Large Aperture Telescope Receiver (LATR) [WBS 1.06.04] Status

Bradford Benson (he/him)

CMB-S4 Collaboration Meeting
April 3-6, 2023

Outline

- Subsystem Team
- Scope
- Technical overview/progress/status
- Near-term plans
- Summary

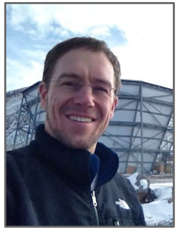
LAT Team

1.06
LARGE APERTURE TELESCOPES
Mike Niemack (Cornell)
Nick Emerson (U. Arizona)

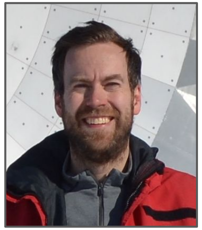
1.06.01
LAT Management
Nick Emerson (U. Arizona)

1.06.02
South Pole Large Aperture Telescopes
Eric Chauvin (U. Chicago)

1.06.03
Chilean Large Aperture Telescopes
Mike Niemack (Cornell U.)



1.06.04
Large Aperture Telescope Receivers
Brad Benson (U. Chicago)



1.06.05
Large Aperture Telescope Commissioning Receiver
Jeff McMahon (U. Chicago)

This talk

1.06.06
Large Aperture Telescope Calibration Hardware
Johanna Nagy (Washington U. St. Louis)

LAT Key Contributors:
Amy Bender (Argonne)
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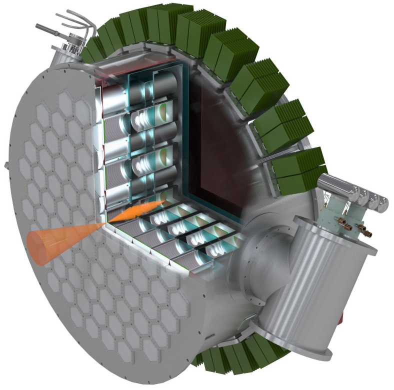
John Carlstrom (Chicago)
Eric Chauvin (Chicago)
Simon Dicker (UPenn)
Nick Emerson (U. Arizona)
Patricio Gallardo (Chicago)
Ian Gullett (Case Western)
Katie Harrington (Argonne)
Richard Hills (Cambridge)
Matt Hollister (Fermilab)
Sherese Humphrey (Chicago)
Michele Limon (U. Penn)
Jeff McMahon (Chicago)
Don Mitchell (Fermilab)
Johanna Nagy (Washington U)
Tyler Natoli (Chicago)
Erik Nichols (Chicago)
Michael Niemack (Cornell)
John Ruhl (Case Western)
Zhilei Xu (MIT)
Jeff Zivick (Chicago)

Scope

- 1.06.04 LATR - The design, fabrication of 3x LATR cryostats, including the cryostat shell and radiation shields; the cryogenics; and the optics tubes, which include the vacuum window, infrared (IR) filtering, and lenses. Responsibilities include: northern integration and testing of the LATR cryostats with installed detector modules and readout components, and shipping (which is the handoff to I&C).
- 1.06.05 LAT-CR - Same as above, but for 3x LAT-CR (Commissioning Receiver) cryostats.

- **1.06.04 - Large Aperture Telescope Receivers (LATR)**
  - 1.06.04.01 - LATR Engineering
  - 1.06.04.02 - LATR Test Equipment (North America)
  - 1.06.04.03 - South Pole LATR (SP-LATR)
  - 1.06.04.04 - Chile LATR1 (CH-LATR1)
  - 1.06.04.05 - Chile LATR2 (CH-LATR2)
- 1.06.05 - Large Aperture Telescope Commissioning Receiver (LAT-CR)
  - 1.06.05.01 - LAT-CR Engineering
  - 1.06.05.02 - LAT Commissioning Fabrication
    - 1.06.05.02.01 - LAT Commissioning Receiver South Pole (SP-LATCR)
    - 1.06.05.02.02 - LAT Commissioning Receiver Chile (CH-LATCR)
    - 1.06.05.02.03 - LAT Commissioning Receiver - US (US-LATCR)

LATR

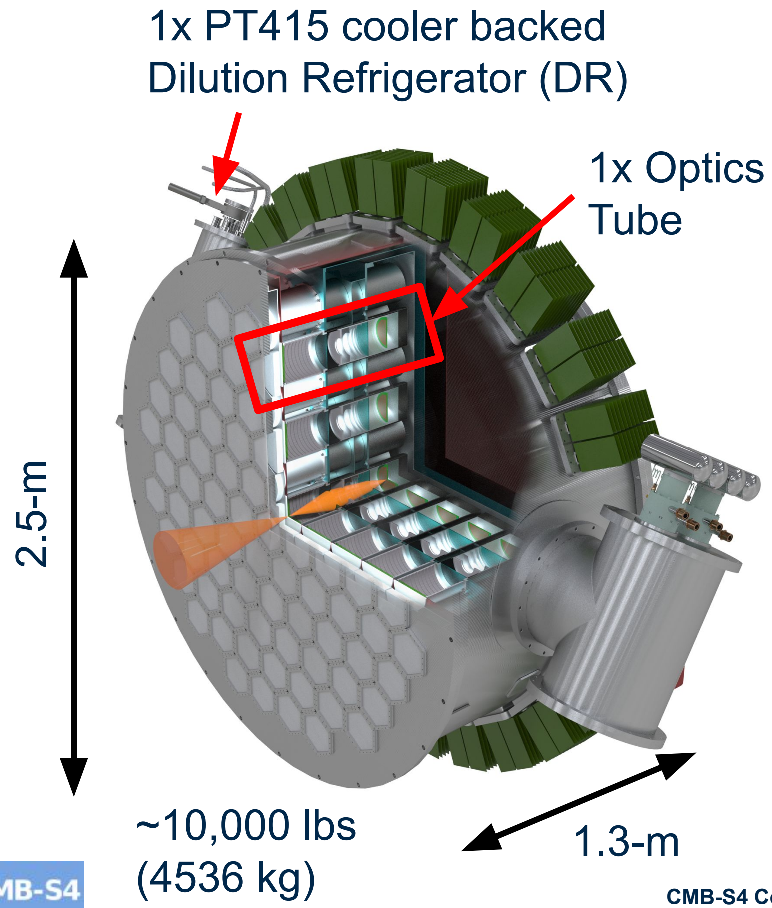


x3

LAT-CR

x3

LATR: Preliminary Baseline Design (PBD)



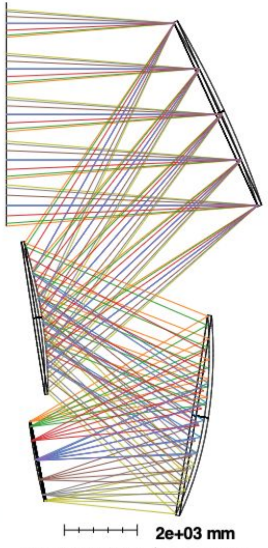
85 Optics Tube Cryostat Design:

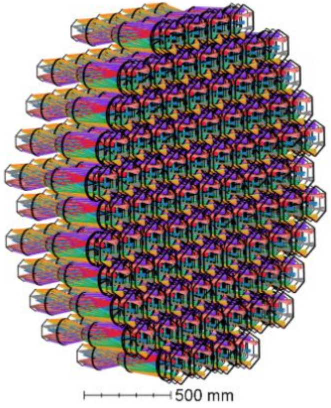
- Each of the 85x optics tubes consist of a 3-lens (18-cm aperture diameter) design that couples to a single (13-cm diameter) detector wafer.
- LATR cryostat design compatible with SPLAT (f/2.5) and CHLAT (f/2.4) telescopes, with some slight modifications:
  - Science goals require slightly different frequency distribution of optics tubes.
  - Different telescope optics designs will require different camera lens designs.
  - Note: Similar dimensions to Simons Observatory LATR, which is a 0.05-m smaller diameter and ~1.0-m longer.

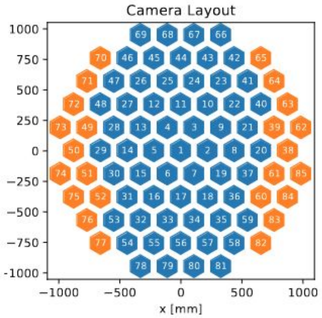
SPLATR Optics Design (see Mike's L2 LAT talk)

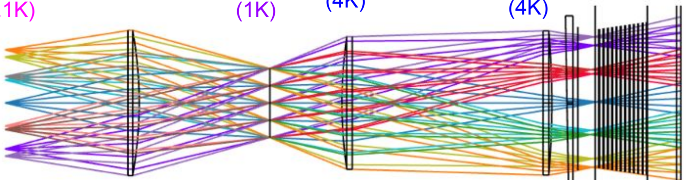
- Substantial progress on TMA and receiver optics optimization and analysis
  - Gravitational & thermal deformation of mirrors
  - Optimization of all 85 cameras
  - Tolerancing analyses
  - Gallardo et al. 2023 *now* in collaboration review

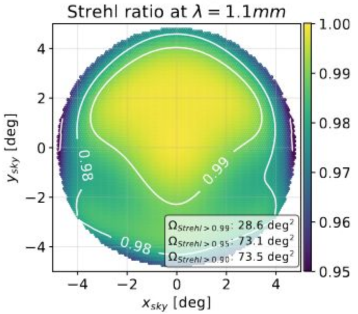
Deformation	Min Strehl [-]	Max Strehl [-]	Defocus [mm]
Nominal	0.96	0.99	0
Thermal	0.96	0.99	-9.69
Gravity	0.94	0.99	-1.36
Thermal + Grav.	0.92	0.99	-10.24





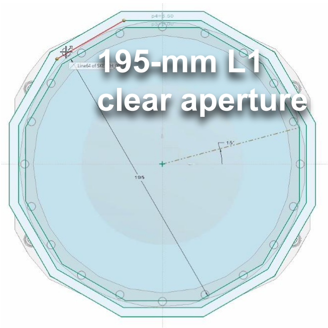


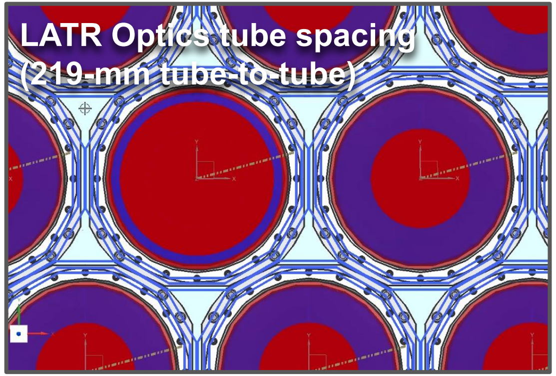


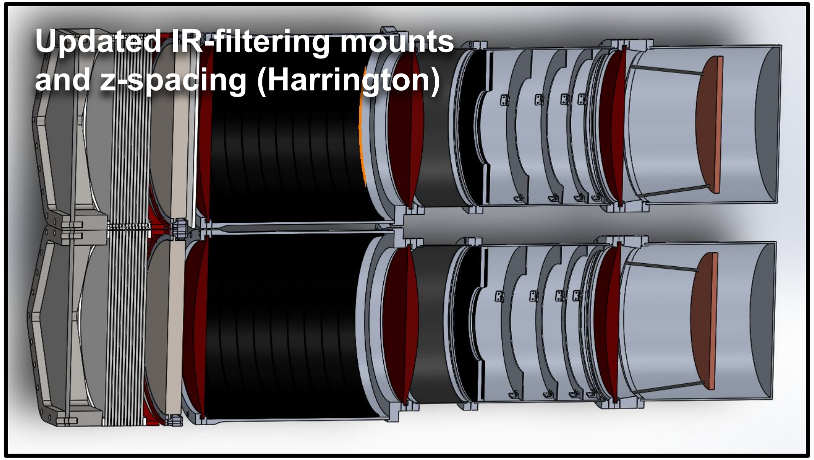


Optics Tube: Opto-Mechanical-Thermal Interfaces

- Continued development of concept for LATR optics tube (OT), including more opto-mechanical details, e.g.
  - Setting radial spacing of tubes and lens apertures, to include realistic lens mount and OT mounting flange
  - Studied LATR IR loading model and committed IR-loading calculator to CMB-S4 GitHub repo optical-load-calculator
  - Updated z-spacing between optical elements near the vacuum window, now incorporating more realistic IR-filter & lens frames
    - Next steps: Iterate with the optics design using this new spacing







LATR Interfaces and Requirements

- Drafted coordinate system definition document for SPLAT, to define multiple coordinate systems for M1, M2, & M3 mirrors and LATR, relative to SPLAT telescope axis
- Wrote technical note (in new CMB-S4 specific format) outlining LATR front-end filter positions and outlining assumptions in their design and relative positions.

SPLAT Coordinate Systems (Emerson, Gallardo)

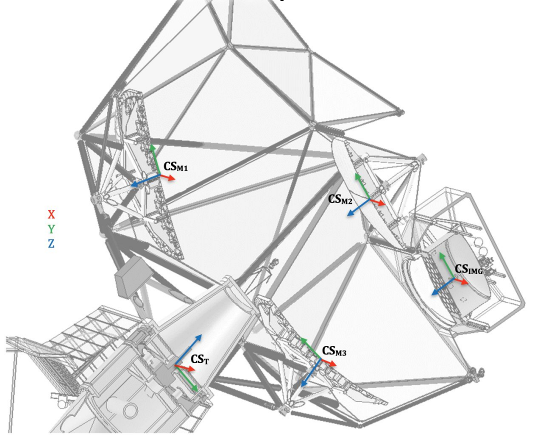
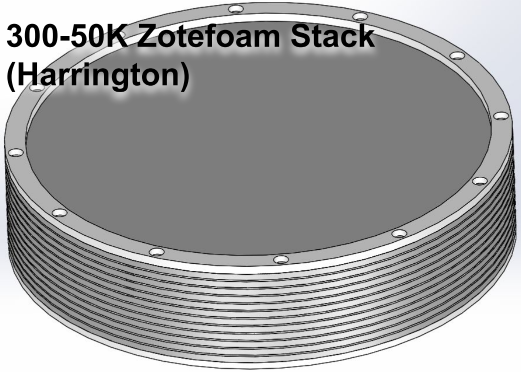
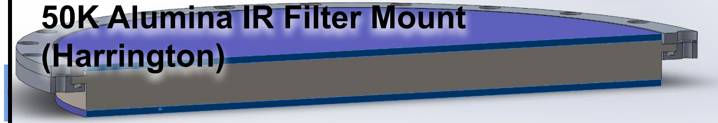


Figure 5 - Mirror and image plane coordinate systems

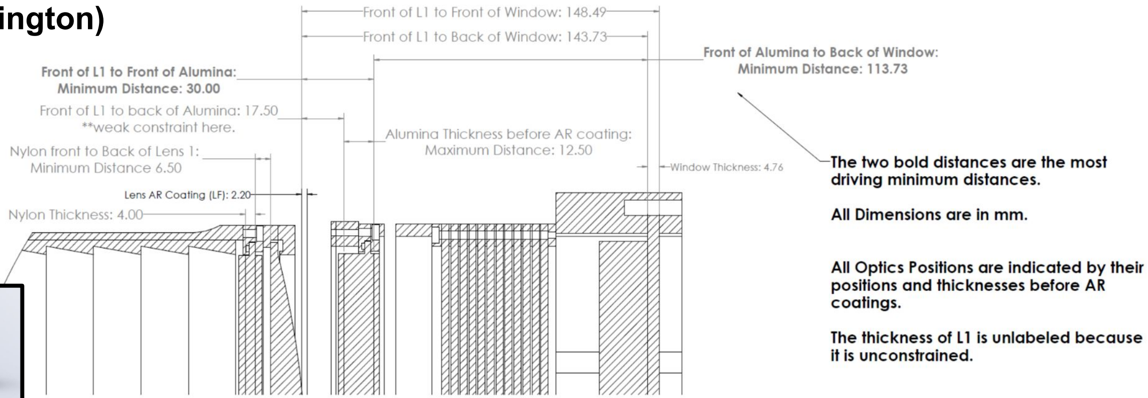
300-50K Zotefoam Stack (Harrington)



50K Alumina IR Filter Mount (Harrington)

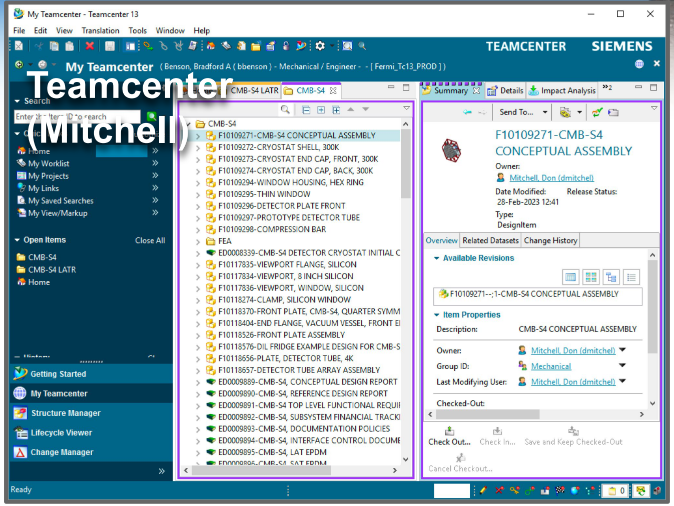


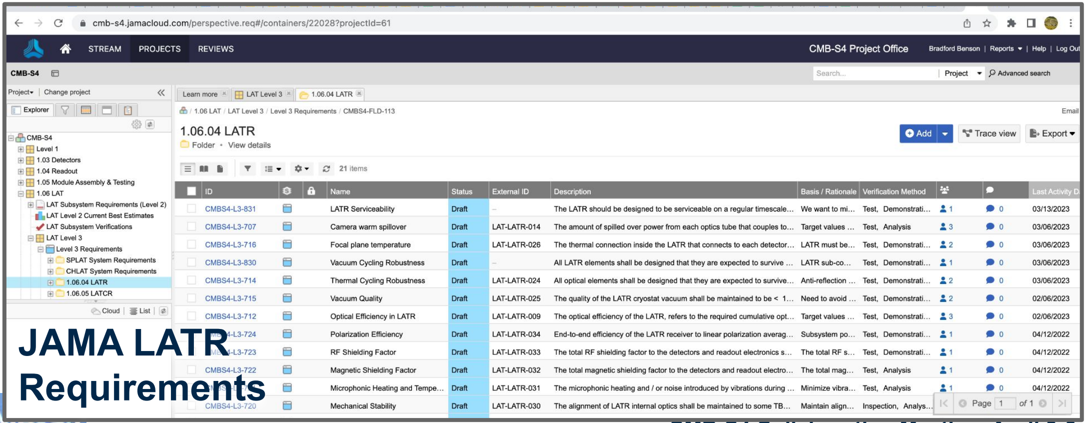
IR-Filtering Front-End Positions (Harrington)



LATR Interfaces and Requirements

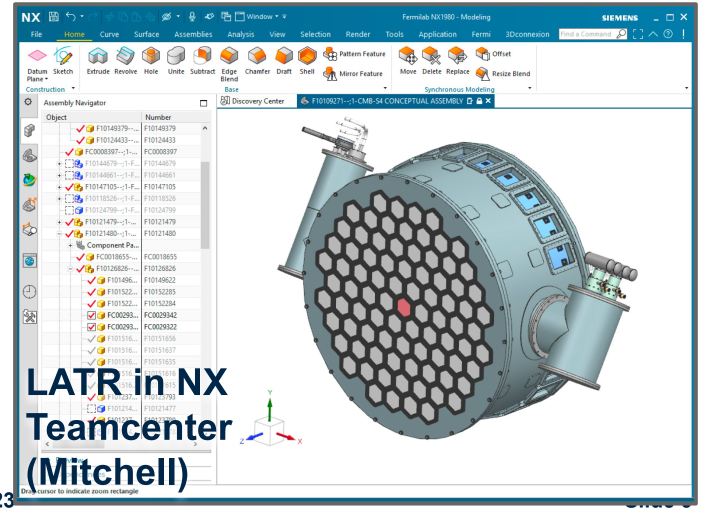
- Started a new LATR engineering telecon (every other Tuesday 12pm central, see S4 calendar)
  - Aims to coordinate LATR engineering design activities across institutions
  - Aiming to use Teamcenter, to accommodate multiple CAD packages (e.g., NX, Solidworks, etc.)
- Midway through a LATR requirements review, aiming to review and update all LATR requirements in JAMA





ID	Name	Status	External ID	Description	Basis / Rationale	Verification Method			Last Activity D
CMBS4-L3-831	LATR Serviceability	Draft	–	The LATR should be designed to be serviceable on a regular timescale...	We want to mi...	Test, Demonstrati...	1	0	03/13/2023
CMBS4-L3-707	Camera warm spillover	Draft	LAT-LATR-014	The amount of spilled over power from each optics tube that couples to...	Target values ...	Test, Analysis	3	0	03/06/2023
CMBS4-L3-716	Focal plane temperature	Draft	LAT-LATR-026	The thermal connection inside the LATR that connects to each detector...	LATR must be...	Test, Demonstrati...	2	0	03/06/2023
CMBS4-L3-830	Vacuum Cycling Robustness	Draft	–	All LATR elements shall be designed that they are expected to survive ...	LATR sub-co...	Test, Demonstrati...	1	0	03/06/2023
CMBS4-L3-714	Thermal Cycling Robustness	Draft	LAT-LATR-024	All optical elements shall be designed that they are expected to survive...	Anti-reflection ...	Test, Demonstrati...	2	0	03/06/2023
CMBS4-L3-715	Vacuum Quality	Draft	LAT-LATR-025	The quality of the LATR cryostat vacuum shall be maintained to be < 1...	Need to avoid ...	Test, Demonstrati...	2	0	02/06/2023
CMBS4-L3-712	Optical Efficiency in LATR	Draft	LAT-LATR-009	The optical efficiency of the LATR, refers to the required cumulative opt...	Target values ...	Test, Demonstrati...	3	0	02/06/2023
CMBS4-L3-724	Polarization Efficiency	Draft	LAT-LATR-034	End-to-end efficiency of the LATR receiver to linear polarization averag...	Subsystem po...	Test, Demonstrati...	1	0	04/12/2022
CMBS4-L3-723	RF Shielding Factor	Draft	LAT-LATR-033	The total RF shielding factor to the detectors and readout electronics s...	The total RF s...	Test, Demonstrati...	1	0	04/12/2022
CMBS4-L3-722	Magnetic Shielding Factor	Draft	LAT-LATR-032	The total magnetic shielding factor to the detectors and readout electro...	The total mag...	Test, Analysis	1	0	04/12/2022
CMBS4-L3-721	Microphonic Heating and Tempe...	Draft	LAT-LATR-031	The microphonic heating and / or noise introduced by vibrations during ...	Minimize vibra...	Test, Analysis	1	0	04/12/2022
CMBS4-L3-720	Mechanical Stability	Draft	LAT-LATR-030	The alignment of LATR internal optics shall be maintained to some TB...	Maintain align...	Inspection, Analys...			

JAMA LATR Requirements



LATR Thermal Modeling

- Have made significant updates to the LATR thermal model:
  - Created a new spreadsheet (also linked to doc-db) with updates to model and better tracking of assumptions
  - Updated for latest readout wiring counts and using S4 GitHub readout_load_calculator
  - Updated for latest optical IR filtering model and using S4 GitHub optical_load_calculator
  - More consistent (and trackable) treatment of mechanical supports, and housekeeping wiring
  - Next steps:
    - Incorporate changes in PBDR
    - Refine loading estimates as thermal FEA's get completed of each stage

Table 3-14: LAT receiver refrigerator summary.

Fridge	Type	qty	Cooling capacity per fridge 40 K	4 K	1 K	100 mK
PT420	Pulse tube	3	55 W	2 W		
SD400	Dilution	1			25 mW	400 μW

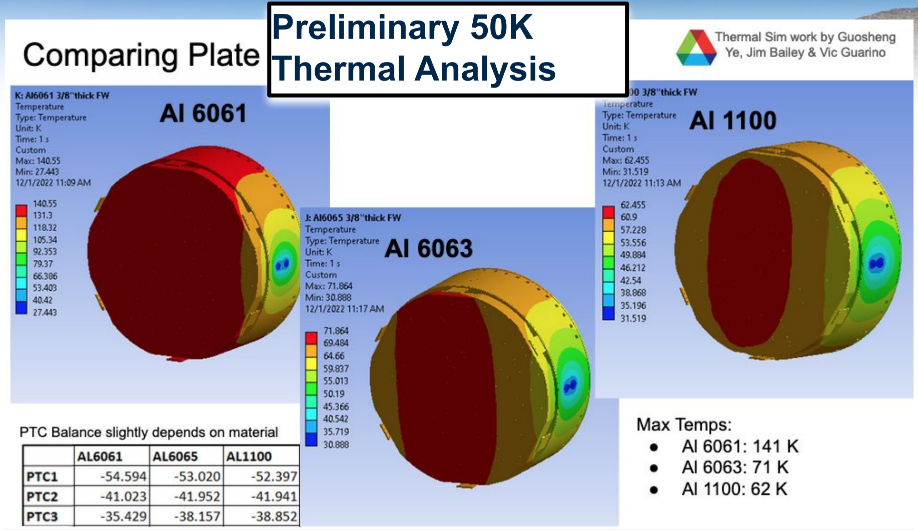
Stage	Support	Radiative	Window	Readout	Total	Cooling capacity
40 K	10.0 W	16.0 W	74.7 W	29.5 W	~~130 W~~	165 W
4 K	0.86 W	0.01 W	0.14 W	1.53 W	~~2.53 W~~	4.0 W
1 K	5.01 mW	0.01 mW	6.46 mW	0.87 mW	~~12.3 mW~~	25.0 mW
100 mK	68.6 μW	0.1 μW	0.5 μW	73.9 μW	~~143 μW~~	400 μW

From PBDR link

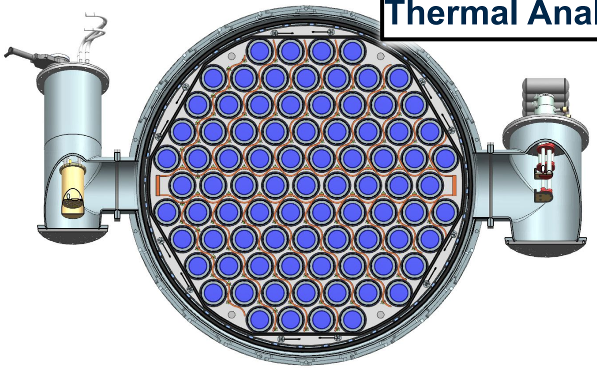
125 W
3.1 W
8.2 mW
222 uW

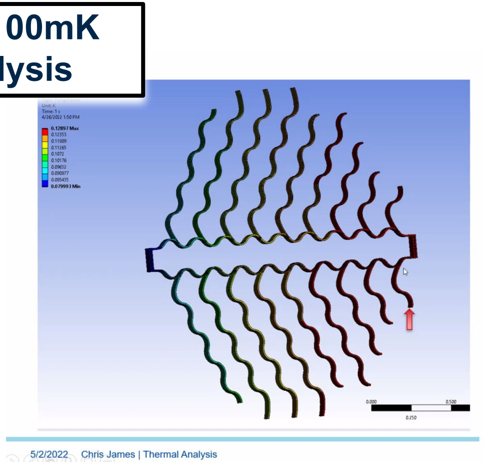
LATR Thermal Modeling

- Identified two areas of highest risk in cryogenic model, and have begun more detailed thermal FEAs of each:
  - **50K stage:** Lowest cooling margin according to thermal model, risk from increased IR loading from hot Alumina filter (Harrington, Guarino, Onecic, ANL)
  - **100 mK stage**: Risk of maintaining <120 mK detector modules across 2-m diameter focal plane, with sufficient cooling power on DR mixing chamber (James, Hollister, Benson, FNAL)



	AL6061	AL6065	AL1100
PTC1	-54.594	-53.020	-52.397
PTC2	-41.023	-41.952	-41.941
PTC3	-35.429	-38.157	-38.852





Near term plans

- Continue iterating on optics tube design, in particular the opto-thermal-mechanical design
- Continue development of thermal simulation of (at least) 100mK and 50K stages, focused on areas with highest cryogenic risk / challenge
- Continue increasing realism in the CAD design, e.g.,
  - on 50K and 100 mK stages, updating readout wiring and heat sink design for new wiring counts, updating mass estimates as design is refined, etc.
- Update basis of estimate (BOE) for CDR

Summary

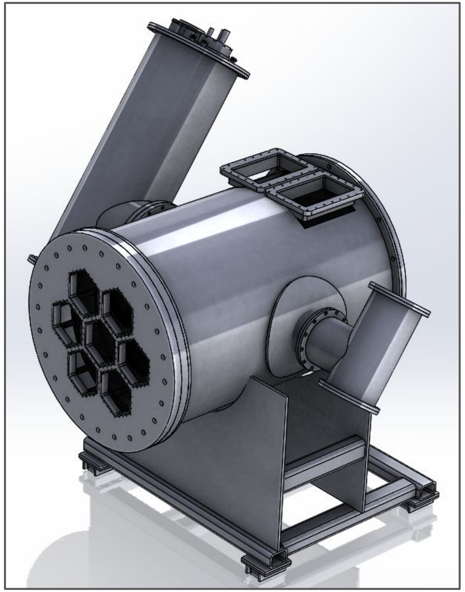
- LATR design is making great progress
- In particular, we have significantly improved documentation over past year for optical, thermal, and mechanical design, linking documents to doc-db

Extras

LAT Commissioning Receivers (LAT-CRs)

Project plans for 3x LAT-CRs, which will have two distinct purposes:

1. **On-sky/telescope commissioning at Chile and the South Pole:**
    a. Telescope performance: Measure beam size, and pointing using point source measurements in all frequency bands, end to end demonstration of observatory function.
    b. Detector performance: Measure noise and system efficiency.
    c. Validate end-to-end commissioning procedures through data analysis.
2. **Optics tube characterization:**
    a. Detailed in-lab optics tube characterization (e.g., efficiency, beams, spillover, detector loading), to verify production components meet requirements, and aid in interpreting commissioning measurements.

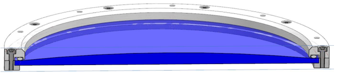


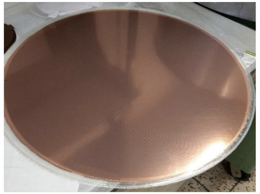
- First LAT-CR shared for the CHLATs commissioning. Second LAT-CR will be used for the SPLAT commissioning. Third will be used optics tube tester / validation in-parallel to US LATR integration.
- The LAT-CRs will include a telescope interface flange and dummy mass, to mimic the full LATR weight, for acceptance tests of telescope servo performance.

Silicon Lens AR Coating Production

- AR lens coating production is on critical path for LATR components, and has been assessed to be one of the largest LATR schedule risks.
  - For example, with 2x dicing saw machines, AR-coating production for 3x85 tubes takes nearly 3-years, with assumed fabrication schedule.
- Current mitigations:
  - Early installation of two Silicon dicing-saw machines at FNAL (pictured above).
- Potential additional mitigations:
  - Earlier prototypes to develop and demonstrate production methods and throughput.
  - Earlier production start.
  - Add a third machine to increase throughput.

Optics Tubes: Workflow and QA





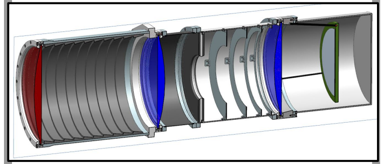
150GHz band 6.8cm-1 LPE filter at 500mm OD, March 2020

Silicon Lenses

QA Steps:
- Metrology / shape with CMM
- Reflectometry meas. to confirm AR-coating
- Index of refraction measurements

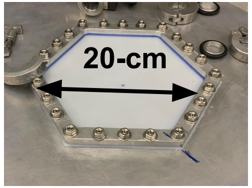
Metal-mesh filters

QA Steps:
- Reflectometry to confirm in-band performance
- Transmission to confirm cutoff



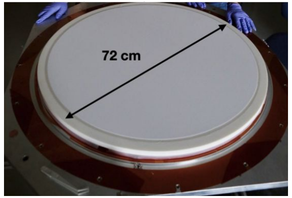
Optics Tubes

QA Steps:
- Romer arm measurements to confirm alignment



Vacuum Window

QA Steps:
- Reflectometry to confirm AR-coating
- Transmission to confirm loss
- Mechanical survival tests

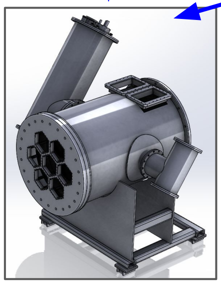


Mid-IR Alumina Filter/Prism

QA Steps:
- Metrology / shape with CMM
- Reflectometry meas. to confirm AR-coating

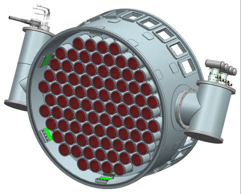
LAT-CR Cryostat

QA Steps:
- On-sky commissioning
- Holography for sidelobes on subset of tubes



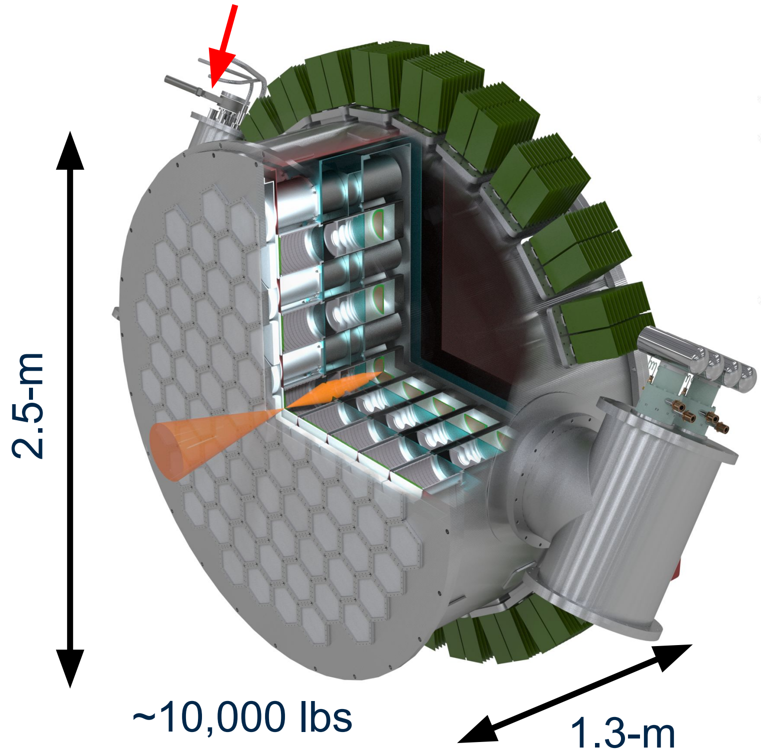
LATR Cryostat

QA Steps:
- Efficiency, bands, radiometric testing with S4 modules



LATR Cryogenics

1x PT420 cooler backed Dilution Refrigerator (DR)



~10,000 lbs (4536 kg)

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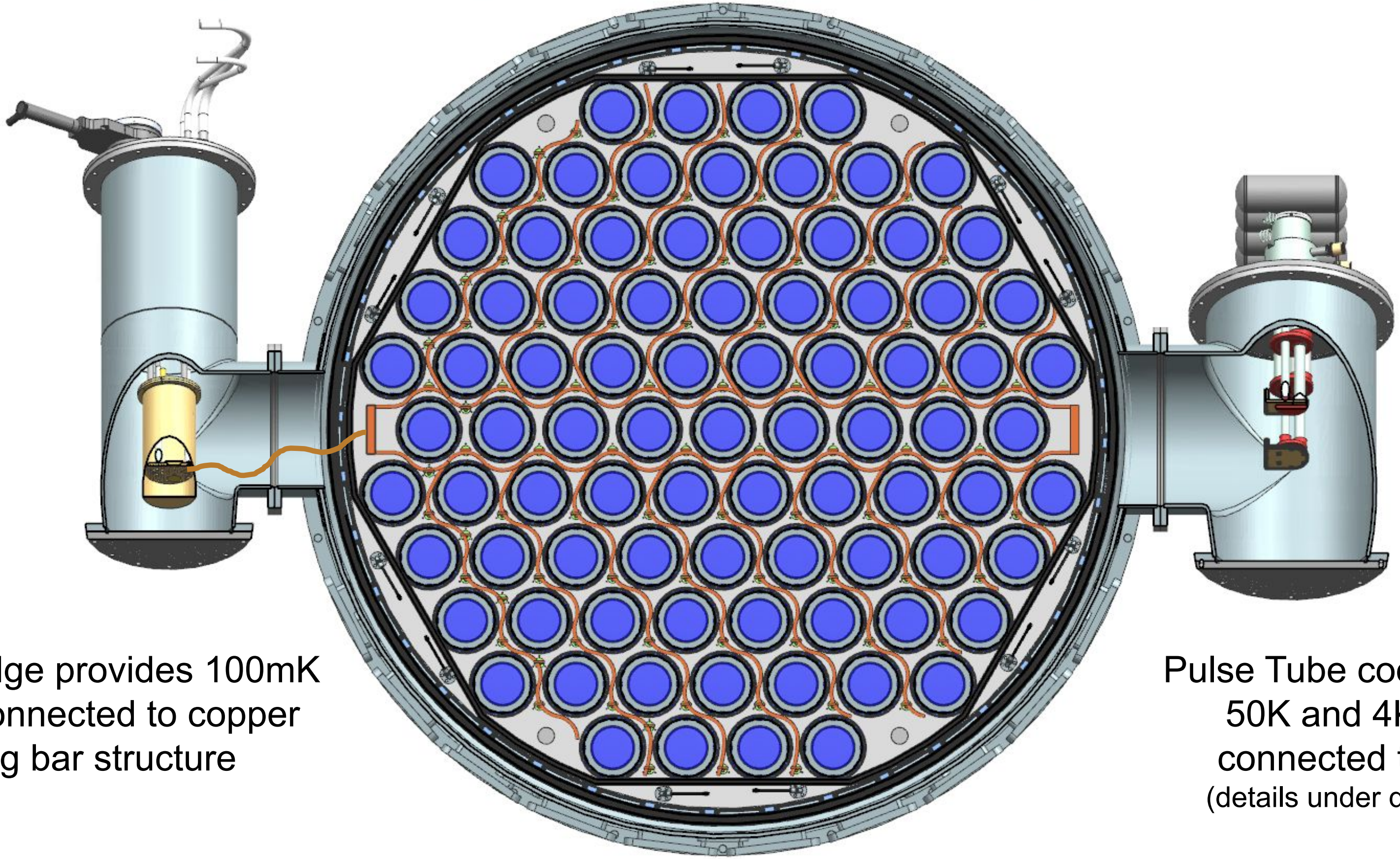
4 K	0.86 W	0.01 W	0.14 W	1.53 W	2.53 W	4.0 W
1 K	5.01 mW	0.01 mW	6.46 mW	0.87 mW	12.3 mW	25.0 mW
100 mK	68.6 μW	0.1 μW	0.5 μW	73.9 μW	143 μW	400 μW

PBDR link

- Preliminary cryogenic estimates suggests sufficient margin on each cold stage.
- Next steps will include:
  - Design detailed mechanical and heat-sinking interfaces,
  - Estimate thermal gradients in cryostat, to verify design meets requirements on various optical, thermal, and readout components.

Conceptual Design: 100mK Cold Bar



Dilution fridge provides 100mK cooling connected to copper cooling bar structure

Pulse Tube coolers provide 50K and 4K cooling connected to shields
(details under development)