Opto-mechanical design and performance of a compact three-frequency camera for the Millimeter Bolometer Array Camera on the Atacama Cosmology Telescope

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ABSTRACT

The 6-meter Atacama Cosmology Telescope will map the cosmic microwave background at millimeter wavelengths. The commissioning instrument for the telescope, the Millimeter Bolometer Array Camera, is based on a refractive optical system which simultaneously images three separate fields of view at three different frequencies: 145, 220, and 280 GHz. Each frequency band contains around twelve individual optical elements at five different temperature stages ranging from 300 K to 300 mK and a 32 x 32 array of Transition Edge Sensor bolometers at 300 mK. We discuss the design of the close-packed on-axis optical design of the three frequencies. The thermal design and performance of the system are presented in the context of the scientific requirements and observing schedule. A major part of the design was the incorporation of multiple layers of magnetic shielding. We discuss the performance of the 145 GHz optical system in 2007 and the implementation of the additional two frequency channels in 2008.

Keywords: mechanical design, cryogenic, millimeter camera, CMB telescope

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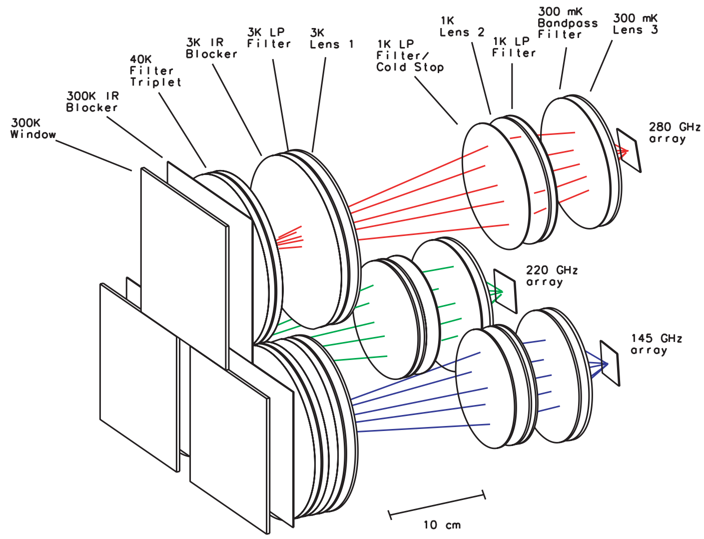

Figure 1. Cold Optics in MBAC. Each band, 145, 220, and 280 GHz, has a separate window, three high purity silicon reimages lenses, cold stop, filter suite, and 32 x 32 array of TES bolometers. For scale, the square windows are roughly 160 mm x 160 mm. Only a few central field points of the ray trace are shown.

1. INTRODUCTION

Measurements of the cosmic microwave background (CMB) can be used to constrain fundamental cosmological parameters including those from inflationary models, the matter-energy distribution of the universe, and overall curvature of the universe.[1] The past decade has seen great progress in constraining the CMB angular power spectrum, due in large part to improvements in detector technology implemented on both space-based and ground-based experiments. Most of these experiments have focused on degree-sized angular scales and larger (e.g., WMAP).

The Atacama Cosmology Telescope (ACT) aims to complement existing surveys by measuring the mm-wave sky with arcminute-scale resolution.[2,3] Another primary goal of the ACT project is to identify galaxy clusters through the Sunyaev-Zeldovich (SZ) effect, the interaction of CMB photons with hot intracluster gas. The spectral signature of the SZ effect, atmospheric transmission windows, and contributions from other sources (such as foreground sources, e.g. dust) dictated the specific millimeter wavelengths at which the Millimeter Bolometer Array Camera (MBAC), the primary instrument for ACT, was designed to observe. The frequency bands are centered on 145, 220, and 280 GHz. Our detectors are arrays of 32 x 32 Transition Edge Sensor (TES) bolometers at each frequency.[4] The telescope was installed in the Atacama Desert in Chile in early 2007. In its first observing season in Nov-Dec of that year, MBAC mapped approximately 200 deg^2 of sky at 145 GHz, approximately half of which are being used for CMB analysis. This paper briefly summarizes the optical design, and concentrates on the mechanical and thermal design of the camera.

2. TELESCOPE AND RECEIVER DESIGN

To achieve arcminute angular resolution at 1-2 mm wavelengths, the primary mirror of the telescope was chosen to be 6 meters in diameter. The telescope is an off-axis Gregorian design.[5] To minimize the effects of $1/f$ noise on the detector signal, the entire telescope structure (including the 2-meter diameter secondary) continuously scans back and forth 10 degrees in azimuth at a rate of 1 deg/sec, which translates to roughly 5 degrees on the sky at our nominal observing elevation. A detailed discussion of the telescope motion is discussed in Hincks *et al.* in these proceedings. The scan strategy drove the design of a fast focus (F $\leq$ 1) primary to make the telescope as compact as possible. The Gregorian focus is also fast (F $\sim$ 2.5), which keeps the size of the cryostat windows required for our field of view relatively small (approximately 16 cm on a side).

The MBAC cryostat[6] is mounted on ACT such that its entrance windows, one for each frequency, are near the Gregorian focus. The cryostat is constructed from two mating cylindrical sections, which when assembled measure approximately 1 meter in diameter and 1.2 meters in length. Inside the cryostat are two aluminum cold plates cooled to 40 K and 4 K through the first and second stages of pulse tube coolers. Further cooling of select optical components and detectors to 1 K and 300 mK is achieved using custom built helium-4 and helium-3 sorption refrigerators.[7]

In each band, a 22×26 arcminute field is reimaged onto a free standing array of popup detectors.[8,9] There is a separate set of cold lenses for each frequency. This has the advantages of making the mechanical design simpler, more compact, and easier to align than using beamsplitters and off-axis reimaging mirrors. The disadvantage is that the three arrays are unable to image the same region of the sky simultaneously. The optics for adjacent bands are packed as closely together as mechanically possible (Fig. 1 and Fig. 2) so that the arrays are near the field center where the Gregorian image quality is best and the overlap of the observations is maximized. The 145 GHz and 220 GHz channels are on opposite sides of the telescope's plane of symmetry.

MBAC's optics are at five different temperatures: 300 K, 40 K, 4 K, 1 K, and 300 mK (Fig. 1). The three windows are at 300K (ambient). The windows are made from ultra-high molecular weight polyethylene and are anti-reflection (AR) coated for their respective frequencies. All lenses are pure, high-resistivity silicon and AR coated with Cirlex.[10] There is a thermal blocking filter[11] immediately behind each window, also at 300K. The next set of optics for each camera is a triplet of filters at 40 K, two capacitive mesh filters[12] with a thermal blocker in between. Following that is a thermal blocking filter, a capacitive mesh filter, and the first lens, all at 4 K, the last of which reimages the primary onto a 1K cold stop.

Each cold stop, at approximately an image of the primary, and the second lens immediately after the cold stop are cooled to 1K by one of the helium-4 fridges. The two final low-pass filters are also at 1 K. Next, there is a band-defining filter that immediately precedes the third and final lens. Both are at 300 mK. The combination of the second and third lens refocuses the sky onto the detectors, which are also at 300 mK. Based on thermal background calculations, the third lens could have been mounted at 1 K. However, due to the tight tolerance on the separation between the focal plane arrays and the third lens, it was decided to keep the two as rigidly coupled as possible, meaning the lens would reside at 300 mK with the detectors.

The 1.05 x 1.05 mm detectors are manufactured in columns of 32 elements. Thirty-two columns are stacked to create a full array, giving 1024 elements at each frequency.[13] In all three arrays, each detector views roughly 40 arcseconds of sky, which is half the beam width at 145 GHz. The size of a fully assembled array is approximately 34 mm x 39 mm.

3. MECHANICAL DESIGN OF 145GHZ, 220GHZ, AND 280 GHZ CHANNELS

3.1 Design Overview

The mechanical design rigidly supports the lenses, filters, and detectors in a space efficient way. Not only were the three frequency channels closely spaced, but the cryostat envelope was fixed, with a large fraction of the volume occupied by the custom refrigerators, radiation shields, and other structures. The design had to consider that the assemblies would be removed from the cryostat, disassembled, and reinstalled a number of times. Furthermore, we wanted to decouple the mechanical structures for the different frequencies so that the arrays could be deployed individually if needed. The coefficients of thermal expansion of the various components were taken into account so that the relative positions between lenses are correct when the instrument is at its operating temperature. Thermal conduction between different temperature stages was minimized to allow for roughly 18-20 hours of uninterrupted observations. Finally, the magnetic sensitivity of the superconducting detector multiplexers and amplifiers required that magnetic shielding be integrated into each optics tube.

To minimize weight, aluminum was generally used to mount elements at 300 K, 40 K, and 4 K. For 1 K and 300 mK assemblies, where conductivity is critical, oxygen-free high conductivity copper (OFHC, Copper 101) was generally used. Another reason for using mostly copper below 1 K is potential problems with trapped magnetic flux in superconducting aluminum alloys.

For flexibility of assembly, we have an interface plate to which all three tubes are bolted (Fig. 3). This plate can be removed from the primary 4 K cold plate, allowing the removal of all three tubes from the cryostat as a

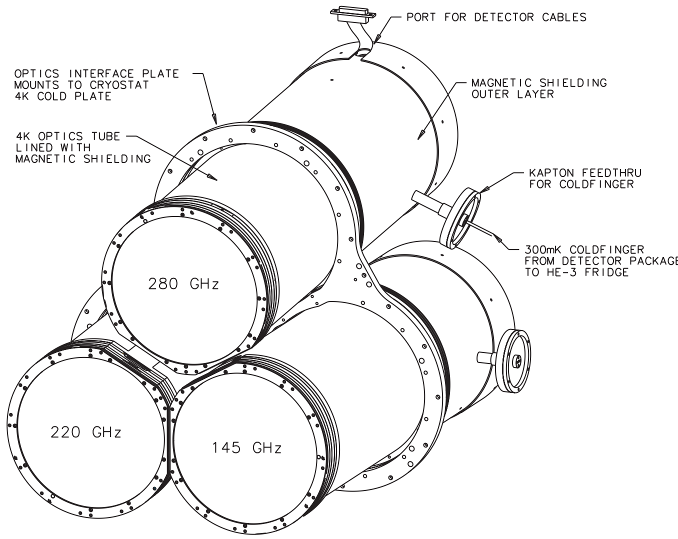

Figure 2. Outside of assembled three-tube mechanical structure.

unit. On this interface plate (Fig. 2) are mounted three individual aluminum wedges. The wedges fix the angles of the different optical axes for each frequency channel, which arise because of the large size of the focal plane spanned by the three channels. The angle is a compound one for 145 GHz and 220 GHz.

Attached on to each wedge is the base of the primary 4 K tube for each frequency. Finally, all of the support structures for the rest of the optical train are mounted onto the base of each 4K tube (Fig. 3). Hence, by removing a 4 K tube from its wedge, each frequency channel can be completely removed from the cryostat, which allowed the 145 GHz optics tube to be deployed in MBAC for the 2007 season while the 220 and 280 GHz optics tubes were being constructed. The three optics tubes are similar; hence the following discussion makes distinctions between frequencies only when appropriate.

3.2 4 K Optics Assembly

The 4 K optics stack consists of an thermal blocking filter, a low-pass filter, and the first lens, each 200 mm in diameter. They mount on the top of the 4 K tube. The cross-section shown in Fig. 3 illustrates how the lenses and low-pass filters in MBAC are clamped in a compliant mount. The spring is a commercial electromagnetic interference gasket from Spira Manufacturing*, used successfully in previous designs.[14] It is wound out of spring temper beryllium copper. The spring accommodates the curved lens surface as well as differential thermal contraction.

We considered a second spiral spring (or other self-centering method) around the perimeter of the lens to provide radial self-centering and conduction. However, space was limited in this direction, and decenter tolerances (roughly 3 mm) were large enough so that omitting this was acceptable.

3.3 1 K Optics Assembly

The temperature of the next stack of optics is at ≈ 1 K. The support structure between the 4 K and 1 K optics needed to provide enough thermal path length to minimize the load on the 1 K refrigerator, while having enough strength to reliably support the remaining 7 kg of optical and detector structures. A support going directly from the 4 K tube to the 1 K optics would not give the required hold-time. Therefore we used two concentric G10 tubes (see Fig. 3), each 0.38 mm thick and readily available, to lengthen the conducting path.

Situated at the bottom of the inner suspension, the 1 K optics stack contains, in order: a low-pass filter, a pupil stop, the second lens, and another low-pass filter. All mechanical structures are Copper 101 (OFHC).

*Internet URL: http://www.spira-emi.com.

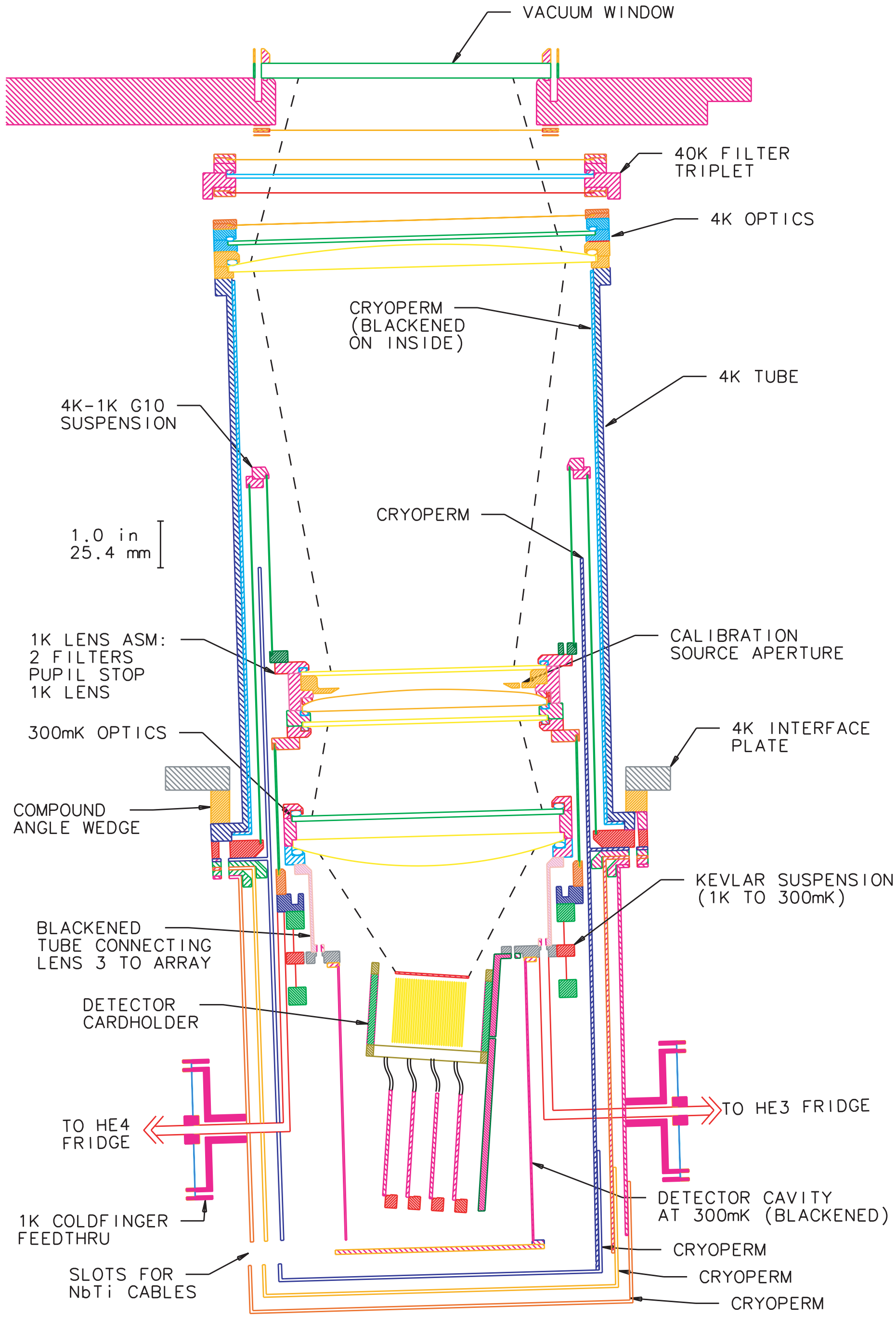

Figure 3. Cross-section of 145 GHz optics tube (the other two frequencies are similar). The dotted lines approximate the envelope of the light rays.

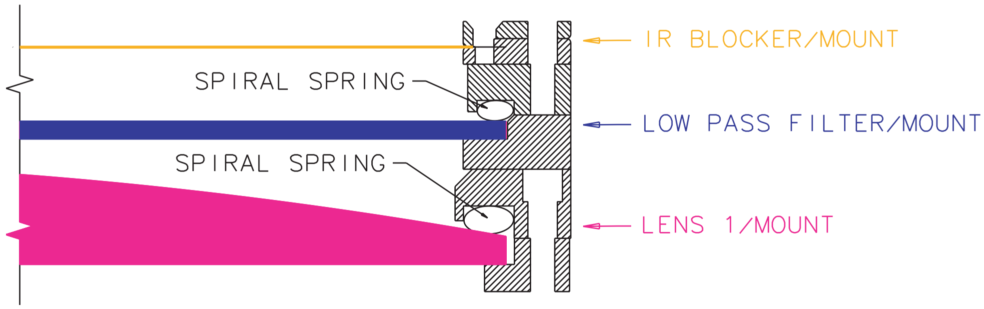

Figure 4. Cross-section of the edge of the 4 K optics stack. Light enters from the top, where a 5 micron-thick IR blocking filter is glued into an aluminum clamp. The next element is a low-pass filter, axially clamped by a spiral spring, as is the plano-convex 4 K lens.

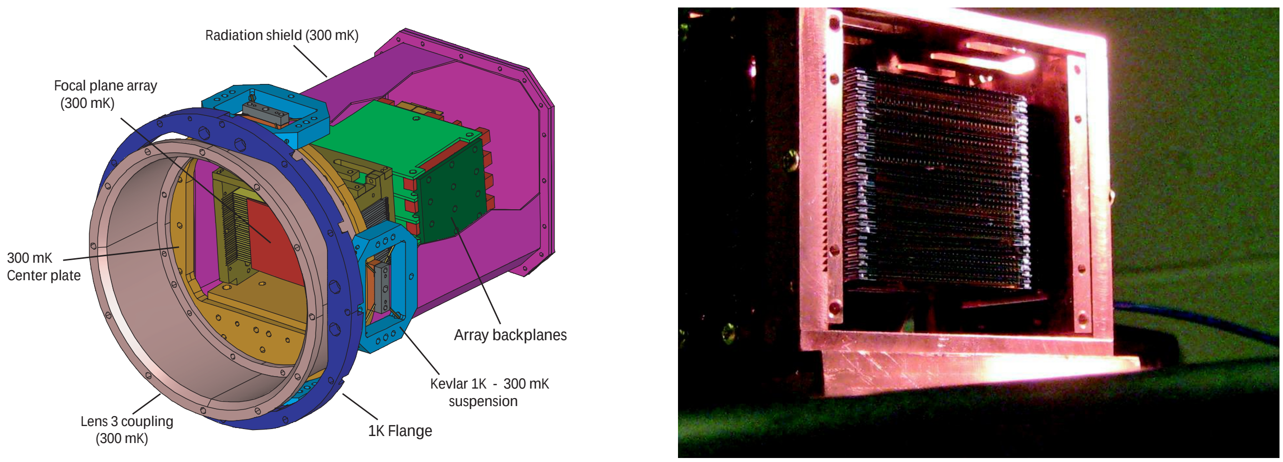

Figure 5. Detector 300 mK assembly. The left panel is a CAD model showing the 1K to 300 mK Kevlar suspension and a cutaway of the 300 mK detector shell. The right panel is a photo of the 145 GHz 32 x 32 array before installation into MBAC.

Mounted on each of the three pupil stops are two calibration sources.[15] These "reverse bolometers" consist of a NiCr thin film deposited on a thin sapphire chip, suspended within a metal ring via nylon fibers. The devices are connected with low thermal conductivity wires that are routed out of the optics tube 4 K cavity through the same ports that the coldfingers feed through. They have acceptable time constants and minimal power dissipation ($\approx$ 60 mW per pulse); they are not seen by thermometers on the 300 mK stage. They provide a calibration transfer standard for each TES over time. Their mounting location on the pupil stop was chosen so that they would illuminate the entire array without interfering with the image of the pupil.

Underneath the 1 K optics stack is a third G10 tube that extends down toward the port for the 1 K coldfinger from the helium-4 fridge. Since one would want high thermal conductivity between the 1K coldfinger and the 1 K optics, the decision to use G10 here was strictly due to overall weight concerns. The G10 tube is copper-clad to increase thermal conductivity along its length. At the end of this 1 K tube is a suspension for supporting the 300 mK assembly. The limited cooling capacity at 300 mK prevented G10 from being used here. Four separate aluminum frames at 1 K hold, via taught Kevlar threads (1 mm diameter), a central inner frame that is bolted to the 300 mK assembly central mount plate (Fig. 5). This arrangement makes the suspended plate extremely rigid in all directions. Due to the tendency of Kevlar to stretch over time as well as its negative coefficient of thermal expansion, each segment was pre-stretched before assembly. After assembly, constant tension is applied to the thread by a system of vented screws and spring washers on each frame.

3.4 300 mK Assembly

The heat sink for the detectors must be well below the critical temperature, $T_c \approx 450$ mK, of the TES devices. Our system has a base (no-load) temperature of 250 mK with a nominal, loaded, temperature of 310 mK achieved via a helium-3 sorption fridge. For reasons already discussed, the final lens and band pass filter were designed to be at the same temperature as the detectors. The lens and detector assemblies are mounted on either side of the center plate supported by the Kevlar suspension. The filter and lens are clamped in a similar way as the 4 K optics. The tube connecting the 300 mK lens cell to the center plate is light tight and is blackened on the inside with a mixture of Stycast© and carbon lamp black to absorb stray radiation.

On the other side of the 300 mK center plate (Fig. 5), the 32 columns of each array are mounted in a array holder manufactured out of tellurium copper (Te copper). This material is considerably easier to machine than OFHC. Although this feature came at the expense of lower thermal conductivity than that of OFHC, it was deemed a worthwhile tradeoff given the complexity of the array holder. Each column is held in place by springs that apply force in two perpendicular directions to achieve the required array alignment specifications of roughly +/- 20 μm.[8,16] The detector side of the 300 mK center plate is enclosed in a shell made of welded copper sheet. This shell shields the detector from 4 K radiation from the surrounding magnetic shielding (Fig. 3). It is blackened on the inside with a similar mixture of Stycast© and carbon lamp black used on other components. The shell also protects the detector when handling the 300 mK assembly. The total mass of the 300 mK assembly for each array is approximately 5 kg.

4. MAGNETIC SHIELDING

The superconducting quantum interference device (SQUID) multiplexers (muxes) and amplifiers are sensitive to changing magnetic fields.[17] Hence they require magnetic shielding both from the Earth's DC field as well as from AC fields from the telescope motion through Earth's field, motors, etc. The SQUID amplifiers are located outside of the optics tubes and are self-contained units enclosed within their own magnetic shielding. The SQUID muxes, however, are mounted on the silicon cards that make up each column in the detector array holder (see Fig. 5). Because of their proximity to the array, they occupy a larger volume, and it would be difficult to provide individual magnetic shielding. The best solution is to surround them with as close to an "infinitely long cylinder" as possible. In that approximation, the effectiveness of the magnetic shielding for a single layer of shielding is given by:

$$A = (\mu/4)[1 - \left(\frac{R_i^2}{R_o^2}\right)] + 1\,, \tag{1}$$

where A is the DC attenuation, μ is the permeability of the shielding material, and R_i and R_o are the inner and outer radii of the shield.

Cryoperm[†] is an alloy with a high nickel concentration. It is designed to provide increased permeability at cryogenic temperatures. To achieve the maximum attenuation, our shielding uses the thickest available Cryoperm, 1.5 mm (0.06 in). We also use multiple layers which, given sufficient spacing between them, approaches the limit of multiplicative increases in the field attenuation. As indicated by Eq. (1), the closer to the SQUIDS the shielding can be built, the more effective it is. Given this, each of the three frequency channels has its own set of magnetic shielding.

Because of the proximity of the third lens to the superconducting multiplexers, for a shield to have a length-to-diameter ratio of at least 4:1 (roughly the lower limit a shield can be treated as an infinite cylinder), it needs to enclose the 300 mK lens cell in addition to the more critical muxes. The length is limited by structures inside the main aluminum 3 K tube, mainly the G10 suspension. Outside of each tube, surrounding cryostat structures, mainly the sorption fridges, limits the size of the shields (see below). The final design features multiple layers of shielding: an upper layer that lines the inside of each 3K tube down to where the tube attaches to the 3 K plate, a "through" layer that extends from the peak of the 3 K to 1 K G10 suspension down beyond the rear of the 300 mK radiation shield, and two additional layers that surround the bottom half of each tube around the location of the muxes.

[†]Cryoperm is a trademark of Vacuumschmelze GmbH in Hanau, Germany

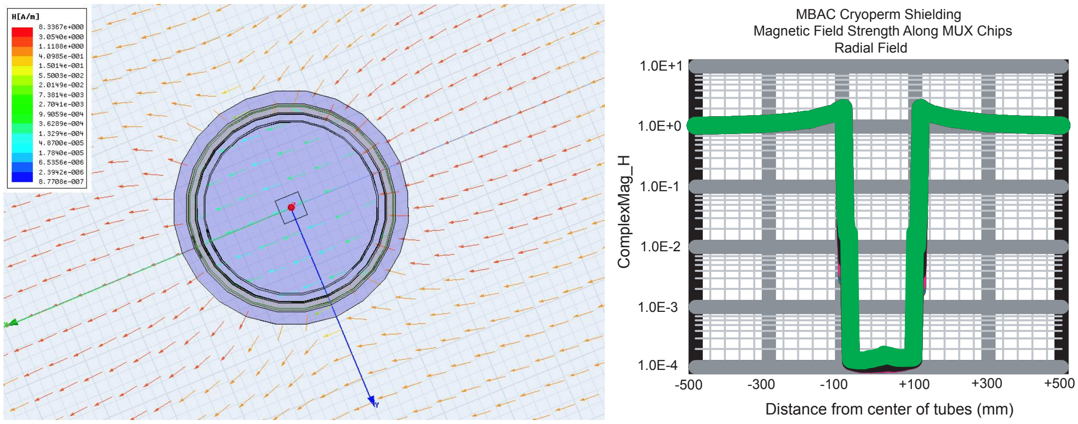

Figure 6. Modelling attenuation. The left panel shows a simulation of a radial AC magnetic field applied to the triple layer of one set of nested shields. The right panel is a plot of the amplitude of the B-field in the region of the mux chips inside the shields (normalized to the field outside).

Each layer of shielding had different dimensions, ports, and tubulations, all of which affect attenuation to varying degrees. This and the fact that the infinite cylinder approximation in Eq.(1) is only for *DC* fields, justified a more careful analysis. Fig. 6 shows an example how computer simulations using Maxwell[‡] have been employed to apply AC fields to the exact geometry of our shields. The simulations produce attenuation estimates that approach 40 dB, which give us a more accurate estimate of the field near the muxes.

Ports are laser cut out of the shielding for feeding through the 1 K and 300 mK coldfingers and the NbTi cables connecting the detector backplanes to the series arrays (Fig. 2). The mass of the magnetic shielding for each tube is approximately 10 kg.

5. TESTING AND PERFORMANCE

Several mechanical tests on prototype subassemblies were conducted before mounting the final lenses and detectors. The first major concern was that the 3 K to 1 K G10 suspension would either not support or flex beyond optical tolerances under the weight of the attached 1K and 300 mK assemblies. To test this, we cantilevered a 9 kg mass (roughly twice the 300 mK mass) off a 0.38 mm thick prototype suspension. Under this load, the initial deflection was approximately 0.10 mm, and approached 0.13 mm after one week. For comparision, the decenter tolerance of the 1K lens was approximately 2 mm. The final suspension deflected less than 0.03 mm under the same load during the same time period.

Another mechanical concern was that the Kevlar suspension would not support the load of the 300 mK assembly. Testing with thread of various thickness showed that the thickest Kevlar thread commercially available was required (which included a factor of safety of about two). However, we were also concerned about potential distortion of the suspension upon cooling. This was tested by mounting a flat mirror at the location of the third lens from the central plate of the suspension. A laser mounted on the front plate of the cryostat was projected through a temporary quartz window (also on the front plate of the cryostat), down to the Kevlar suspension, reflecting it off the mirror and back outside the cryostat onto a target. The long path length increased our sensitivity to any deflection. There was no detectable movement of the kevlar mount as it was cooled from ambient temperature to approximately 10 K, at which point the test was concluded.

At the site in 2007, the cryogenic and optical systems performed well with the 145 GHz channel installed in MBAC. The hold-time goal of 18-20 hours at 1K and 300 mK was achieved. Both the plate scale and the beam profile were in excellent agreement with expecations.[18]

‡Maxwell is a product of Ansoft. Internet URL: http://www.ansoft.com

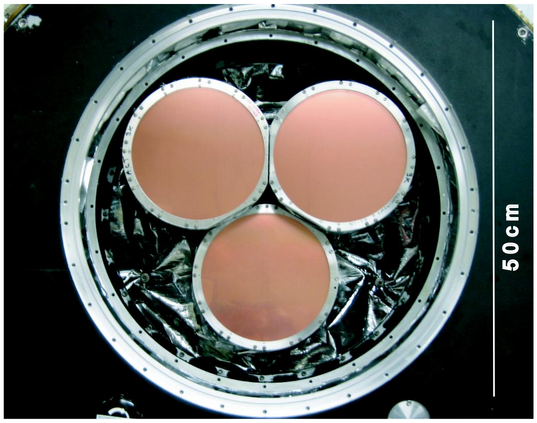

Figure 7. Assembled optics tubes. The left picture shows the three sets of optics as viewed from the front of the cryostat. The visible elements are the 3K IR blocking filters. On the right are the exposed back ends of the tubes as viewed from the rear of the cryostat, where the triple layers of magnetic shielding and routed cold straps to the sorption fridges are visible.

6. SUMMARY AND STATUS

We have designed a three-frequency cryogenic camera, with separate optics and arrays for each frequency, for the Millimeter Bolometer Array Camera on the Atacama Cosmology telescope. In the design of the various mechanical structures comprising the camera, we have successfully addressed a number of design challenges. The 145 GHz camera was installed in MBAC and deployed to Chile for the first observing season of ACT in Nov-Dec 2007. The 220 GHz and 280 GHz arrays are currently being tested to prepare for the shipment of the fully outfitted MBAC back to the site in June 2008.

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