Developing a Large-Scale Cryogenic System for the Simultaneous Operation of Three Detector Focal Planes in TolTEC, A New Multichroic Imaging Polarimeter

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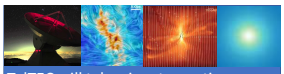
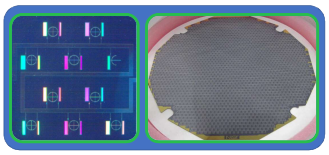
TolTEC is an upcoming millimeter-wave imaging polarimeter designed to fill the focal plane of the 50-m diameter Large Millimeter Telescope (LMT). Combined with the LMT, TolTEC will offer high angular resolution (5"-10") simultaneous, polarization-sensitive observations in three wavelength bands: 1.1, 1.4, and 2.0 mm. Additionally, TolTEC will feature mapping speeds greater than 2 deg^2/mJy^2/hr, thus enabling wider surveys of large-scale structure, galaxy evolution, and star formation. These improvements are only possible through the integration of approximately 7000 low-noise, high-responsivity superconducting Lumped Element Kinetic Inductance Detectors (LEKIDs). To utilize three focal planes of detector arrays requires the design, fabrication, and characterization of a unique, large-scale cryogenic system. Based on thermal models and expected photon loading, the focal planes must have a base operational temperature below 150 mK. To achieve this base temperature, TolTEC utilizes two cryocoolers, a Cryomech pulse tube cooler and an Oxford dilution refrigerator, to establish four thermal stages: 45 K, 4 K, 1 K, and 100 mK. During the design phase, we developed an object-oriented Python code to model the heat loading on each stage as well as the thermal gradients throughout the system. This model has allowed us to improve thermal gradients in the system as well as locate areas of poor thermal conductivity prior to ending a cooldown. The results of our model versus measurements from our cooldowns will be presented along with a detailed overview of TolTEC's cryogenic system. We anticipate TolTEC to be commissioned at the LMT in Fall 2019.

Motivation

TolTEC hosts three focal plane arrays to examine the mm-wave sky as never before. Each array features over 1000 lumped element kinetic inductance detectors (LEKIDs) and offers simultaneous dual polarization. In order to physically accommodate all three arrays, and image with each one at the same time, we required the design, fabrication, and thorough characterization of a unique, large-scale cryogenic system.



TolTEC will take aim at questions concerning the dust content of galaxies across cosmic time and studies investigating the environment and physics of star formation. Our high resolution will allow us to be directly comparable to the next generation of optical/IR, UV, x-ray observatories.

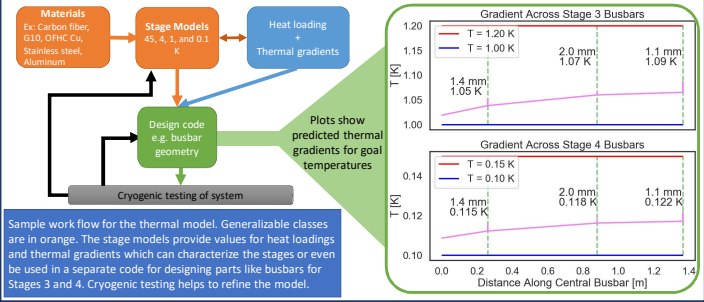


TolTEC will host 7000 Lumped Element Kinetic Inductance Detectors across three focal planes [1, 2]. Credit: J. Austermann

The cryogenics have been customized in both design and fabrication; however, using Python, we developed a generalizable thermal model. With it we have well-characterized and troubleshot the system. This was necessary to meet specifications required to perform the next generation of mm-wave astronomy.

Thermal Model

- Simple, but powerful object-oriented Python code that can be generalized to other projects in the future
- Two primary types of classes: Materials and Thermal stages
- Code was used to make predictions of: Radiation, Conductance, Thermal gradients, and Cooling time
- Code will be accessible to public following commissioning at LMT



Sample work flow for the thermal model. Generalizable classes are in orange. The stage models provide values for heat loadings and thermal gradients which can characterize the stages or even be used in a separate code for designing parts like busbars for Stages 3 and 4. Cryogenic testing helps to refine the model.

Physical Properties

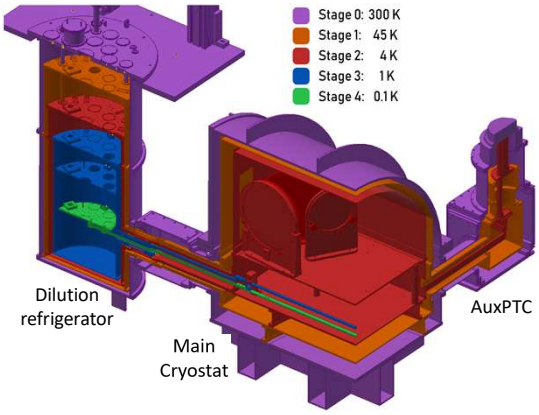
Stage	Mass [kg]	Cold Head Temperature [K]
1	102.9	39.21
2	164.8	3.997
3	7.9	1.025
4	11.8	0.1340

The four thermal stages within TolTEC are listed with the mass of copper and aluminum the stage and the average base temperatures of the stage's cold head (average taken across multiple cooldowns).

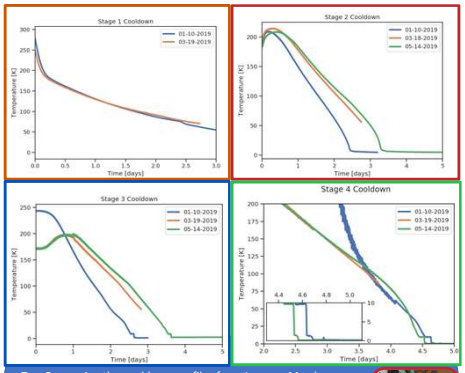
TolTEC also features two cryocoolers:

- A Cryomech pulse tube cooler (AuxPTC)
- An Oxford dilution refrigerator (DF)

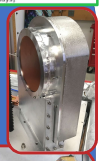
The AuxPTC is responsible for cooling the two warmer stages of the system to 45K and 4K. The DF performing cooling at all four stages, with the bulk of its cooling power being on 1 and 0.1 K. We utilize flexible copper straps and G10 supports to reduce vibrations in the system. There is no evidence of the vibrations in the detector noise data, which suggests that the system is **background limited**.

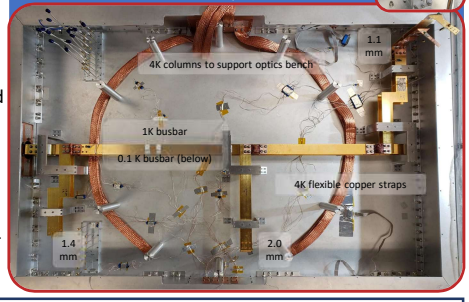


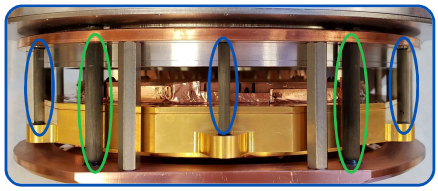
The thermal stages of TolTEC. The nested shell design isolates the thermal, electronic, and optical systems to facilitate maintenance or modifications on the system.



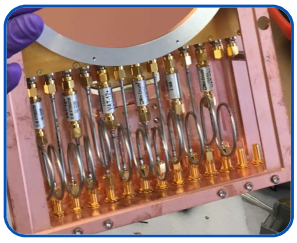
Top: Comparing the cooldown profiles from January, March, and May. We consistently reach base temp after numerous cooldowns and modifications to the system.
Right: The 1.1 mm array detector assembly installed on the 4K optics bench. Picture is from the most recent cooldown with one lens installed.
Bottom: Top down view of the interior of the 4K volume **below** the optics bench. This shows some of our flexible copper straps in use as well as the 1 and 0.1 K thermal paths.







Above: 1 and 0.1 K carbon fiber supports in detector assembly (colours indicate the same thermal stages as in center figure).



Left: Coax cables installed in detector assembly
Right: Custom designed and fabricated flexible copper straps

Heat Loading and Cooling Power

Thermal Stage	Radiative Loading	G10 + Carbon fiber	Coax cables	Total Predicted Heat Load	Estimated Cooling Power	Total Measured Load
45 K	15.9 W	2.37 W	0.68 W	25 W	40 W (APTC) + 10 W (DF)	40.7 W*
4 K	0.01 W	0.16 W	0.03 W	0.4 W	1 W (APTC) + 1 W (DF)	0.378 W*
1 K	0.98 uW	1.25 uW	1.16 mW	2 mW	<= 50 mW	~4 mW*
0.1 K	0.98 uW	41.1 uW	11.7 uW	< 100 uW	450 uW	~10 uW*

*one detector array

Results/Summary

- The goal of this cryogenic design was to have a system that worked in parallel, yet isolation, alongside TolTEC's other subsystems
- We have demonstrated predictive and characterization power of our Python-based thermal model
- We tested and confirmed capability of cryogenic design/modeling through repeated successful operations of four-stage thermal system
  - Base temperature of 1.1 mm focal plane achieved in dark system: 138 mK
- We have proved capability of system in preparation for final integration of the remaining two focal planes (1.4 mm band and 2.0 mm band) in the next month (Aug 2019)

References
[1] Austermann, J. et. al. 2017; [2] Bryan, S. et. al. 2018; [3] Day, P.K. et. al. 2003; [4] Zmuidzinas, J. 2012; [5] McCarrick, H. et. al. (2018)

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