simulations run with the nominal and measured antenna profiles.

The boxplots in Figure 13 also highlight an oscillatory, almost sinusoidal pattern in the measurements of the holes centers coordinates as a function of the antenna number. This is likely a systematic effect in our measurement. In fact, this behavior correlates with the row-by-row scanning of the antenna holes in the square antenna array. Unfortunately, however, we could not clearly identify this effect, neither in the measurement strategy nor in the measurement machine, so that this remains a reasonable hypothesis that is not demonstrated yet. For this reason we preferred not to decorrelate this effect from the data and left it as an additional source of uncertainty.

### 3.4 Electromagnetic measurements

In this section we present the measured electromagnetic performance of the QUBIC TD feedhorns compared with simulations obtained using the measured profiles of all the feedhorns

![Figure 12. Definition of the form tolerance parameter.](image-url)
in the array. In our measurements we tested a subset of feedhorns, each identified with a pair of numbers corresponding to the row and column position in the array.

In Figure 14 we show four grids summarizing the measurements that we have conducted on the TD arrays. Each grid represents the $8 \times 8$ horn array in each module. On the top of each grid we have specified the number of the module and the type of measurements performed. In each grid we identify with black cells the horns tested at 150 GHz, with red cells the horns tested at 220 GHz and with black-red cells the horns tested at both frequencies. Notice that we do not report return loss measurements for the TD array at 220 GHz. In this case the measurements presented in this paper were carried out on the two central horns of the two modules of the QUBIC Full Instrument (FI) that share the identical electromagnetic design and manufacturing technique of the TD (see Section 3.5).

3.4.1 Experimental setup and procedures

The experimental setup consisted of a Vector Network Analyser (VNA) equipped with millimeter extensions for full 2-ports characterization in the 110–170 GHz and 170–260 GHz bands. To sample the beam patterns, the TD feedhorn array was mounted on a goniometer fixed on an optical bench. Since the feedhorn output waveguide is circular, we used a set of adapters to connect the rectangular waveguide of the millimeter extension to the feed. The following list summarizes the components in our experimental setup:

1. VNA Agilent Technologies PNA-X® model N5246A
2. Agilent Technologies Millimeter Head Controller model N5261A

Figure 13. Results of the metrological measurements of the antenna holes of array 1. Top-left and top-right: deviation of measured $x$ and $y$ center coordinates from the nominal value. Bottom-left: deviation of measured diameters from the nominal value. Bottom-right: measured form tolerances. The red line corresponds to the expected deviation, while the green area highlights the expected manufacturing tolerance.
### Return loss measurements

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### Array 1

### Beam pattern measurements

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### Array 2

### Figure 14. Grids summarizing the electromagnetic measurements carried out on the TD feedhorn arrays. See text for further details.

3. Two OML millimeter extensions model V06VNA2-T/R-A for full 2-port S-matrix characterization in the 110–170 GHz band

4. Radiometer Physics 25 dB gain corrugated circular feedhorn for 110–170 GHz band measurements used to illuminate the array
Figure 15. Left: the setup used for beam pattern measurements in the lower band (110–170 GHz). Right: the setup used for beam pattern measurements in the upper band (170–260 GHz). In this case the length of cables allowed us to span the range (−45°, +45°).

5. D-band OML TRL calibration kit

6. Two VDI millimeter extensions model WR4.3VNATxRx-M for full 2-port S-matrix characterization in the 170–260 GHz band

7. Millitech G band 23 dB rectangular standard horn for 144–220 GHz measurements used to illuminate the array (this horn is single-moded up to 240 GHz and the beam patterns in the upper band are limited to 220 GHz)

8. VDI TRL calibration kit for WR4.3 band

9. Home-made custom adapter (circular waveguide) to fit the horn non-standard flange to the UG-387U standard flange

10. Millitech rectangular-to-circular waveguide taper for the 110–170 GHz band


12. Edmund Optics manual X-Y-θ stages

13. Newport optical bench

To measure the return loss we connected the array to the VNA by means of a cascade of adapters. To clean the data from the effects of the mismatch in the adapters chain we performed a time domain gating, retaining the back-scattered signals coming only from the horn. To this aim, before measuring the DUT scattering parameters, we carried out a TRL calibration of the system to identify the reference plane from which we calculated the gating window to mask the undesired signals.

In the beam pattern measurements the experimental setup was almost coincident with the one used for the return loss. The only extra components were a pair of corrugated circular standard gain horns (Radiometer Physics) one used to illuminate the feedhorn array and the other for reference. In these measurements we moved the DUT in azimuth with an angular step of 1° and selected the proper reference plane (E-plane or H-plane) by properly rotating the launcher and the DUT.
It is important to underline that these measurements were conducted considering only the principal propagation mode in both the 150 and 220 GHz bands. Consequently also the results of the simulations displayed in Figures 16, 17 and 18 regard single-mode propagation.

3.4.2 Results
In this section we summarize the measured return loss and beam patterns with simulations and show that we obtain an overall match within the uncertainties given by the mechanical differences among the horns.

Return loss. In Figure 16 we show the results of the return loss measurement in both bands compared with the simulations. The orange area is the envelope of the return loss simulated for all the 128 feedhorns in the array, each with its own measured profile, while the blue area is the envelope of the measured return loss for all the tested horns (refer to Figure 16).

We see that the measured reflection matches the simulation, within the scatter given by the mechanical differences among the horns. We also see that the average achieved return loss at 150 GHz lies around $-20$ dB, while in the higher band it is around $-25$ dB up to 230 GHz and then degrades to about $-10$ dB as expected. The large scatter among simulations is likely to be caused by the out-of-spec in the mechanical tolerance discussed in Section 3.3. Given the improvements adopted in the manufacturing procedure we believe that this scatter is significantly reduced in the FI horn array.

![Figure 16. Measured return loss compared with simulation.](image)

The reader may notice that the measured return loss between 190 and 230 GHz is about $-25$ dB, therefore 5 dB lower than the value resulting from the simulation of the nominal feedhorn (see the left panel of Figure 4). This is because the measurements and the simulations displayed in Figure 16 are relative to single-mode propagation, while the simulation in Figure 4 considers all the possible modes that can propagate in the 220 GHz band.
**Beam patterns.** We show our beam pattern measurements compared with simulations in Figures 17 and 18. Also in these figures the orange area is the envelope of the simulated patterns for all the feedhorns in the arrays and the blue area is the envelope of the measured patterns.

In the 150 GHz band (Figure 17) measured $E$- and $H$-plane diagrams for three frequencies: 145, 150 and 155 GHz. Measurements match simulations very well (with a few dB discrepancy) down to about $-30$ dB. The scatter increases at larger angles, where the detected power is smaller and the measurement becomes sensitive to signal reflections.

We have obtained similar results in the 220 GHz band (Figure 18). In this case we measured only the $H$-plane diagram at five frequencies, equally spaced between 190 and 230 GHz. Also in this band there is a very good match between measurements and simulations down to $-30$ dB.

**Figure 17.** Measured co-polar and cross-polar beam patterns at 150 GHz compared with simulations. *Left:* $E$-plane. *Middle:* $H$-plane. *Right:* $45^\circ$ cross-polar plane.

### 3.5 The full instrument feed horn array

Here we present briefly the feed-horn array developed for the QUBIC full instrument (FI), shown in Figure 19. The FI horn system has the same electromagnetic design of the TD and we manufactured it with the same technique: the inner part by chemically etching 0.3 mm
thick aluminum sheets and the front and back flanges by mechanical milling 3 mm and 6 mm thick aluminum plates. All plates were silver-coated before the final integration.

In this array we measured the geometrical profile of a large subset of horns in the two modules. This allowed us to simulate the expected performance of this subset and to compare it with laboratory measurements.

The detailed discussion of the development and testing of this part is out of the scope of this paper so that we defer the full discussion of the QUBIC FI horns to a forthcoming dedicated paper.

4 Switch system

4.1 Switch requirements and design

The QUBIC switch array is used to select the baselines during calibration phase. Theoretically the self-calibration procedure requires to acquire data from a known calibration source for all
possible baselines, each obtained by closing all the horns apart from the pair of the selected baseline. This approach, however, doesn’t prevent variable heat load from unwanted radiation.

In QUBIC we apply a different, but mathematically equivalent approach (see [4]) in which we close only the horns of the baseline under test, thus maximizing the signal stability during calibration.

In Table 2 we list the main requirements of our switch system. In particular the insertion loss must be as low as possible, even if the 1K working temperature helps at least in reducing its noise figure, while we require high isolation and fast commutation for accurate and efficient baseline calibration.

We designed each switch around the smallest commercially available coil manufactured by Line Electric (model TO-5S). Thanks to the tiny dimensions it was possible to implement a shutter driven by this coil which was compatible with the horns high filling factor. The area occupied by the whole device is so small that the minimum horn inter-axis is not determined by the switch, but by the horn mouth diameter.

In its rest position the switch is open. Only when the coil is energized, a small ferrite is attracted inside the coil to minimize the energy of the magnetic circuit. The ferrite is
Table 2. Main requirements for the QUBIC switch array

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insertion loss</td>
<td>$&lt;-0.1,\text{dB}$</td>
<td>Driven by minimizing signal dynamic losses and thermal noise</td>
</tr>
<tr>
<td>Isolation</td>
<td>$&gt;50,\text{dB}$</td>
<td>Driven by maximizing contrast in fringe patterns during calibration</td>
</tr>
<tr>
<td>Return loss</td>
<td>$&lt;-20,\text{dB}$</td>
<td>Over the 130–240 GHz bandwidth</td>
</tr>
<tr>
<td>Switch commutation time</td>
<td>$\sim\text{ms}$</td>
<td>To be negligible in the calibration duty cycle</td>
</tr>
<tr>
<td>Heat load</td>
<td>as low as possible</td>
<td>To minimize thermal drifts of the 1 K stage(^a)</td>
</tr>
<tr>
<td>Mass</td>
<td>as low as possible</td>
<td>Must be suspended on the top of the optical combiner</td>
</tr>
</tbody>
</table>

connected to a hook pulling a steel blade inside the circular waveguide, short-circuiting it. When the bias is off, a phosphor-bronze spring pushes the ferrite out of the coil, returning the switch in its normally open position.

The coil nominal ohmic impedance is 80 $\Omega$ at room temperature, but it reduces down to 19 $\Omega$ at 4 K. We use a constant current of 90 mA to hold the ferrite inside the coil, resulting in a Joule dissipation of 150 mW per shutter. By limiting to 4 the number of switches energized at the same time, we reduce the extra heat load to 600 mW. Thanks to the large mass of the horns plus switches system, the heat released increases horn-switch block temperature in a timescale much longer than the RF load change not weakening the self-calibration effectiveness.

Another reason why the number of active switches is limited to 4 is because the minimum number of wires necessary to drive N devices is $(N+1)$, where the extra wire is used for current return of the N coils. Since the driving current per coil is not negligible, the return wire must be made of copper instead of phosphor-bronze or manganine (other reasons are discussed in Section 4.3.1). To minimize the conductive heat load, the copper wire must be thin ($\leq 200\,\mu\text{m}$), reducing the number of coils active at the same time to two per return wire. Since there are two switch banks, operated by two electronic boards, there are a maximum of four switch shut at the same time.
4.2 Single channel prototype

We developed a single channel prototype at the APC Laboratory in Paris [9] to test the electromagnetic performance, the effectiveness of the linear motion design and the compatibility with the cryogenic environment. We realized both the single channel prototype and the full array for the QUBIC TD in Al-6061T6. The 3-D sketch in figure 21 shows the switch with the lid cut out to uncover the coil pulling the shutter inside a 150 \( \mu \text{m} \) gap placed between the two sections of the circular waveguide. When the shutter is outside the waveguide, the switch is on and the coil is not biased. To mask the gap, a choke trap is milled around one of the waveguides. The shutter movements are limited by a couple of stainless steel alignment pins.

![Solid model of the single channel prototype](image)

**Figure 21.** Solid model of the single channel prototype: the lid is cut out at the level of the waveguide to reveal the solenoid and the shutter in their open position. This prototype was realized to be tested in LN2 and characterized at 150 GHz.

The prototype was tested several times at 77K (LN2) to verify the coil lifetime. The functionality of the back and forth movement of the shutter was verified by means of an optical fiber. This prototype never showed any issue in LN2.

4.2.1 Switch electromagnetic measurements

We characterized the single channel prototype at room temperature in both the QUBIC bands: 135–165 GHz and 190–220 GHz using the VNA available at the laboratory of the University of Milano-Bicocca. We used a pair of rectangular-to-circular tapers to connect the VNA to the switch. Since the expected insertion loss of the switch was low, we measured and subsequently removed the contribution of the tapers.

Figures 22 and 23 summarize the results carried out on this prototype. The left plots report the insertion and return losses when the switch is open (ON) while the right plots show the same quantities when the switch is closed (OFF).

We see that when the switch is open at 150 GHz the insertion loss is very low already at room temperature, \( \text{IL} = -0.13 \pm 0.03 \text{dB} \). We can estimate the improvement at cryogenic
temperature (4 K) using the results found by [10]. In that paper the authors quote a factor 10 (from 0.1 dB/m to 0.01 dB/m) at 10 GHz, passing from room temperature to 4 K. In our case we cannot expect a factor 10, because at our frequencies we cannot completely neglect the surface roughness. We can expect, however, at least a factor 2 improvement, which makes us confident to be compliant with the requirement $\text{IL} \leq -0.1 \text{dB}$. Moreover, in the QUBIC TD switch array the switch is 5 mm shorter than this prototype, potentially resulting in a loss reduced by 20%.

The measured return loss, shown in the bottom plots, confirms that reflections are well within the requirement of $-20 \text{dB}$ specified in Table 2.

At 220 GHz the insertion and return loss requirements are not met, but this was expected because the prototype was designed and manufactured taking into account only the QUBIC lower band. Moreover, the TD works at 150 GHz, so the 220 GHz performances are not critical. In the Final Instrument the waveguide surface roughness will be compatible with the desired electromagnetic specifications.

Figure 22. Measured Insertion Loss (top) and Return Loss (bottom) of the switch prototype in the band 135-165 GHz. Left: Switch ON. Right: Switch OFF. $1-\sigma$ confidence bands are plotted in blue.

4.3 The technological demonstrator switch array

4.3.1 Switch manufacturing

The TD switch array design is based on the single channel prototype. It reflects the $8 \times 8$ structure of the feed-horn array which was chosen as a trade-off between the required filling factor and the possibility to leave enough room for the screws used to pack the platelets and mate the horns to the switch array. It was designed at APC in Paris and manufactured at the
machine-shop of the University of Milano-Bicocca using Al-6061T5 for the two main shells. The main body is made by two parts. The first is a base housing most of the waveguide, the PCB and the coils+shutters. The bottom part of the base has the threaded holes to interface with the bottom horn array. The second part is a lid with the rest of the waveguide length and the threaded holes to interface with the top horn array. The shutters are a replica (64 times) of the single channel shutter. They are mounted on a custom PCB sharing the same the footprint of the waveguides. Since the limited cooling power at 1K, the number of wires reaching the 1K zone is reduced to a minimum. The heat dissipated by the coils while energized to close the shutters is also non negligible. So, in the $8 \times 8$ TD it is possible to close only a small fraction of the shutters and not in an arbitrary configuration.

A modular electronics is used to operate the shutters and read their position. Every electronic module is in charge of fifty shutters, being able to operate two of them at a time. Every module is composed of two arbitrary current generators to energize the coils. A small sinusoidal modulation of the coil current is used to read the shutter position, using the different phase delay between $I$ and $V$ when the ferrite is outside (shutter open) or inside (shutter closed) the coil. A set of six Analogue to Digital Converters capture the AC current, AC voltage and DC voltage during the 8ms after the the command to close a shutter is set. The DC voltage is used to evaluate the ohmic load of the lines+coil system, in order to verify that there is electrical continuity. The AC signals are used to calculate the phase delay in a way similar to what is done in Phase Locked Loop (PLL) circuits. The sinusoidal current and voltage signals are digitized as follows: when the signal is above its average value, it is
recorded as 1, otherwise as 0. In this way two squared waves are generated, which phase delay is easily computed as $\pi$ times the average value of a third square wave obtained by applying XOR operator to the first two. When a switch is set to closed, a current pulse of 350mA lasting $\sim 5$ms is used to energize the switch coil and the ferrite is attracted inside it. Once the ferrite is inside, the current is reduced to 90mA, which is enough to hold in place to shuter reducing the heat load.

An alternative method to compute the phase difference was tested too. It is based on the fits of the digitized signals (voltage and current) and the consequent computation of the phase delay. This approach, which in principle is more accurate, has a computational cost much higher than the XOR method because of the necessity to digitally filter the data and run fitting algorithms. A direct comparison of the two methods showed us that the two are perfectly compatible within the statistical uncertainties.

4.3.2 Switch cryogenic tests

We tested the TD switch array at 5K in the Milano Bicocca Millimeter Lab using a custom cryofacility. The cryofacility is composed of an aluminum vacuum chamber operated by Cryomech PT407 pulse tube. The vacuum is realised and maintained by a Varian Navigator turbo pump with the assistance of an Agilent Scroll as primary pump. A SRS CTC-100 cryogenic temperature controller is in charge of the temperature readings and stabilization by means of load resistors. Temperature sensors are calibrated DT-470 Lake Shore diodes. The base temperature with no heat load is 3.5K.

![Technological demonstrator switch and horn array assembled and placed in the cryofacility for cryogenic functional tests.](image)

Once we assembled the TD switch array with the two horn arrays, we placed it in the cryofacility (Figure 24) to 5K because of the heat load of the numerous needed harness. We
considered 5K to be representative of the behaviour of the device at its nominal working temperature (1K).

The aim of these tests was to find the effective current values to move the shutters and maintain them in closed position in a harness configuration similar to that in the QUBIC cryostat and with the shutter release spring stiffness due to cryogenic temperature, very similar to the operative one. Moreover, an important goal of the tests was to verify the switch functionality and reliability at cryogenic temperature.

Figure 25 shows the phase between voltage and current for every switch and for increasing values of exciting current. We rose the excitation current from 20 mA up to 350 mA. All the switches didn’t move till a current value of 250 mA for which part of them closed and the rest staid open. At 300 mA all the switches moved to closed position. We set as default a conservative value of 350 mA. We also found that once a switch is closed, a much lower holding current can be applied. Experimental verification led to a value of 90 mA as the holding current capable to keep every switch in closed position. A typical excitation pulse at cryogenic temperature with the superimposed oscillating current can be seen in Figure 26. The phase value doesn’t change from 350 mA to 90 mA, proving that the switch is kept in closed position even with the lower current.

Once we found the proper excitation current, we tested one by one all the switches, starting from a situation at room temperature where 3 of them were defective (numbers 5, 26 and 60 because open or short circuited) and two of them (n.1 and n.32) were mechanically stuck in the open position. These last two switches were stuck probably because a non perfectly plane shutter. However, at cold temperature n.1 resulted operative. The result of
Figure 26. Technological demonstrator switch excitation and readout current example. The excitation continuous current, plus the monitoring sinusoidal one, is kept at 20 mA for the first 6 ms, then a 350 mA pulse lasting 4 ms is applied to make the ferrite enter the coil and move the shutter. After 10 ms the current is lowered to 90 mA to reduce heat load.

This test is reported in Figure 27.

Figure 27. Phase between voltage and current measured by XOR algorithm. Left: shutters in open position. Right: shutters in closed position. Switch n.1 was operative @5K. N.5, 26 and 60 were defective and n. 32 was stuck open.

Finally we performed a statistical test operating each working switch 100 times. We computed the phase delay in open and closed position using both the functional fit and the XOR algorithm, applied to the data acquired by the AC coupled ADCs. Both methods gave
consistent values, as reported in Table 3.

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<td>Open</td>
<td>Closed</td>
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<tr>
<td>1.52±0.01</td>
<td>1.32±0.01</td>
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However, every switch shows a distinctive mean phase delay with a standard deviation which is one third of the one of the full population, reflecting on one side the intrinsic different impedance of each single coil, and on the other side the intrinsic accuracy of the phase measurement of our electronics which is of the order of 0.003 rad (10'). For this reason, we defined a standard calibration procedure to be run when the focal plane is cold, to compile a look-up table of the phase delay of every switch in open and closed position, based on a statistical analysis of 100 switch operations. The look-up table will then be used to decide if the switch moves in the right position or not and, if needed, to repeat the command.

Despite the overall good behaviour of the TD switch array, the mechanical tolerances needed to operate the shutters resulted in a certain level of unreliability. The main issue is that certain shutters didn’t completely enter the waveguide, even if their ferrites were totally inside the coil. The main cause of this is the hook soldered on the ferrite responsible of the back and forth movement which is not guided well enough to guarantee an ideal displacement of the shutter. We modified the original design of the stainless steel blade to reduce this uncertainty and this much improved the reliability.

4.4 The full instrument switch array

The Final Instrument switch array was designed replicating the TD to fill the circular aperture of the 400 horns. Unfortunately the TO5 shaped coils resulted out of stock and the manufacturer ceased its activity. Regardless all the effort we did to find a similar product, we failed due to the very tiny volume available for each switch and we were forced to change the design (Figure 28) adapting it to only one viable alternative, keeping the lattice of the Final Instrument horn arrays which were already manufactured.

We selected a bi-stable micro-shutter (BOS7/10) by a Japanese company (Takano Co. LTD) and modified the design to fit the room available. The driving electronics already developed for the previous shutters is easily adaptable to the new ones by simply changing the time profile of the excitation current (the direction of the shutter movement depend on the current direction). Being bi-stable, the new shutters do not dissipate any energy but during the movement which lasts only few ∼ms. They can be operated, in sequence, in any number from 1 to 400. Since this model is designed for room temperature, we tested it at 4K to confirm that they remain operative at cryogenic temperatures. We collected several thousands of movements without any problem, simply adjusting the excitation current with temperature. The Final Instrument switch array should be manufactured in the next months.

5 Conclusions

In this paper we have described the design, manufacturing and testing of the feedhorn-switch system of the QUBIC technological demonstrator (TD), which will demonstrate the concept of bolometric interferometry by observing the polarized microwave sky from the high-altitude
Alto Chorillo site in Argentina. The TD is the precursor of the QUBIC Full Instrument (FI), that will measure the CMB polarization from the same site.

The TD horn-switch system is composed by a square array of 64 back-to-back corrugated feedhorns interspersed by 64 mechanical switches that can open and close the connecting circular waveguides. We designed the horns to allow the propagation of two wide bands centered at 150 and 220 GHz, and manufactured them in platelets that were drilled with a combination of photo-chemical etching (inner, 0.3 mm plates) and mechanical milling (outer, 3 mm and 6 mm flanges).

We fully characterized the mechanical profile of all horns and found that the hole diameters of the inner plates were, on average, larger than the expected tolerance. The cause was the etching time that was not properly controlled during the process. We eliminated this problem in the full instrument (FI) horns and found that this out-of-spec was not critical for the objectives of the TD.

The measured electromagnetic performance agrees with simulations. In particular we obtained a return loss around $-20\,\text{dB}$ up to $230\,\text{GHz}$ and beam patterns agreeing with simulations down to $-30\,\text{dB}$.

Regarding the switches, we performed electromagnetic characterizations on the single channel prototype, finding return and insertion losses at 150 GHz coherent with expectations ($<-25\,\text{dB}$ and $\sim-0.1\,\text{dB}$ respectively) and an isolation grater than $70\,\text{dB}$ (specification was 50 dB). At 220 GHz, return and insertion losses specifications are not met, but this is expected because the prototype was designed and manufactured for the QUBIC lower band, which is the only one operative in the TD. The Final Instrument manufacturing will satisfy the electromagnetic requirements of both bands. We also positively tested both in lab and inside

**Figure 28. TO BE UPDATED** Open view of the Final Instrument switch array based on the new bi-stable shutter.
the QUBIC cryostat the switch array at a temperature 5K close to the nominal one (1K). We developed a readout system able to monitor the actual switch positions with a very good repeatability and reliability, as witnessed by the fringe pattern detection (CITATION?). Since the micro-miniaturized coils of the TD are no more available, we found an alternative for the FI which forced us to redesign the whole mechanism around a bi-stable shutter which has been already tested at 5K with very positive results.

Currently we have completed the development of the feedhorn arrays while the switch system will be completed in few months after the submission of this paper. After their mutual integration the whole system will be ready for the upgrade from the TD to the FI.

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