Post-CDR Thermal Design and Analysis of the StarBurst Instrument

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Presented By

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Outline

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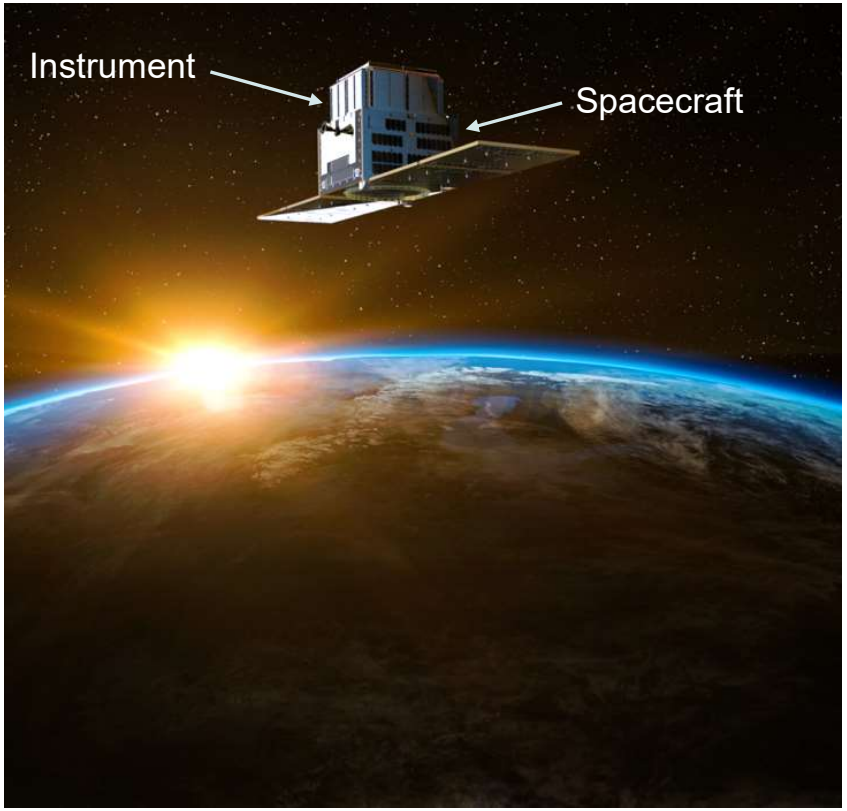
StarBurst Background

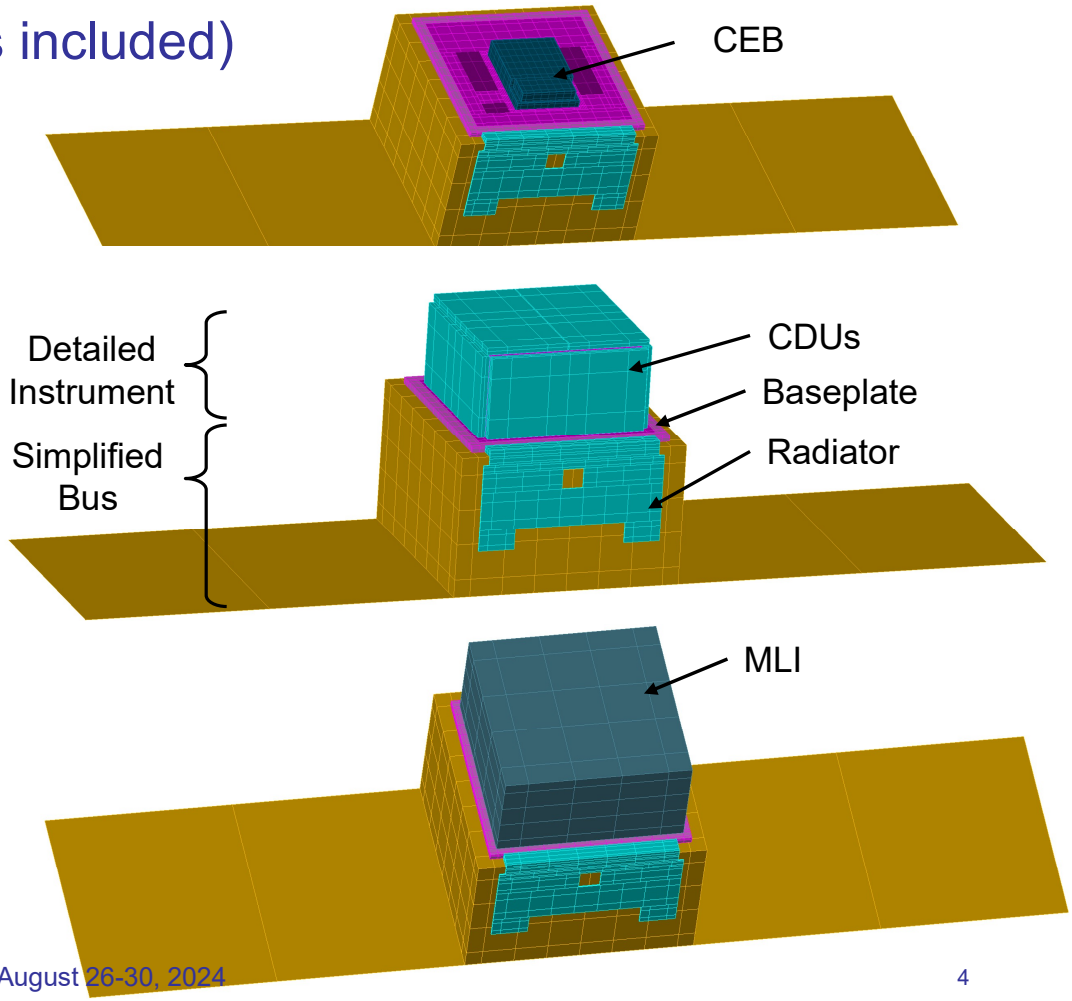
- **The StarBurst Multimessenger Pioneer** is a highly sensitive and wide field gamma-ray monitor designed to detect the prompt emission of short gamma-ray bursts (SGRBs), a key EM signature of neutron star mergers
- The StarBurst instrument consists of 12 Crystal Detector Units (CDUs) to detect these gamma-rays, and associated electronics
- StarBurst Partnership Roles:
  - **NASA Marshall Space Flight Center (MSFC):** Principal Investigator institution and overall project management
  - **Naval Research Lab (NRL):** StarBurst instrument design and fabrication
  - **University of Alabama Huntsville (UAH):** Instrument flight software
  - **University Space Research Alliance (USRA):** Science operations center
  - **University of Toronto Institute for Aerospace Studies (UTIAS) Space Flight Lab (SFL):** Spacecraft bus and mission operations center



https://science.nasa.gov/mission/starburst/

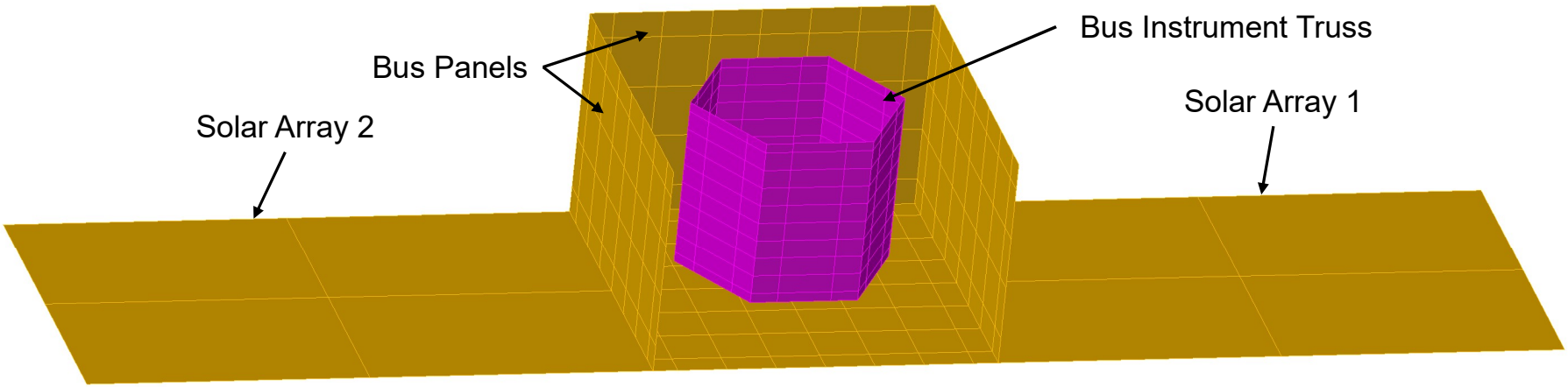
CDR Thermal Analysis & Design: Overview

- NASA MSFC thermal model (images included)
  - Simplified spacecraft bus model
    - Spacecraft
    - Solar Arrays
    - Instrument Truss
  - Detailed instrument model
    - Crystal Detector Units (CDUs)
    - Control Electronics Box (CEB)
    - Baseplate & Support Structure
- SFL thermal model
  - Detailed spacecraft bus model
  - Simplified instrument model



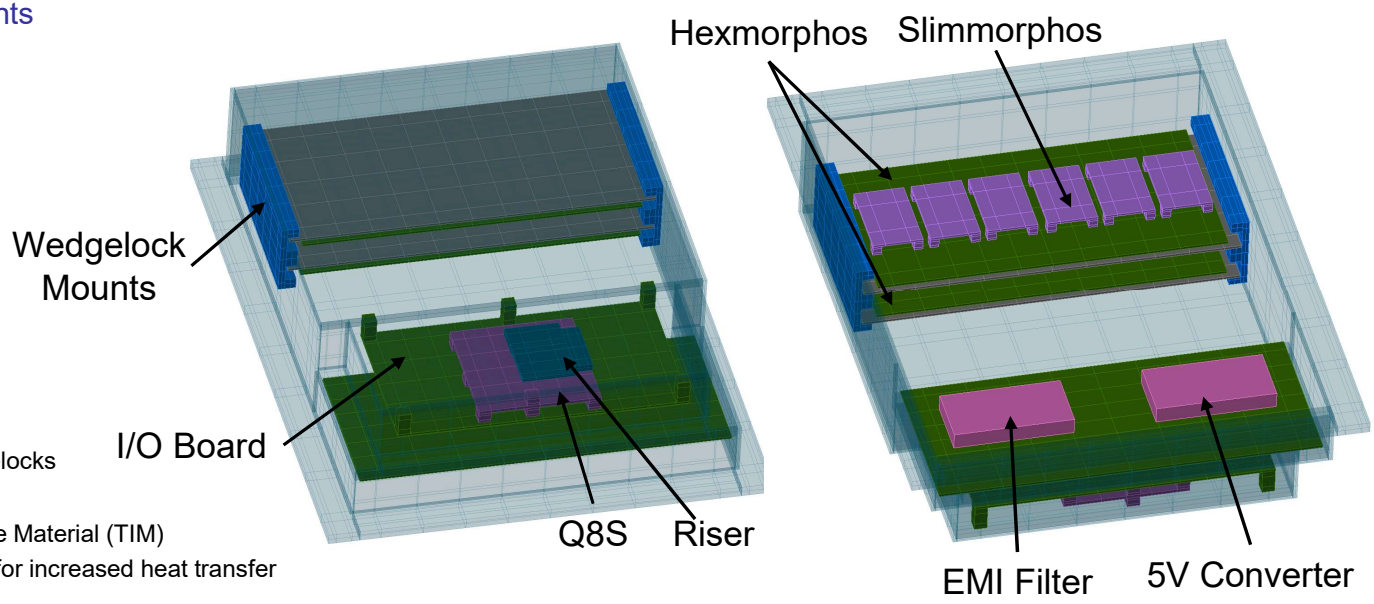
CDR Thermal Analysis & Design: Spacecraft

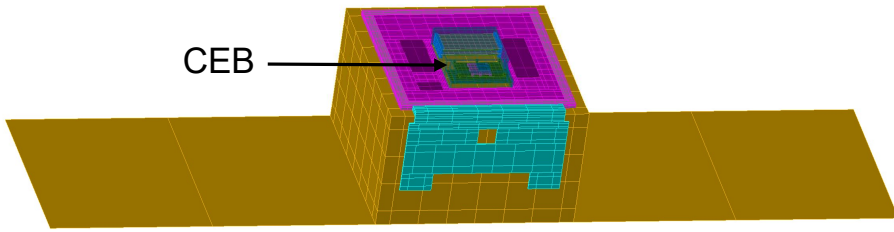
- SFL provided details
  - Materials and optical properties of spacecraft panels, internal truss, and solar arrays
  - Thermal contacts between bus components
  - Thermal contact between spacecraft bus panel and baseplate
  - Total bus heat dissipation, max and min
    - Bus instruments are mounted to internal instrument truss so heat dissipation is evenly distributed across all instrument truss surfaces in the simplified model



CDR Thermal Analysis & Design: Instrument CEB

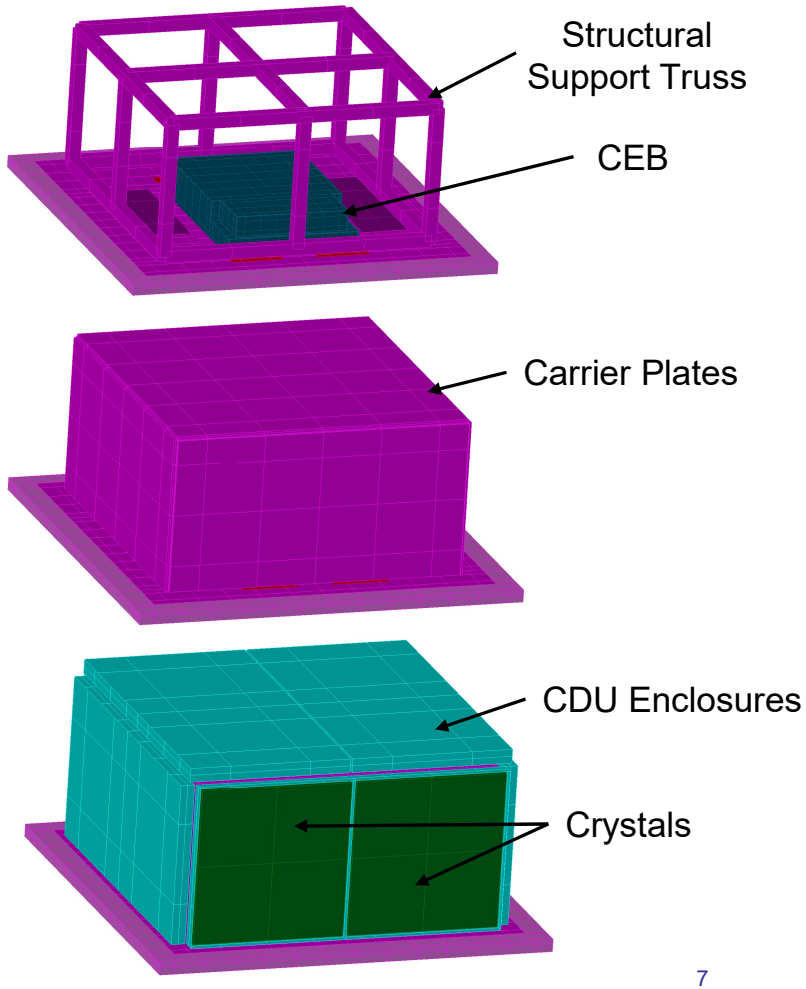
- Control Electronics Box (CEB) components
  - Hexmorphos x2
  - Slimmorphos x12
  - Power Board
    - 5V converter
    - EMI filter
  - I/O Board
  - Xiphos Q8S processor
  - Standoffs
- Key design aspects
  - Hexmorphos
    - Mounted to aluminum mounting plane
    - Al mounting plane mounted via Wedgelocks
  - Xiphos Q8S
    - Using CoolZorb Ultra Thermal Interface Material (TIM)
    - A riser is machined into the enclosure for increased heat transfer
  - CEB mounted to baseplate
  - Thermal contacts
    - Heat transfer through Wedgelocks is based on specific part number datasheet
    - Heat transfer through TIM is based on material datasheet and compression
    - Power board is bolted directly to enclosure shelf
    - Contacts between boards and standoffs are based on bolting parameters (bolt number, bolt diameter, torque, and contact area)
  - Material properties
    - Printed Circuit Boards (PCBs) thermophysical properties are anisotropic and based on specific copper content of each board





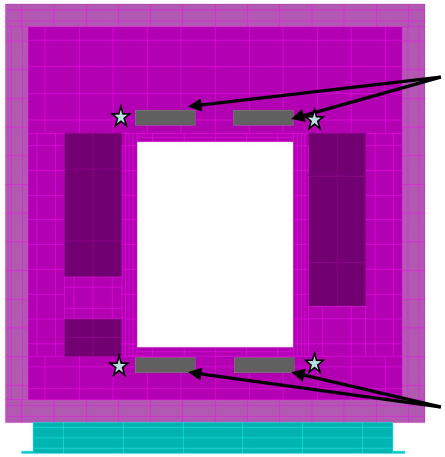
CDR Thermal Analysis & Design: Instrument CDUs

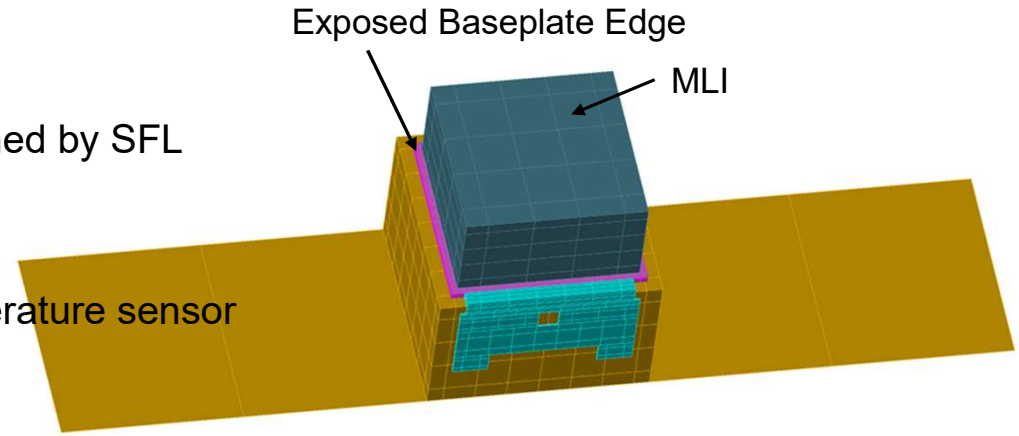
- Crystal Detector Units (CDUs) components
  - Enclosures
  - Crystals – Sodium Iodide
- Support structure components
  - Baseplate
  - Structural support truss
- Key design aspects
  - Baseplate is based on NRL design CAD
  - Structural support including truss and carrier plates are assumptions
  - Thermal contacts
    - Thermal contacts between truss, carrier plates, and CDU enclosures are assumed
    - Thermal contacts between crystals and enclosure are based on preliminary design of CDU



CDR Thermal Analysis & Design: Passive TCS

- Radiator
  - Designed by SFL as part of spacecraft design
  - Outward facing coating = Z93 white paint (α=0.17, ε=0.92)
- MLI
  - Modeled effective emissivity ε*=0.05
  - Outer layer = aluminized beta cloth (α=0.22, ε=0.3)
  - MLI coverage leaves 1'' of baseplate perimeter exposed
    - Exposed portion of baseplate is covered with silver-Teflon tape (α=0.05, ε=0.68)
    - Effectively adds radiator area
- Heaters
  - Locations determined by NRL, parameters defined by SFL
  - Four 1x4'' Kapton heaters on baseplate
  - Set points off/on = -21/-23C
  - Each heater is controlled by an individual temperature sensor next to the heater location





CDR Thermal Analysis & Design: Environments

- Environments are bracketed by Worst-Case-Cold (WCC) and Worst-Case-Hot (WCH) assumptions
- Model Cases include:
  - WCH Operational
  - WCC Operational
  - WCC Non-Operational
    - Instrument heat dissipation is 0W, spacecraft heat dissipation is the WCC assumption

SiPM and LT1801 are components in CDU

Component	Quantity	WCC	WCH
Hexmorpho Board (each)	2	2.97	4.00
IO Board	1	0.60	1.15
SiPM (each)	12	0.088	1.223
LT1801 (each)			
Power Board - 30V Converter	1	0.91	3.66
Power Board - 5V Converter	1	5.01	6.41
Power Board - EMI filter	1	0.21	0.46
Power Board +/-5V Converter	1	1.29	1.48
Q8S Board	1	3.08	7.48
Slimmorpho Board (each)	12	0.15	0.15
Total Instrument power		19.89	45.10
Bus Power	1	29.97	37.37

Environment	WCC	WCH
Altitude [km]	545	545
Beta Angle [°]	0	67
Inclination [°]	0	44
RA of Ascending Node [°]	0	180
Solar Flux [W/m2]	1322	1414
Earth Albedo	0.24	0.36
Earth IR Planetshine [W/m2]	226	242

CDR Thermal Analysis & Design: Results

- CDR Margin: +/-10C

[°C]	Operational Limits		Non-Operational Limits		WCH Operational		WCC Operational (heaters)		WCC Non-Operational (heaters)	
Component	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**
Baseplate	40	-30	45	-30	14.54	5.02	-19.32	**-24.71**	**-22.81**	**-28.33**
All Crystals	30	-25	45	-30	17.46	14.83	**-20.86**	**-21.39**	**-24.64**	**-25.17**
Q8S	60	-40	60	-40	22.51	17.84	-14.86	-18.03	-24.84	-25.68
Power Board	125	-55	125	-55	23.51	14.18	-11.83	-19.75	-24.96	-26.17
I/O Board	80	-40	80	-40	26.64	24.27	-11.92	-14.11	-24.84	-25.61
DC Converter - 5V	125	-55	125	-55	42.25	41.93	3.26	2.09	-25.16	-26.00
EMI Filter	125	-55	125	-55	19.21	18.93	-16.00	-17.18	-25.22	-25.92
Slim Morphos	60	-40	60	-40	33.08	28.58	-2.15	-7.02	-24.13	-24.77
Hex Morphos	70	-40	70	-40	26.45	23.62	-9.72	-12.77	-24.03	-24.84
Heater 1A Duty Cycle	80%				n/a		91%		100%	
Heater 1B Duty Cycle	80%				n/a		67%		100%	
Heater 2A Duty Cycle	80%				n/a		0%		100%	
Heater 2B Duty Cycle	80%				n/a		0%		100%	

	> 10 °C margin
	5 to 10 °C margin
	0 to 5 °C margin
	outside limits

- Observations to note:
  - In WCC environments, crystals are cold despite heaters turning on
  - Baseplate “requirement” is more of a perceived design solution than a hardware limit

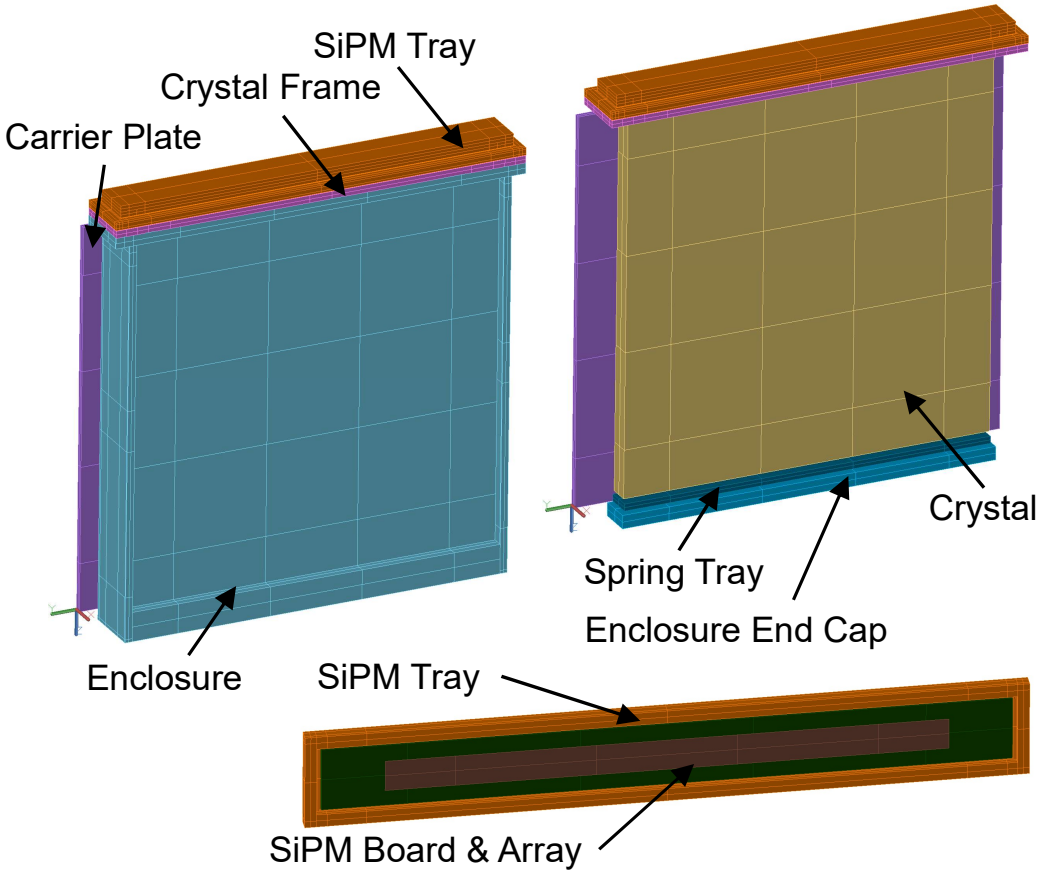
CDR Thermal Analysis & Design: Known Deficiencies

- CDU and structural support truss is low fidelity
  - The CDUs are critical science-measuring components, yet represented in low fidelity
  - The CDU design down-select was completed recently prior to CDR
- MLI coverage is unreliable
  - Graphical representation of the MLI does not account for significant thickness
  - The attachment of the MLI to the baseplate would need to be very precise to expose the exact amount of baseplate needing to be exposed
- Heaters are designed to control the baseplate temperature within the baseplate temperature limit defined in the requirements, not to control the CDU temperatures within limits
- These design deficiencies were known prior to CDR, however the decision was made to update the fidelity of the CDUs and structural support post-CDR, after CDU design down-select, and use the updated model to adjust the TCS

Post-CDR Thermal Analysis & Design: Instrument CDUs

- The CDU was modeled in greater detail as a separate thermal model and block-referenced into the system model for each CDU
  - Geometry based on updated CAD design
  - Crystal material updated to Cesium Iodide

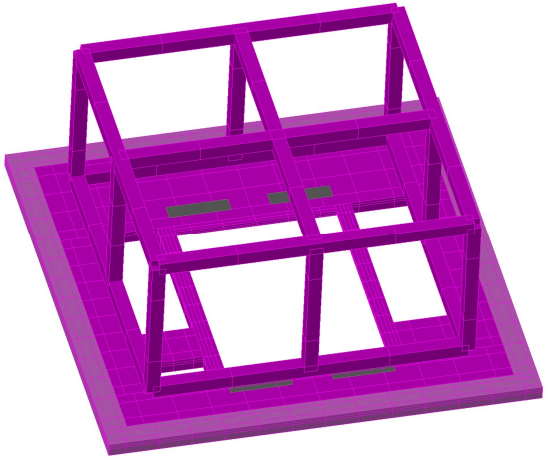
Model Aspect	CDR	Post-CDR
Components represented with geometry	Crystal Enclsoure Carrier Plate	Crystal Enclosure Carrier Plate Carrier Plate Shield SiPM Tray SiPM Board & Array Crystal Frame Enclosure End Cap Spring Tray
Heat Dissipation Location	End surface of enclosure	SiPM Array
Heat Dissipation WCC (each CDU)	0.088 W	1.223 W
Heat Dissipation WCH (each CDU)	0.174 W	1.111 W
TD Nodes	36	843
Thermal Contacts between Crystal and Enclosure	Based on previous shim materials	Based on updated shim materials
Thermal Contacts between Other Components	Assumed	Calculated based on bolting parameters and material



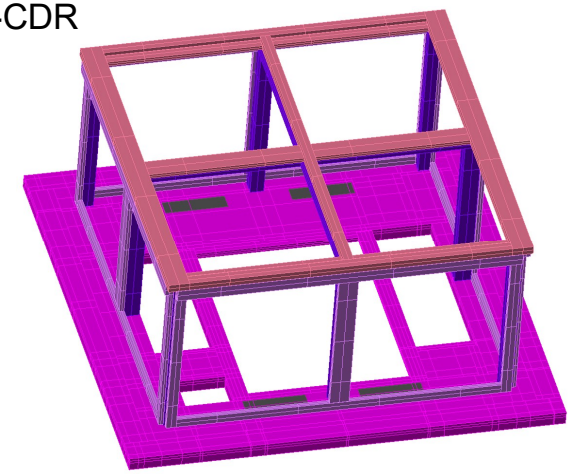
Post-CDR Thermal Analysis & Design: Instrument CDUs

- The instrument baseplate and structural support truss was also modeled in greater detail
  - Baseplate
    - Based on the updated CAD from NRL
    - Mass of model was adjusted to represent the mass of the hardware
  - Structural support truss
    - Based on the updated CAD from NRL
    - Individual components are represented
    - Mass of model was adjusted to represent the mass of the hardware
    - Thermal contacts between each component were calculated based on the specific bolting parameters of number of bolts, bolt diameter, torque, and contact area

CDR



Post-CDR



Post-CDR Thermal Analysis & Design: Heat Dissipations

- CEB heat dissipations were refined with updated power-draw measurements
- SiPM heat dissipation was reduced based on the design change to the array size
- 15% growth margin included at CDR for WCH was also removed

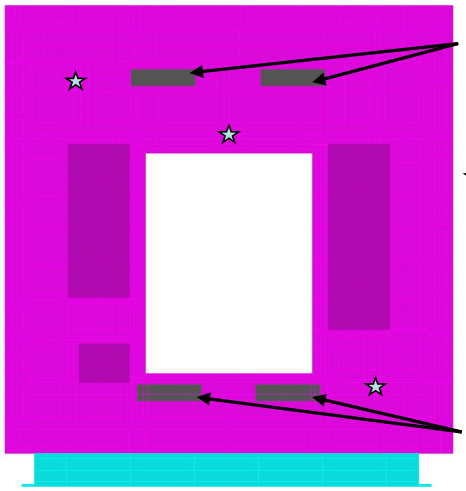
		CDR [W]		Post-CDR [W]	
Component	**Quantity**	**WCC**	**WCH**	**WCC**	**WCH**
Hexmorpho Board (each)	2	2.97	4.00	2.99	2.99
IO Board	1	0.60	1.15	0.6	1
SiPM (each)	12	0.088	1.223	0.013	0.950
LT1801 (each)				0.161	0.161
Power Board - 30V Converter	1	0.91	3.66	0.91	3.18
Power Board - 5V Converter	1	5.01	6.41	5.01	5.57
Power Board - EMI filter	1	0.21	0.46	0.21	0.4
Power Board +/-5V Converter	1	1.29	1.48	1.29	1.29
Q8S Board	1	3.08	7.48	3.08	6.5
Slimmorpho Board (each)	12	0.15	0.15	0.15	0.15
Total Instrument power		19.89	45.10	20.96	39.05
Bus Power	1	29.97	37.37	29.97	37.37

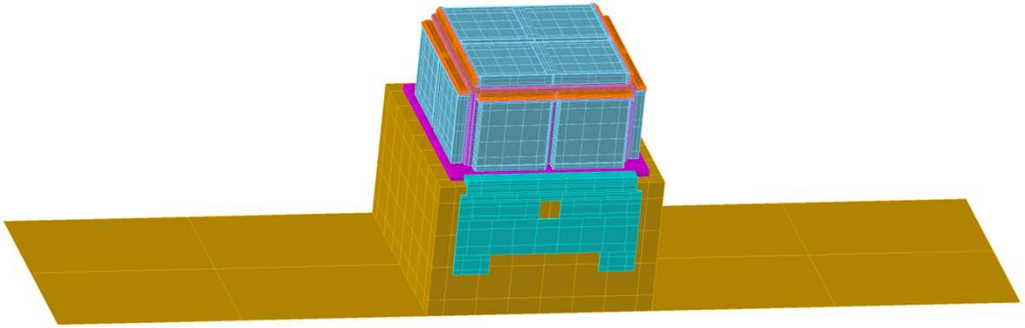
Post-CDR Thermal Analysis & Design: Spacecraft

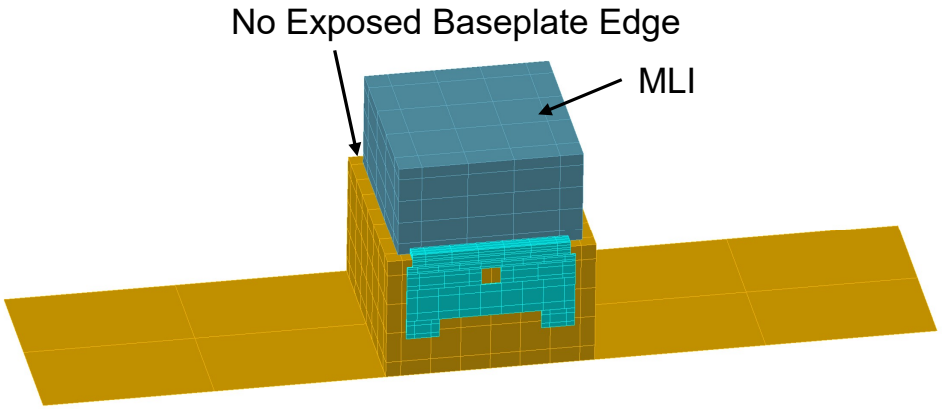
- Spacecraft updates based on inputs from SFL
  - Thermal contacts
    - Instrument baseplate to the spacecraft +x panel updated from 1.51 W/C to 2.1 W/C
    - Spacecraft panels to the solar arrays
    - Interfaces between the spacecraft panels
    - Instrument baseplate to the radiator
  - Materials of the spacecraft panels
  - Optical properties of the spacecraft panels

Post-CDR Thermal Analysis & Design: Passive TCS

- MLI
  - Outer layer = beta cloth (α=.15, ε=0.88)
    - Result of trade study comparing multiple outer layers
  - MLI covers entire baseplate
    - Reduces uncertainty of exposed area
    - Makes attachment options easier
    - No longer need silver-Teflon tape on baseplate perimeter
- Heaters
  - Locations updated based on NRL design update
  - Four 1x4" heaters on baseplate
  - Set points off/on = -21/-23C
  - All heaters are controlled by ALL temperature sensors







Post-CDR Thermal Analysis & Design: Results Cases

- Results are shown in order of following changes to show the impact of each change

	Case Number	MLI location	CDU, Support Structure Models	Heat Dissipation Values	MLI Outer Layer	Spacecraft Updates
CDR	1	CDR	CDR	CDR	CDR	CDR
	2	Post-CDR	CDR	CDR	CDR	CDR
	3	Post-CDR	Post-CDR	CDR	CDR	CDR
	4	Post-CDR	Post-CDR	Post-CDR	CDR	CDR
	5	Post-CDR	Post-CDR	Post-CDR	Post-CDR	CDR
Post-CDR	6	Post-CDR	Post-CDR	Post-CDR	Post-CDR	Post-CDR

- Margin was updated from +/-10C to +10/-5C because the instrument is heater controlled

Post-CDR Thermal Analysis & Design: Results

WCH Op

WCC Op

WCC Non-Op

WCH			CDR										Post-CDR	
	Operational Limits		1		2		3		4		5		6	
Component	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Baseplate	40	-30	14.54	5.02	20.08	10.55	22.42	14.71	21.55	13.82	18.10	10.72	18.70	11.35
Crystals	30	-25	17.46	14.83	**22.57**	**20.04**	**24.03**	**20.13**	**21.07**	17.30	17.16	13.89	17.76	14.42
SiPM	30	-25					**24.50**	**21.92**	**21.49**	19.00	17.59	15.39	18.19	15.95
Q8S	60	-40	22.51	17.84	27.98	23.42	29.77	26.02	28.88	25.12	25.59	21.83	18.70	11.35
Power Board	125	-55	23.51	14.18	28.93	19.76	30.77	23.07	29.88	22.17	26.64	18.90	26.21	22.45
I/O Board	80	-40	26.64	24.27	32.01	29.72	33.21	31.44	32.33	30.56	29.10	27.32	27.26	19.53
DC Converter - 5V	125	-55	42.25	41.93	47.63	47.40	47.00	47.00	46.12	46.12	42.90	42.90	23.58	23.58
EMI Filter	125	-55	19.21	18.93	24.71	24.51	27.13	27.13	26.23	26.23	22.96	22.96	33.33	31.33
Slim morphos	60	-40	33.08	28.58	38.45	34.06	38.63	34.88	37.77	34.01	34.49	30.73	35.10	26.48
Hex Morphos	70	-40	26.45	23.62	31.95	29.23	32.08	30.11	31.20	29.23	27.84	25.87	29.71	26.74
WCC Operational (heaters)														
	Operational Limits		1		2		3		4		5		6	
Component	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Baseplate	40	-30	-19.32	-24.71	-18.41	-24.22	-15.92	-20.93	-15.24	-20.30	-18.02	-23.23	-16.80	-20.86
Crystals	30	-25	**-20.86**	**-21.39**	-19.59	**-20.32**	-17.57	-19.08	-16.81	-18.39	-19.84	**-21.56**	-18.29	-19.42
SiPM	30	-25					-18.42	-17.94	-16.72	-18.04	**-20.54**	**-20.43**	-18.22	-19.08
Q8S	60	-40	-14.86	-18.03	-14.31	-17.34	-11.60	-14.00	-10.93	-13.33	-13.63	-16.39	-12.32	-14.32
Power Board	125	-55	-11.83	-19.75	-11.43	-19.23	-8.74	-15.80	-8.08	-15.13	-10.74	-18.18	-9.43	-16.07
I/O Board	80	-40	-11.92	-14.11	-11.31	-13.43	-8.63	-10.14	-7.97	-9.48	-10.64	-12.51	-9.32	-10.50
DC Converter - 5V	125	-55	3.26	2.09	3.71	2.63	6.38	5.97	7.04	6.62	4.39	3.61	5.70	5.70
EMI Filter	125	-55	-16.00	-17.18	-15.61	-16.61	-12.85	-13.22	-12.19	-12.55	-14.87	-15.61	-13.54	-13.54
Slim morphos	60	-40	-2.15	-7.02	-1.29	-6.00	1.29	-2.88	1.99	-2.19	-0.67	-5.20	0.58	-3.29
Hex Morphos	70	-40	-9.72	-12.77	-8.85	-11.74	-6.21	-8.54	-5.49	-7.82	-8.22	-10.91	-6.95	-8.94
Heater 1A Duty Cycle	80%		91%		0%		0%		0%		0%		0%	
Heater 1B Duty Cycle	80%		67%		0%		0%		0%		0%		0%	
Heater 2A Duty Cycle	80%		0%		0%		0%		0%		0%		0%	
Heater 2B Duty Cycle	80%		0%		0%		0%		0%		0%		0%	
WCC Non-Operational (heaters)														
	Non-Operational Limits		1		2		3		4		5		6	
Component	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Baseplate	45	-30	-22.81	**-28.33**	-20.79	**-26.65**	-19.08	-23.53	-19.08	-23.53	-19.33	**-25.62**	-19.44	-22.75
Crystals	45	-30	-24.64	**-25.17**	-23.11	-23.63	-18.33	-21.22	-18.33	-21.22	-18.92	-23.42	-18.73	-20.96
SiPM	45	-30					-18.89	-18.44	-18.89	-18.44	-19.43	-20.80	-18.24	-19.77
Q8S	60	-40	-24.84	-25.68	-22.87	-24.24	-20.73	-21.39	-20.73	-21.39	-21.03	-23.50	-20.75	-20.78
Power Board	125	-55	-24.96	-26.17	-23.05	-24.66	-20.81	-21.73	-20.81	-21.73	-21.15	-23.83	-20.89	-21.10
I/O Board	80	-40	-24.84	-25.61	-22.88	-24.18	-20.71	-21.35	-20.71	-21.35	-21.00	-23.46	-20.71	-20.79
DC Converter - 5V	125	-55	-25.16	-26.00	-23.21	-24.51	-20.94	-21.59	-20.94	-21.59	-21.25	-23.69	-20.99	-20.99
EMI Filter	125	-55	-25.22	-25.92	-23.22	-24.47	-20.96	-21.56	-20.96	-21.56	-21.24	-23.67	-20.99	-20.99
Slim morphos	60	-40	-24.13	-24.77	-22.15	-23.42	-20.26	-20.80	-20.26	-20.80	-20.54	-22.96	-20.21	-20.22
Hex Morphos	70	-40	-24.03	-24.84	-22.09	-23.45	-20.21	-20.86	-20.21	-20.86	-20.54	-22.99	-20.19	-20.22
Heater 1A Duty Cycle	80%		100%		100%		0%		0%		11%		12%	
Heater 1B Duty Cycle	80%		100%		100%		0%		0%		11%		12%	
Heater 2A Duty Cycle	80%		100%		56%		0%		0%		11%		12%	
Heater 2B Duty Cycle	80%		100%		91%		0%		0%		11%		12%	

	within limits with margin
	outside limits with margin
	outside limits

Post-CDR Thermal Analysis & Design: Results

WCH Op

WCH			CDR										Post-CDR	
	Operational Limits		1 →		2		3		4		5		6	
Component	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Baseplate	40	-30	14.54	5.02	20.08	10.55	22.42	14.71	21.55	13.82	18.10	10.72	18.70	11.35
Crystals	30	-25	17.46	14.83	**22.57**	**20.04**	**24.03**	**20.13**	**21.07**	17.30	17.16	13.89	17.76	14.42
SiPM	30	-25					**24.50**	**21.92**	**21.49**	19.00	17.59	15.39	18.19	15.95
Q8S	60	-40	22.51	17.84	27.98	23.42	29.77	26.02	28.88	25.12	25.59	21.83	18.70	11.35
Power Board	125	-55	23.51	14.18	28.93	19.76	30.77	23.07	29.88	22.17	26.64	18.90	26.21	22.45
I/O Board	80	-40	26.64	24.27	32.01	29.72	33.21	31.44	32.33	30.56	29.10	27.32	27.26	19.53
DC Converter - 5V	125	-55	42.25	41.93	47.63	47.40	47.00	47.00	46.12	46.12	42.90	42.90	23.58	23.58
EMI Filter	125	-55	19.21	18.93	24.71	24.51	27.13	27.13	26.23	26.23	22.96	22.96	33.33	31.33
Slim morphos	60	-40	33.08	28.58	38.45	34.06	38.63	34.88	37.77	34.01	34.49	30.73	35.10	26.48
Hex Morphos	70	-40	26.45	23.62	31.95	29.23	32.08	30.11	31.20	29.23	27.84	25.87	29.71	26.74

WCC Op

WCC Operational (heaters)														
	Operational Limits		1 →		2		3		4		5		6	
Component	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Baseplate	40	-30	-19.32	-24.71	-18.41	-24.22	-15.92	-20.93	-15.24	-20.30	-18.02	-23.23	-16.80	-20.86
Crystals	30	-25	**-20.86**	**-21.39**	-19.59	**-20.32**	-17.57	-19.08	-16.81	-18.39	-19.84	**-21.56**	-18.29	-19.42
SiPM	30	-25					-18.42	-17.94	-16.72	-18.04	**-20.54**	**-20.43**	-18.22	-19.08
Q8S	60	-40	-14.86	-18.03	-14.31	-17.34	-11.60	-14.00	-10.93	-13.33	-13.63	-16.39	-12.32	-14.32
Power Board	125	-55	-11.83	-19.75	-11.43	-19.23	-8.74	-15.80	-8.08	-15.13	-10.74	-18.18	-9.43	-16.07
I/O Board	80	-40	-11.92	-14.11	-11.31	-13.43	-8.63	-10.14	-7.97	-9.48	-10.64	-12.51	-9.32	-10.50
DC Converter - 5V	125	-55	3.26	2.09	3.71	2.63	6.38	5.97	7.04	6.62	4.39	3.61	5.70	5.70
EMI Filter	125	-55	-16.00	-17.18	-15.61	-16.61	-12.85	-13.22	-12.19	-12.55	-14.87	-15.61	-13.54	-13.54
Slim morphos	60	-40	-2.15	-7.02	-1.29	-6.00	1.29	-2.88	1.99	-2.19	-0.67	-5.20	0.58	-3.29
Hex Morphos	70	-40	-9.72	-12.77	-8.85	-11.74	-6.21	-8.54	-5.49	-7.82	-8.22	-10.91	-6.95	-8.94
Heater 1A Duty Cycle	80%		91%		0%		0%		0%		0%		0%	
Heater 1B Duty Cycle	80%		67%		0%		0%		0%		0%		0%	
Heater 2A Duty Cycle	80%		0%		0%		0%		0%		0%		0%	
Heater 2B Duty Cycle	80%		0%		0%		0%		0%		0%		0%	

WCC Non-Op

WCC Non-Operational (heaters)														
	Non-Operational Limits		1 →		2		3		4		5		6	
Component	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Baseplate	45	-30	-22.81	**-28.33**	-20.79	**-26.65**	-19.08	-23.53	-19.08	-23.53	-19.33	**-25.62**	-19.44	-22.75
Crystals	45	-30	-24.64	**-25.17**	-23.11	-23.63	-18.33	-21.22	-18.33	-21.22	-18.92	-23.42	-18.73	-20.96
SiPM	45	-30					-18.89	-18.44	-18.89	-18.44	-19.43	-20.80	-18.24	-19.77
Q8S	60	-40	-24.84	-25.68	-22.87	-24.24	-20.73	-21.39	-20.73	-21.39	-21.03	-23.50	-20.75	-20.78
Power Board	125	-55	-24.96	-26.17	-23.05	-24.66	-20.81	-21.73	-20.81	-21.73	-21.15	-23.83	-20.89	-21.10
I/O Board	80	-40	-24.84	-25.61	-22.88	-24.18	-20.71	-21.35	-20.71	-21.35	-21.00	-23.46	-20.71	-20.79
DC Converter - 5V	125	-55	-25.16	-26.00	-23.21	-24.51	-20.94	-21.59	-20.94	-21.59	-21.25	-23.69	-20.99	-20.99
EMI Filter	125	-55	-25.22	-25.92	-23.22	-24.47	-20.96	-21.56	-20.96	-21.56	-21.24	-23.67	-20.99	-20.99
Slim morphos	60	-40	-24.13	-24.77	-22.15	-23.42	-20.26	-20.80	-20.26	-20.80	-20.54	-22.96	-20.21	-20.22
Hex Morphos	70	-40	-24.03	-24.84	-22.09	-23.45	-20.21	-20.86	-20.21	-20.86	-20.54	-22.99	-20.19	-20.22
Heater 1A Duty Cycle	80%		100%		100%		0%		0%		11%		12%	
Heater 1B Duty Cycle	80%		100%		100%		0%		0%		11%		12%	
Heater 2A Duty Cycle	80%		100%		56%		0%		0%		11%		12%	
Heater 2B Duty Cycle	80%		100%		91%		0%		0%		11%		12%	

	within limits with margin
	outside limits with margin
	outside limits

- Case 1 to 2:
  - MLI Coverage updated to cover entire baseplate
  - WCH: CDU temps increase
  - WCC: CDU temps increase, heater power decrease

WCC Non-Op

Post-CDR Thermal Analysis & Design: Results

WCH Op

WCH			CDR												Post-CDR	
	Operational Limits		1		2		→ 3		4		5		6			
Component	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min		
Baseplate	40	-30	14.54	5.02	20.08	10.55	22.42	14.71	21.55	13.82	18.10	10.72	18.70	11.35		
Crystals	30	-25	17.46	14.83	**22.57**	**20.04**	**24.03**	**20.13**	**21.07**	17.30	17.16	13.89	17.76	14.42		
SiPM	30	-25					**24.50**	**21.92**	**21.49**	19.00	17.59	15.39	18.19	15.95		
Q8S	60	-40	22.51	17.84	27.98	23.42	29.77	26.02	28.88	25.12	25.59	21.83	18.70	11.35		
Power Board	125	-55	23.51	14.18	28.93	19.76	30.77	23.07	29.88	22.17	26.64	18.90	26.21	22.45		
I/O Board	80	-40	26.64	24.27	32.01	29.72	33.21	31.44	32.33	30.56	29.10	27.32	27.26	19.53		
DC Converter - 5V	125	-55	42.25	41.93	47.63	47.40	47.00	47.00	46.12	46.12	42.90	42.90	23.58	23.58		
EMI Filter	125	-55	19.21	18.93	24.71	24.51	27.13	27.13	26.23	26.23	22.96	22.96	33.33	31.33		
Slim morphos	60	-40	33.08	28.58	38.45	34.06	38.63	34.88	37.77	34.01	34.49	30.73	35.10	26.48		
Hex Morphos	70	-40	26.45	23.62	31.95	29.23	32.08	30.11	31.20	29.23	27.84	25.87	29.71	26.74		

WCC Op

WCC Operational (heaters)																
	Operational Limits		1		2		→ 3		4		5		6			
Component	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min		
Baseplate	40	-30	-19.32	-24.71	-18.41	-24.22	-15.92	-20.93	-15.24	-20.30	-18.02	-23.23	-16.80	-20.86		
Crystals	30	-25	**-20.86**	**-21.39**	-19.59	**-20.32**	-17.57	-19.08	-16.81	-18.39	-19.84	**-21.56**	-18.29	-19.42		
SiPM	30	-25					-18.42	-17.94	-16.72	-18.04	**-20.54**	**-20.43**	-18.22	-19.08		
Q8S	60	-40	-14.86	-18.03	-14.31	-17.34	-11.60	-14.00	-10.93	-13.33	-13.63	-16.39	-12.32	-14.32		
Power Board	125	-55	-11.83	-19.75	-11.43	-19.23	-8.74	-15.80	-8.08	-15.13	-10.74	-18.18	-9.43	-16.07		
I/O Board	80	-40	-11.92	-14.11	-11.31	-13.43	-8.63	-10.14	-7.97	-9.48	-10.64	-12.51	-9.32	-10.50		
DC Converter - 5V	125	-55	3.26	2.09	3.71	2.63	6.38	5.97	7.04	6.62	4.39	3.61	5.70	5.70		
EMI Filter	125	-55	-16.00	-17.18	-15.61	-16.61	-12.85	-13.22	-12.19	-12.55	-14.87	-15.61	-13.54	-13.54		
Slim morphos	60	-40	-2.15	-7.02	-1.29	-6.00	1.29	-2.88	1.99	-2.19	-0.67	-5.20	0.58	-3.29		
Hex Morphos	70	-40	-9.72	-12.77	-8.85	-11.74	-6.21	-8.54	-5.49	-7.82	-8.22	-10.91	-6.95	-8.94		
Heater 1A Duty Cycle	80%		91%		0%		0%		0%		0%		0%			
Heater 1B Duty Cycle	80%		67%		0%		0%		0%		0%		0%			
Heater 2A Duty Cycle	80%		0%		0%		0%		0%		0%		0%			
Heater 2B Duty Cycle	80%		0%		0%		0%		0%		0%		0%			

WCC Non-Op

WCC Non-Operational (heaters)																
	Non-Operational Limits		1		2		→ 3		4		5		6			
Component	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min		
Baseplate	45	-30	-22.81	**-28.33**	-20.79	**-26.65**	-19.08	-23.53	-19.08	-23.53	-19.33	**-25.62**	-19.44	-22.75		
Crystals	45	-30	-24.64	**-25.17**	-23.11	-23.63	-18.33	-21.22	-18.33	-21.22	-18.92	-23.42	-18.73	-20.96		
SiPM	45	-30					-18.89	-18.44	-18.89	-18.44	-19.43	-20.80	-18.24	-19.77		
Q8S	60	-40	-24.84	-25.68	-22.87	-24.24	-20.73	-21.39	-20.73	-21.39	-21.03	-23.50	-20.75	-20.78		
Power Board	125	-55	-24.96	-26.17	-23.05	-24.66	-20.81	-21.73	-20.81	-21.73	-21.15	-23.83	-20.89	-21.10		
I/O Board	80	-40	-24.84	-25.61	-22.88	-24.18	-20.71	-21.35	-20.71	-21.35	-21.00	-23.46	-20.71	-20.79		
DC Converter - 5V	125	-55	-25.16	-26.00	-23.21	-24.51	-20.94	-21.59	-20.94	-21.59	-21.25	-23.69	-20.99	-20.99		
EMI Filter	125	-55	-25.22	-25.92	-23.22	-24.47	-20.96	-21.56	-20.96	-21.56	-21.24	-23.67	-20.99	-20.99		
Slim morphos	60	-40	-24.13	-24.77	-22.15	-23.42	-20.26	-20.80	-20.26	-20.80	-20.54	-22.96	-20.21	-20.22		
Hex Morphos	70	-40	-24.03	-24.84	-22.09	-23.45	-20.21	-20.86	-20.21	-20.86	-20.54	-22.99	-20.19	-20.22		
Heater 1A Duty Cycle	80%		100%		100%		0%		0%		11%		12%			
Heater 1B Duty Cycle	80%		100%		100%		0%		0%		11%		12%			
Heater 2A Duty Cycle	80%		100%		56%		0%		0%		11%		12%			
Heater 2B Duty Cycle	80%		100%		91%		0%		0%		11%		12%			

	within limits with margin
	outside limits with margin
	outside limits

- Case 2 to 3:
  - CDU and instrument structural support fidelity increase
  - WCH: CDU temps increase
  - WCC: CDU temps increase, heater power decrease

Post-CDR Thermal Analysis & Design: Results

WCH Op

WCH			CDR						Post-CDR					
	Operational Limits		1		2		3 → 4				5		6	
Component	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Baseplate	40	-30	14.54	5.02	20.08	10.55	22.42	14.71	21.55	13.82	18.10	10.72	18.70	11.35
Crystals	30	-25	17.46	14.83	**22.57**	**20.04**	**24.03**	**20.13**	**21.07**	17.30	17.16	13.89	17.76	14.42
SiPM	30	-25					**24.50**	**21.92**	**21.49**	19.00	17.59	15.39	18.19	15.95
Q8S	60	-40	22.51	17.84	27.98	23.42	29.77	26.02	28.88	25.12	25.59	21.83	18.70	11.35
Power Board	125	-55	23.51	14.18	28.93	19.76	30.77	23.07	29.88	22.17	26.64	18.90	26.21	22.45
I/O Board	80	-40	26.64	24.27	32.01	29.72	33.21	31.44	32.33	30.56	29.10	27.32	27.26	19.53
DC Converter - 5V	125	-55	42.25	41.93	47.63	47.40	47.00	47.00	46.12	46.12	42.90	42.90	23.58	23.58
EMI Filter	125	-55	19.21	18.93	24.71	24.51	27.13	27.13	26.23	26.23	22.96	22.96	33.33	31.33
Slim morphos	60	-40	33.08	28.58	38.45	34.06	38.63	34.88	37.77	34.01	34.49	30.73	35.10	26.48
Hex Morphos	70	-40	26.45	23.62	31.95	29.23	32.08	30.11	31.20	29.23	27.84	25.87	29.71	26.74

WCC Op

WCC Operational (heaters)														
	Operational Limits		1		2		3 → 4				5		6	
Component	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Baseplate	40	-30	-19.32	-24.71	-18.41	-24.22	-15.92	-20.93	-15.24	-20.30	-18.02	-23.23	-16.80	-20.86
Crystals	30	-25	**-20.86**	**-21.39**	-19.59	**-20.32**	-17.57	-19.08	-16.81	-18.39	-19.84	**-21.56**	-18.29	-19.42
SiPM	30	-25					-18.42	-17.94	-16.72	-18.04	**-20.54**	**-20.43**	-18.22	-19.08
Q8S	60	-40	-14.86	-18.03	-14.31	-17.34	-11.60	-14.00	-10.93	-13.33	-13.63	-16.39	-12.32	-14.32
Power Board	125	-55	-11.83	-19.75	-11.43	-19.23	-8.74	-15.80	-8.08	-15.13	-10.74	-18.18	-9.43	-16.07
I/O Board	80	-40	-11.92	-14.11	-11.31	-13.43	-8.63	-10.14	-7.97	-9.48	-10.64	-12.51	-9.32	-10.50
DC Converter - 5V	125	-55	3.26	2.09	3.71	2.63	6.38	5.97	7.04	6.62	4.39	3.61	5.70	5.70
EMI Filter	125	-55	-16.00	-17.18	-15.61	-16.61	-12.85	-13.22	-12.19	-12.55	-14.87	-15.61	-13.54	-13.54
Slim morphos	60	-40	-2.15	-7.02	-1.29	-6.00	1.29	-2.88	1.99	-2.19	-0.67	-5.20	0.58	-3.29
Hex Morphos	70	-40	-9.72	-12.77	-8.85	-11.74	-6.21	-8.54	-5.49	-7.82	-8.22	-10.91	-6.95	-8.94
Heater 1A Duty Cycle	80%		91%		0%		0%		0%		0%		0%	
Heater 1B Duty Cycle	80%		67%		0%		0%		0%		0%		0%	
Heater 2A Duty Cycle	80%		0%		0%		0%		0%		0%		0%	
Heater 2B Duty Cycle	80%		0%		0%		0%		0%		0%		0%	

WCC Non-Op

WCC Non-Operational (heaters)														
	Non-Operational Limits		1		2		3 → 4				5		6	
Component	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Baseplate	45	-30	-22.81	**-28.33**	-20.79	**-26.65**	-19.08	-23.53	-19.08	-23.53	-19.33	**-25.62**	-19.44	-22.75
Crystals	45	-30	-24.64	**-25.17**	-23.11	-23.63	-18.33	-21.22	-18.33	-21.22	-18.92	-23.42	-18.73	-20.96
SiPM	45	-30					-18.89	-18.44	-18.89	-18.44	-19.43	-20.80	-18.24	-19.77
Q8S	60	-40	-24.84	-25.68	-22.87	-24.24	-20.73	-21.39	-20.73	-21.39	-21.03	-23.50	-20.75	-20.78
Power Board	125	-55	-24.96	-26.17	-23.05	-24.66	-20.81	-21.73	-20.81	-21.73	-21.15	-23.83	-20.89	-21.10
I/O Board	80	-40	-24.84	-25.61	-22.88	-24.18	-20.71	-21.35	-20.71	-21.35	-21.00	-23.46	-20.71	-20.79
DC Converter - 5V	125	-55	-25.16	-26.00	-23.21	-24.51	-20.94	-21.59	-20.94	-21.59	-21.25	-23.69	-20.99	-20.99
EMI Filter	125	-55	-25.22	-25.92	-23.22	-24.47	-20.96	-21.56	-20.96	-21.56	-21.24	-23.67	-20.99	-20.99
Slim morphos	60	-40	-24.13	-24.77	-22.15	-23.42	-20.26	-20.80	-20.26	-20.80	-20.54	-22.96	-20.21	-20.22
Hex Morphos	70	-40	-24.03	-24.84	-22.09	-23.45	-20.21	-20.86	-20.21	-20.86	-20.54	-22.99	-20.19	-20.22
Heater 1A Duty Cycle	80%		100%		100%		0%		0%		11%		12%	
Heater 1B Duty Cycle	80%		100%		100%		0%		0%		11%		12%	
Heater 2A Duty Cycle	80%		100%		56%		0%		0%		11%		12%	
Heater 2B Duty Cycle	80%		100%		91%		0%		0%		11%		12%	

	within limits with margin
	outside limits with margin
	outside limits

- Case 3 to 4:
  - Heat dissipation update
  - WCH: CDU temps decrease
  - WCC: CDU temps increase

Post-CDR Thermal Analysis & Design: Results

WCH Op

WCH			CDR										Post-CDR	
	Operational Limits		1		2		3		4		→ 5		6	
Component	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Baseplate	40	-30	14.54	5.02	20.08	10.55	22.42	14.71	21.55	13.82	18.10	10.72	18.70	11.35
Crystals	30	-25	17.46	14.83	**22.57**	**20.04**	**24.03**	**20.13**	**21.07**	17.30	17.16	13.89	17.76	14.42
SiPM	30	-25					**24.50**	**21.92**	**21.49**	19.00	17.59	15.39	18.19	15.95
Q8S	60	-40	22.51	17.84	27.98	23.42	29.77	26.02	28.88	25.12	25.59	21.83	18.70	11.35
Power Board	125	-55	23.51	14.18	28.93	19.76	30.77	23.07	29.88	22.17	26.64	18.90	26.21	22.45
I/O Board	80	-40	26.64	24.27	32.01	29.72	33.21	31.44	32.33	30.56	29.10	27.32	27.26	19.53
DC Converter - 5V	125	-55	42.25	41.93	47.63	47.40	47.00	47.00	46.12	46.12	42.90	42.90	23.58	23.58
EMI Filter	125	-55	19.21	18.93	24.71	24.51	27.13	27.13	26.23	26.23	22.96	22.96	33.33	31.33
Slim morphos	60	-40	33.08	28.58	38.45	34.06	38.63	34.88	37.77	34.01	34.49	30.73	35.10	26.48
Hex Morphos	70	-40	26.45	23.62	31.95	29.23	32.08	30.11	31.20	29.23	27.84	25.87	29.71	26.74

WCC Op

WCC Operational (heaters)														
	Operational Limits		1		2		3		4		→ 5		6	
Component	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Baseplate	40	-30	-19.32	-24.71	-18.41	-24.22	-15.92	-20.93	-15.24	-20.30	-18.02	-23.23	-16.80	-20.86
Crystals	30	-25	**-20.86**	**-21.39**	-19.59	**-20.32**	-17.57	-19.08	-16.81	-18.39	-19.84	**-21.56**	-18.29	-19.42
SiPM	30	-25					-18.42	-17.94	-16.72	-18.04	**-20.54**	**-20.43**	-18.22	-19.08
Q8S	60	-40	-14.86	-18.03	-14.31	-17.34	-11.60	-14.00	-10.93	-13.33	-13.63	-16.39	-12.32	-14.32
Power Board	125	-55	-11.83	-19.75	-11.43	-19.23	-8.74	-15.80	-8.08	-15.13	-10.74	-18.18	-9.43	-16.07
I/O Board	80	-40	-11.92	-14.11	-11.31	-13.43	-8.63	-10.14	-7.97	-9.48	-10.64	-12.51	-9.32	-10.50
DC Converter - 5V	125	-55	3.26	2.09	3.71	2.63	6.38	5.97	7.04	6.62	4.39	3.61	5.70	5.70
EMI Filter	125	-55	-16.00	-17.18	-15.61	-16.61	-12.85	-13.22	-12.19	-12.55	-14.87	-15.61	-13.54	-13.54
Slim morphos	60	-40	-2.15	-7.02	-1.29	-6.00	1.29	-2.88	1.99	-2.19	-0.67	-5.20	0.58	-3.29
Hex Morphos	70	-40	-9.72	-12.77	-8.85	-11.74	-6.21	-8.54	-5.49	-7.82	-8.22	-10.91	-6.95	-8.94
Heater 1A Duty Cycle	80%		91%		0%		0%		0%		0%		0%	
Heater 1B Duty Cycle	80%		67%		0%		0%		0%		0%		0%	
Heater 2A Duty Cycle	80%		0%		0%		0%		0%		0%		0%	
Heater 2B Duty Cycle	80%		0%		0%		0%		0%		0%		0%	

WCC Non-Op

WCC Non-Operational (heaters)														
	Non-Operational Limits		1		2		3		4		→ 5		6	
Component	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Baseplate	45	-30	-22.81	**-28.33**	-20.79	**-26.65**	-19.08	-23.53	-19.08	-23.53	-19.33	**-25.62**	-19.44	-22.75
Crystals	45	-30	-24.64	**-25.17**	-23.11	-23.63	-18.33	-21.22	-18.33	-21.22	-18.92	-23.42	-18.73	-20.96
SiPM	45	-30					-18.89	-18.44	-18.89	-18.44	-19.43	-20.80	-18.24	-19.77
Q8S	60	-40	-24.84	-25.68	-22.87	-24.24	-20.73	-21.39	-20.73	-21.39	-21.03	-23.50	-20.75	-20.78
Power Board	125	-55	-24.96	-26.17	-23.05	-24.66	-20.81	-21.73	-20.81	-21.73	-21.15	-23.83	-20.89	-21.10
I/O Board	80	-40	-24.84	-25.61	-22.88	-24.18	-20.71	-21.35	-20.71	-21.35	-21.00	-23.46	-20.71	-20.79
DC Converter - 5V	125	-55	-25.16	-26.00	-23.21	-24.51	-20.94	-21.59	-20.94	-21.59	-21.25	-23.69	-20.99	-20.99
EMI Filter	125	-55	-25.22	-25.92	-23.22	-24.47	-20.96	-21.56	-20.96	-21.56	-21.24	-23.67	-20.99	-20.99
Slim morphos	60	-40	-24.13	-24.77	-22.15	-23.42	-20.26	-20.80	-20.26	-20.80	-20.54	-22.96	-20.21	-20.22
Hex Morphos	70	-40	-24.03	-24.84	-22.09	-23.45	-20.21	-20.86	-20.21	-20.86	-20.54	-22.99	-20.19	-20.22
Heater 1A Duty Cycle	80%		100%		100%		0%		0%		11%		12%	
Heater 1B Duty Cycle	80%		100%		100%		0%		0%		11%		12%	
Heater 2A Duty Cycle	80%		100%		56%		0%		0%		11%		12%	
Heater 2B Duty Cycle	80%		100%		91%		0%		0%		11%		12%	

	within limits with margin
	outside limits with margin
	outside limits

- Case 4 to 5:
  - MLI outer layer change from aluminized beta cloth to beta cloth
    - Aluminized beta cloth α/ε=0.733
    - Beta cloth α/ε=0.17
  - WCH: CDU temps decrease
  - WCC: CDU temps decrease, heater power increase

Post-CDR Thermal Analysis & Design: Results

WCH Op

WCC Op

WCC Non-Op

WCH			CDR										Post-CDR	
	Operational Limits		1		2		3		4		5		→ 6	
Component	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Baseplate	40	-30	14.54	5.02	20.08	10.55	22.42	14.71	21.55	13.82	18.10	10.72	18.70	11.35
Crystals	30	-25	17.46	14.83	**22.57**	**20.04**	**24.03**	**20.13**	**21.07**	17.30	17.16	13.89	17.76	14.42
SiPM	30	-25					**24.50**	**21.92**	**21.49**	19.00	17.59	15.39	18.19	15.95
Q8S	60	-40	22.51	17.84	27.98	23.42	29.77	26.02	28.88	25.12	25.59	21.83	18.70	11.35
Power Board	125	-55	23.51	14.18	28.93	19.76	30.77	23.07	29.88	22.17	26.64	18.90	26.21	22.45
I/O Board	80	-40	26.64	24.27	32.01	29.72	33.21	31.44	32.33	30.56	29.10	27.32	27.26	19.53
DC Converter - 5V	125	-55	42.25	41.93	47.63	47.40	47.00	47.00	46.12	46.12	42.90	42.90	23.58	23.58
EMI Filter	125	-55	19.21	18.93	24.71	24.51	27.13	27.13	26.23	26.23	22.96	22.96	33.33	31.33
Slim morphos	60	-40	33.08	28.58	38.45	34.06	38.63	34.88	37.77	34.01	34.49	30.73	35.10	26.48
Hex Morphos	70	-40	26.45	23.62	31.95	29.23	32.08	30.11	31.20	29.23	27.84	25.87	29.71	26.74
WCC Operational (heaters)														
	Operational Limits		1		2		3		4		5		→ 6	
Component	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Baseplate	40	-30	-19.32	-24.71	-18.41	-24.22	-15.92	-20.93	-15.24	-20.30	-18.02	-23.23	-16.80	-20.86
Crystals	30	-25	**-20.86**	**-21.39**	-19.59	**-20.32**	-17.57	-19.08	-16.81	-18.39	-19.84	**-21.56**	-18.29	-19.42
SiPM	30	-25					-18.42	-17.94	-16.72	-18.04	**-20.54**	**-20.43**	-18.22	-19.08
Q8S	60	-40	-14.86	-18.03	-14.31	-17.34	-11.60	-14.00	-10.93	-13.33	-13.63	-16.39	-12.32	-14.32
Power Board	125	-55	-11.83	-19.75	-11.43	-19.23	-8.74	-15.80	-8.08	-15.13	-10.74	-18.18	-9.43	-16.07
I/O Board	80	-40	-11.92	-14.11	-11.31	-13.43	-8.63	-10.14	-7.97	-9.48	-10.64	-12.51	-9.32	-10.50
DC Converter - 5V	125	-55	3.26	2.09	3.71	2.63	6.38	5.97	7.04	6.62	4.39	3.61	5.70	5.70
EMI Filter	125	-55	-16.00	-17.18	-15.61	-16.61	-12.85	-13.22	-12.19	-12.55	-14.87	-15.61	-13.54	-13.54
Slim morphos	60	-40	-2.15	-7.02	-1.29	-6.00	1.29	-2.88	1.99	-2.19	-0.67	-5.20	0.58	-3.29
Hex Morphos	70	-40	-9.72	-12.77	-8.85	-11.74	-6.21	-8.54	-5.49	-7.82	-8.22	-10.91	-6.95	-8.94
Heater 1A Duty Cycle	80%		91%		0%		0%		0%		0%		0%	
Heater 1B Duty Cycle	80%		67%		0%		0%		0%		0%		0%	
Heater 2A Duty Cycle	80%		0%		0%		0%		0%		0%		0%	
Heater 2B Duty Cycle	80%		0%		0%		0%		0%		0%		0%	
WCC Non-Operational (heaters)														
	Non-Operational Limits		1		2		3		4		5		→ 6	
Component	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Baseplate	45	-30	-22.81	**-28.33**	-20.79	**-26.65**	-19.08	-23.53	-19.08	-23.53	-19.33	**-25.62**	-19.44	-22.75
Crystals	45	-30	-24.64	**-25.17**	-23.11	-23.63	-18.33	-21.22	-18.33	-21.22	-18.92	-23.42	-18.73	-20.96
SiPM	45	-30					-18.89	-18.44	-18.89	-18.44	-19.43	-20.80	-18.24	-19.77
Q8S	60	-40	-24.84	-25.68	-22.87	-24.24	-20.73	-21.39	-20.73	-21.39	-21.03	-23.50	-20.75	-20.78
Power Board	125	-55	-24.96	-26.17	-23.05	-24.66	-20.81	-21.73	-20.81	-21.73	-21.15	-23.83	-20.89	-21.10
I/O Board	80	-40	-24.84	-25.61	-22.88	-24.18	-20.71	-21.35	-20.71	-21.35	-21.00	-23.46	-20.71	-20.79
DC Converter - 5V	125	-55	-25.16	-26.00	-23.21	-24.51	-20.94	-21.59	-20.94	-21.59	-21.25	-23.69	-20.99	-20.99
EMI Filter	125	-55	-25.22	-25.92	-23.22	-24.47	-20.96	-21.56	-20.96	-21.56	-21.24	-23.67	-20.99	-20.99
Slim morphos	60	-40	-24.13	-24.77	-22.15	-23.42	-20.26	-20.80	-20.26	-20.80	-20.54	-22.96	-20.21	-20.22
Hex Morphos	70	-40	-24.03	-24.84	-22.09	-23.45	-20.21	-20.86	-20.21	-20.86	-20.54	-22.99	-20.19	-20.22
Heater 1A Duty Cycle	80%		100%		100%		0%		0%		11%		12%	
Heater 1B Duty Cycle	80%		100%		100%		0%		0%		11%		12%	
Heater 2A Duty Cycle	80%		100%		56%		0%		0%		11%		12%	
Heater 2B Duty Cycle	80%		100%		91%		0%		0%		11%		12%	

	within limits with margin
	outside limits with margin
	outside limits

- Case 5 to 6:
  - Spacecraft bus updates
  - WCH: CDU temps increase
  - WCC: CDU temps increase, heater power increase

Conclusions

- The StarBurst Instrument post-CDR updates were able to increase the confidence in the thermal model by adding details and refining parameters, which resulted in more accurate thermal predictions and TCS design
- Technical lessons learned
  - Importance of increasing model fidelity
    - The low fidelity CDU model was appropriate for the details known when it was built and used for predicting thermal performance and developing the TCS
    - Greater confidence in the model and a more accurate design will be achieved with a more detailed model IF those details are known
  - TCS design decisions must consider practicality regarding physical limitations
  - Thermal design & analysis is not complete after CDR
    - Known updates
    - Unknown updates
- Non-technical lessons learned
  - Meet with partner thermal engineer
  - Understand roles and responsibilities of each partner
  - Define margin early with project

Acknowledgements

- Starburst team including partners at SFL and NRL

Thank you!

Questions?