BICEP Array cryostat and mount design

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ABSTRACT

BICEP Array is a Cosmic Microwave Background (CMB) polarization experiment that will begin observing at the South Pole in early 2019. This experiment replaces the five BICEP2 style receivers that compose the Keck Array with four larger BICEP3 style receivers observing at six frequencies from 30 to 270GHz. The 95GHz and 150GHz receivers will continue to push the already deep BICEP/Keck CMB maps while the 30/40GHz and 220/270GHz receivers will constrain the synchrotron and galactic dust foregrounds respectively. Here we report on the design and performance of the BICEP Array instruments focusing on the mount and cryostat systems.

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1. INTRODUCTION

2. CRYOSTAT DESIGN

BICEP array continues the successful design philosophy of the previous Bicep / Keck receivers.An 80" tall vacuum shell contains two nested stages with nominal operating temperatures of 50K and 4K. A cross section of the cryostat is shown in Figure **??**. The top section of the vacuum jacket is sealed by an HDPE window and houses a stack of Zotefoam filters which reduce infrared loading onto the colder stages. The intermediate 50K stage serves as a radiation shield for the interior 4K stage. The top of this stage accommodates an Alumina filter which further reduces infrared loading and the lower $\sim$70% of the intermediate 50K stage is wrapped with a 0.04" thick magnetic shield layer composed of Amuneal A4K. The 4K stage provides radiation shielding for the sub-K focal plane and electronics while also housing two cold Alumina lenses and optical baffles.

The cryostat is designed to be disassembled by lifting off shells successively from the outside in, leaving a stand-alone base behind which contains the sub-Kelvin focal plane assembly, readout electronics, and the cooling system as shown in Figure **??**. In this state, the focal plane and detector modules may be freely accessed for maintenance and other technical activities. Access to the underside of the focal plane and the readout electronics is provided by hatches on the bottom side of the Vacuum shell and 50K bases. This scheme significantly reduces the time required for disassembly when accessing the focal plane and re-assembly afterwards by allowing critical thermal junctions and difficult part matings to remain undisrupted.

2.1 Thermal Architecture

The 50K and 4K radiation shields are cooled by the first and second stages respectively of a Cryomech PT415-RM Pulse Tube cooler. This cryocooler is capable of maintaining a first stage temperature of < 45K under a 40W load and a second stage temperature of < 4K under a 1.5W load. The interior stages must therefore be carefully shielded in order to stay within the thermal budget.

The radiation absorbed by the interior stages is reduced by the use of Multi Layer Insulation wrapped around the outside of the 50K and 4K stages. Where there is insufficient room for uncompressed insulation, high emissivity Aluminum tape is used to decrease the radiation absorbed by the lower temperature surface. We calculate the total radiation loading absorbed by the 50K and 4K stages respectively to be 2.75 W and 6.9 mW respectively.

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The radiation shields are additionally attached to higher temperature stages via a low thermal conductivity support system. The front end of each shell constrained by thin Ti-Al-4V straps which are flexible along the axial direction of the cryostat which sees substantial thermal contraction. At the back end, each stage is supported by six trusses each of which has two high tensile strength / thermal conductivity rods bonded to Aluminum blocks with Stycast epoxy. We use G10-FR4 for the backend supports between the Vacuum shell and the 50K radiation shield but switch to Carbon Fiber between the 50K and 4K shells due to the former's lower thermal conductivity at low temperatures. Figure **??** shows these fabricated internal supports. We calculate the loading due to these supports to be < 2.85W on the 50K stage and < 0.157W on the 4K stage.

In addition to providing radiation shielding and mount points for low temperature optics, the 50K and 4K stages provide natural heat sinks for the cryocables that connect the subK electronics to the exterior - room temperature - data acquisition system.

While the pulse tube maintains the temperatures of the radiation shields, the tiered focal plane assembly is cooled still further by a three stage Helium sorption fridge which cools the tiers to successively lower temperatures of 2.8K, 340mK and < 250mK. Like the supports for the 4K radiation shield, the tiers of the focal plane assembly are separated by carbon fiber support trusses which have extremely low thermal conductivity.

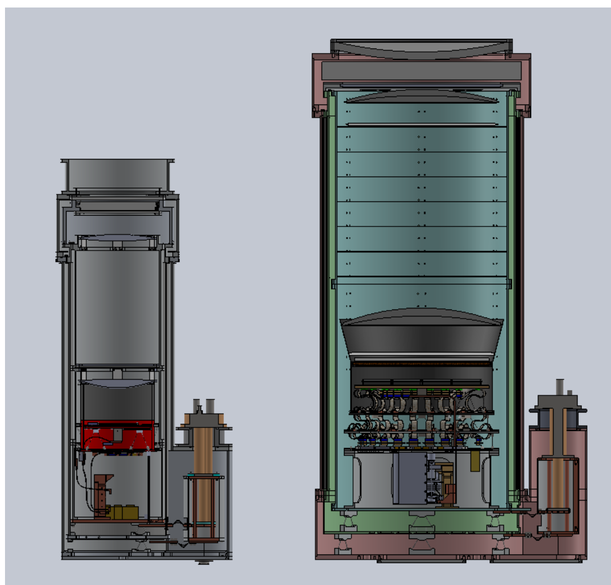

Figure 1. A CAD cross section of a single Keck Array receiver (left) and a Bicep Array receiver (right). The Bicep Array cryostats more than double the volume of their Keck Array counterparts with mapping speed equal to ~5 times that of a Keck receiver at the same frequency.

2.2 Copper Braid Heat Straps

The heat straps connecting the pulse tube cooler to the 50K and 4K stages of the cryostat needs to have large thermal conductance but also be fairly flexible to suppress vibrations transmitted to the focal plane. Bicep Array uses custom made OFHC Copper assemblies each composed of a large number of flexible Copper braids. As shown in Figure **??** each heat strap consists of two end blocks connected by a series of multi-layered braided straps. The braided straps comprise seven layers of OFHC braid pressure fused into a small diameter OFHC pipe section on either end. The pressure fusing is performed by a hydraulic press under a load of 40 Tons while external constraint is provided by a Steel die. We have been able to achieve thermal conductance of $G = 600\frac{\mathrm{mW}}{\mathrm{K}}$ @4K per strap in laboratory tests.

The heat straps in the Bicep Array cryostat combine a number of these straps to achieve high thermal conductance. Two layers of braided straps are sandwiched around an OFHC plate on both ends. These plates provide mounting interfaces to the rest of the cryostat and the pulse tube cooler. Stainless steel plates on the top and bottom sides of this interface allow the use of 1/4" stainless steel bolts to create a high pressure joint and reduce thermal contact resistance. Figure **??** shows a fully assembled heat strap assembly that interfaces between the 4K radiation shield and the 2nd stage of the pulse tube.

3. MOUNT

The larger size of the Bicep Array as compared to the Keck array it replaces requires a larger motorized platform for operation. Designed by Eric Chauvin, the new Bicep Array mount uses the same three axis design as the previous Bicep / Keck experiments which augments the Azimuth and Elevation scans with rotation about the optical axis hereafter referred to as "Deck". A cross section of the new mount assembly is shown below in Figure 2. As with previous Bicep and Keck experiments, the cryostats are enclosed within an accordion-like environmental shield which co-rotates in azimuth and flexes as the mount tips down in elevation. A separate central plate then co-rotates in deck and maintains the environmental seal as the mount rotates about its boresight.

The Bicep Array mount includes two separate rotary unions which allow continuous rotation about the azimuth and deck axes without the need for a cable wrap. These rotary unions were designed at DSTI and each contain 10 Helium channels, eight of which connect the pulse tubes and their compressors while two channels serve as pressure guards. An additional Nitrogen channel provides a pressurized environment on the backside of a thin membrane structures which shield the receivers' HDPE windows from the Antarctic winter. Inclusion of slip rings at both ends of the union additionally provide data and power connections to electronics that co-rotate with the cryostats. These rotary unions allow the Helium compressors - required to operate the pulse tube coolers - to sit well below the mount structure in the stationary tower. Helium lines route upwards into the lower fixed half of the first rotary union and then out through the upper half which rotates in Azimuth along with the receivers. The hoses from the upper half are then routed through a short cable chain that provides flexure when rotating in elevation. A second rotary union is then similarly connected with the free section rotating about deck.

4. OPERATIONS

The Bicep Array will consist of four receivers observing in 6 frequency bands. Two receivers will continue to observe in the 95 and 150 GHz bands where the Bicep/Keck group's maps are deepest and where combined foreground signal is at a minimum. These will be augmented by two dual-band receivers at 30/40 GHz and 220/270 GHz with the two frequencies interleaved in a checkerboard pattern. With the increased sensitivity at 95 and 150 GHz these two additional receivers will be required to push constraints on polarized emission from galactic synchrotron and dust further than the currently available data. Galactic synchrotron is already detected at modest signficiance in the Bicep/Keck data. The 30/40 GHz receiver will extend the observations into two new bands at which the synchrotron foreground is expected to dominate. The Keck array is already observing in the 220 and 270 GHz bands. However with significantly increased throughput and a detector count of over 9 times the entire Keck Array, the dual band 220/270 GHz Bicep Array receiver will rapidly eclipse the sensitivity of the Keck Array and produce better constraints on the polarized emission from galactic dust. In only a few days of observation, this receiver will surpass the dust sensitivity of Planck's 353 GHz data in the Bicep/Keck field.

4.1 Scan Strategy

The observing power of Bicep Array will continue to focus on the same ~ 400 deg^2 patch of sky as the rest of the Bicep Keck data. By directly observing cosmological foregrounds with the new dual band receivers in the patch at which the Bicep/Keck data is already the deepest we will be able to directly constrain these foregrounds in our own patch of sky, significantly reducing the effect of any spatial variation in the foregrounds' spectral energy distribution. Increasing foreground constraints will be complemented by simultaneously increasing sensitivity to r with the single band receivers.

The sensitivity of these two dual band receivers also suggests a number of alternate scan strategies. Figure **??** shows two alternate sky patches which the Bicep Array will observe.

Should probably include something about the new scan patches but need to see if I can actually take it from the proposal or not. Also these scans could techincally be done now, they aren't all of a sudden availible The freedom of rotation afforded by these rotary joints will allow Bicep Array to pursue additional scanning modes and strategies. One such strategy is a Bicep Array Sky Survey covering $\sim 20\%$ of the sky as shown below in **??**.

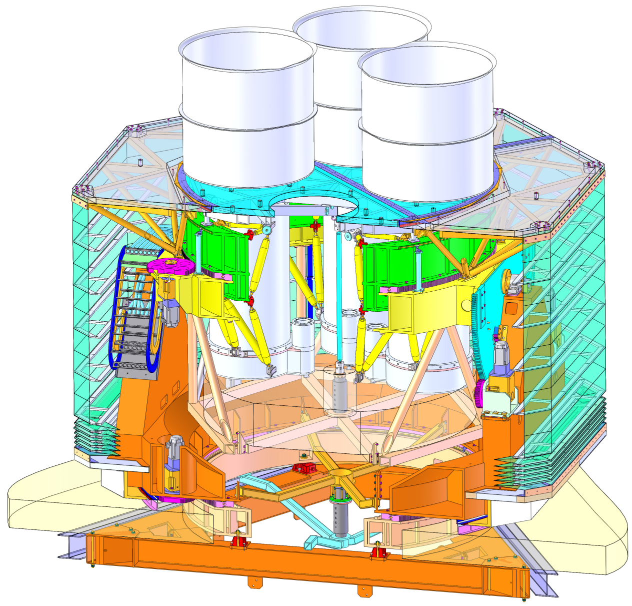

Figure 2. A CAD rendering of the new Bicep Array. The surrounding accordion-like environmental shield is shown in teal while the two rotary unions are depicted in gray and can be seen along the central axis of the mount.