Grid Thermal Distortion

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Large Synoptic Survey Telescope

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Grid Thermal Distortion Analysis Plans

- This analysis is essential to understand the distortion of the Grid—and focal plane—due to changes in temperatures and heat flow in the Grid
  - These changes are largely uncorrectable, so these distortions need to be minimized
  - The structural and heat transfer components of the Grid have been designed with the goal of minimizing heat load on the Grid and thereby reducing temperature gradients which can cause distortions
  - This analysis serves to assess how well the design meets our goals

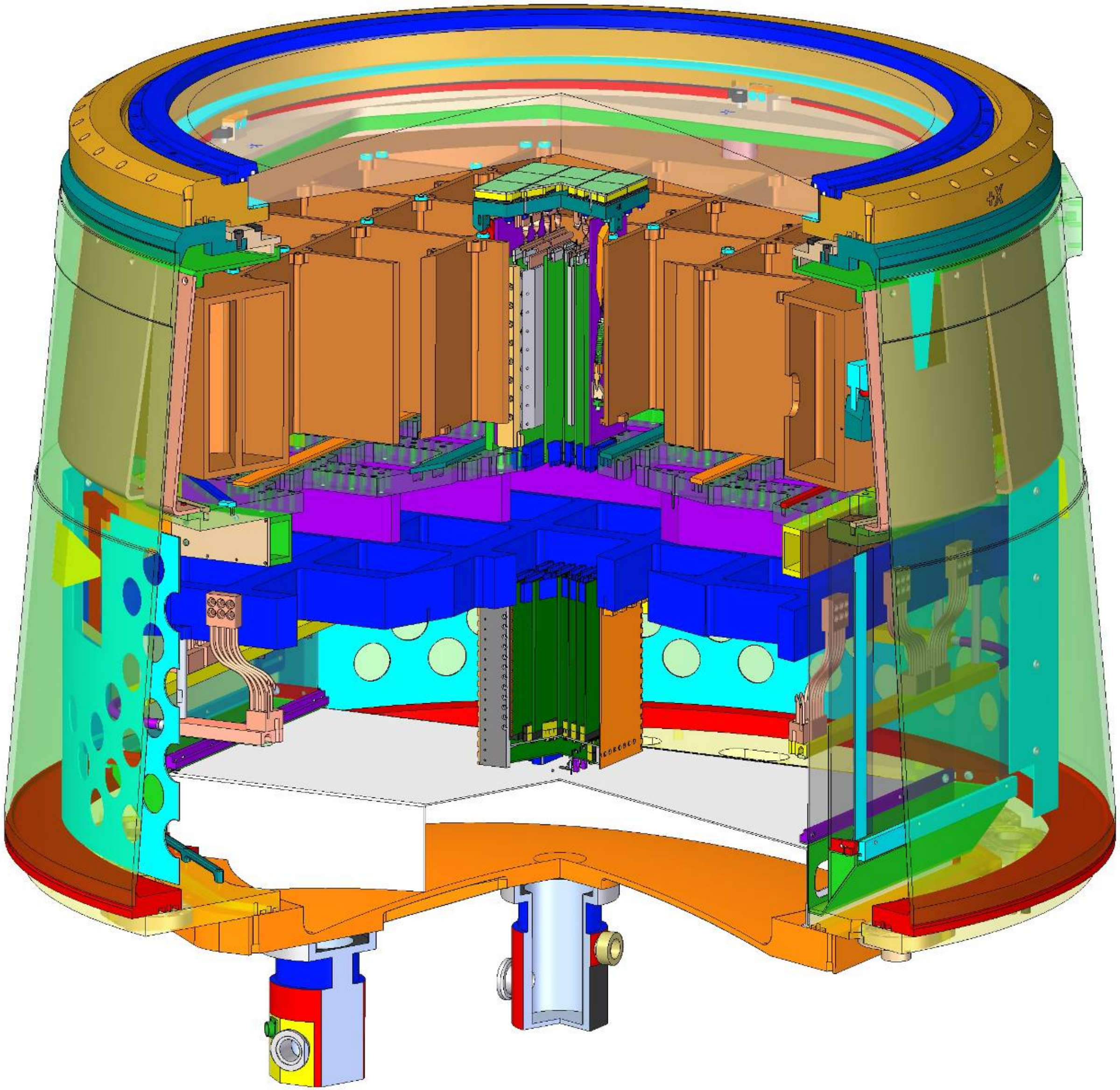
- Step 1: Grid analysis (complete)
  - Model the Grid as a stand-alone structure
  - Cold straps to Cryo Plate sink against a perfectly uniform temperature boundary
  - Analyze distortions due purely to Grid geometry and heat loads
  - Run different analyses for each heat load case to assess the relative influence of each source
- Step 2: Grid + Cryo Plate analysis (just starting)
  - Add Cryo Plate to the Grid model, so cold straps are allowed to float in temperature
  - Model the fluid flow circuits and heat conduction paths in the Cryo Plate
  - This will help us understand how much of the Grid distortion is due to temperature gradients in the Cryo Plate, due to the (many) compromises we have had to make in its design
- Step 3: Radiation analysis of Grid + Cryo Plate (not started)
  - Add the cryostat and Raft Towers to the model
  - Add radiation view factors to the Rafts from L3 and from the cryostat walls
  - Assess how changes to the radiation heat load produce gradients in the Grid

Grid Distortion

- **Potential causes of distortions in the Grid**
  - **Structural deflections**
    - Inertial mass subject to gravity and other accelerations
    - Directly-applied external forces
    - External or interface forces imparted on Grid due to non-kinematic nature of the supports
  - **Thermally-induced deformations**
    - Temperature gradients caused by heat flow through the Grid → covered in this analysis
    - Differential expansion/contraction → partially covered in this analysis
    - Changing material properties

- **Types of thermal distortion**
  - **Due to constant heat loads and gradients**
    - This analysis focused on steady-state heat loads
  - **Due to cool down**
    - Flexure cooling
    - Grid shrinkage
    - Transient temperature gradients causing deformations
    - Changing CTE as a function of temperature
  - **Due to changing heat loads and gradients**
    - Steady-state analysis will give some indication of our ability to handle transients
    - Z-offsets due to changes in cryostat temperature are discussed here

Cryostat Front End Thermal Design



Grid Thermal Design

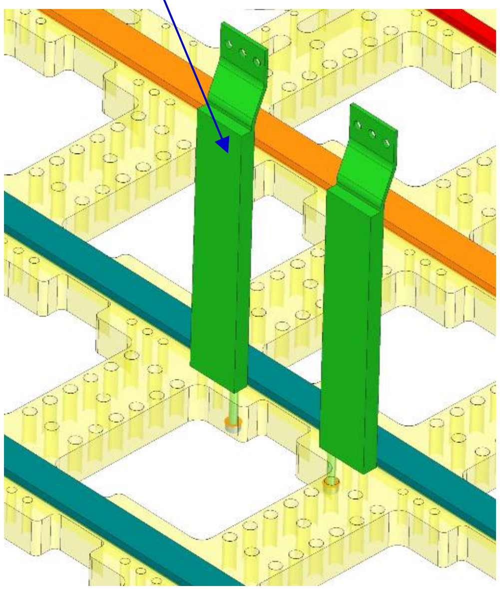
- **Thermal design: isolation from all possible heat loads**
  - **Grid is isolated from radiation heat loads by the Cryo Plate and Shroud that surround all surfaces except those where Rafts are mounted**
  - **No process or radiant heat is intentionally conducted through the Grid**

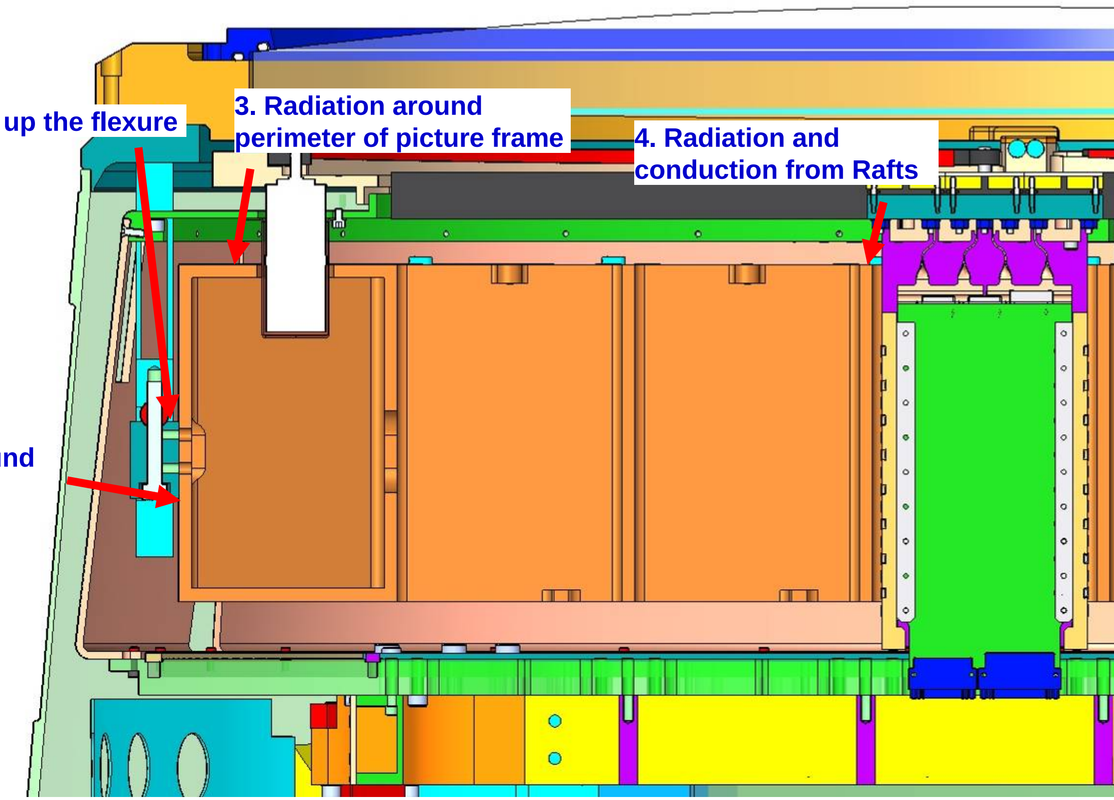
- **Potential heat loads and design features to minimize the heat flux**
  1. **Support flexure heat leak**
     - Low thermal conductivity titanium flexures with thin blades
     - Kinematic ball mount to maximize contact resistance
  2. **Radiation on Grid perimeter from shroud**
     - Shroud + MLI isolates the Grid from views of the warm cryostat wall
     - MLI may not be used, to reduce water load—this increases heat load by 16x
  3. **Radiation on Grid perimeter picture frame structure from front of cryostat and L3 lens**
     - Shroud plate + MLI shields the front face of the Grid
     - This cannot any specularly-reflecting or shiny surface—without MLI, heat load increases by 16x
  4. **Radiation and conduction heat loading from Rafts**
     - Raft will only be slightly warmer than the Grid, so this heat load will be small
     - Kinematic coupling balls reduce contact conduction significantly

- **Heat sinks from the Grid**
  - **Grid cold straps**
    - Straps sink down to Cryo Plate
    - Location of the strap mounting points on the Grid could affect temperature gradients
    - Variations in Cryo Plate temperature may propagate forward into the Grid

Heat Sources and Sinks

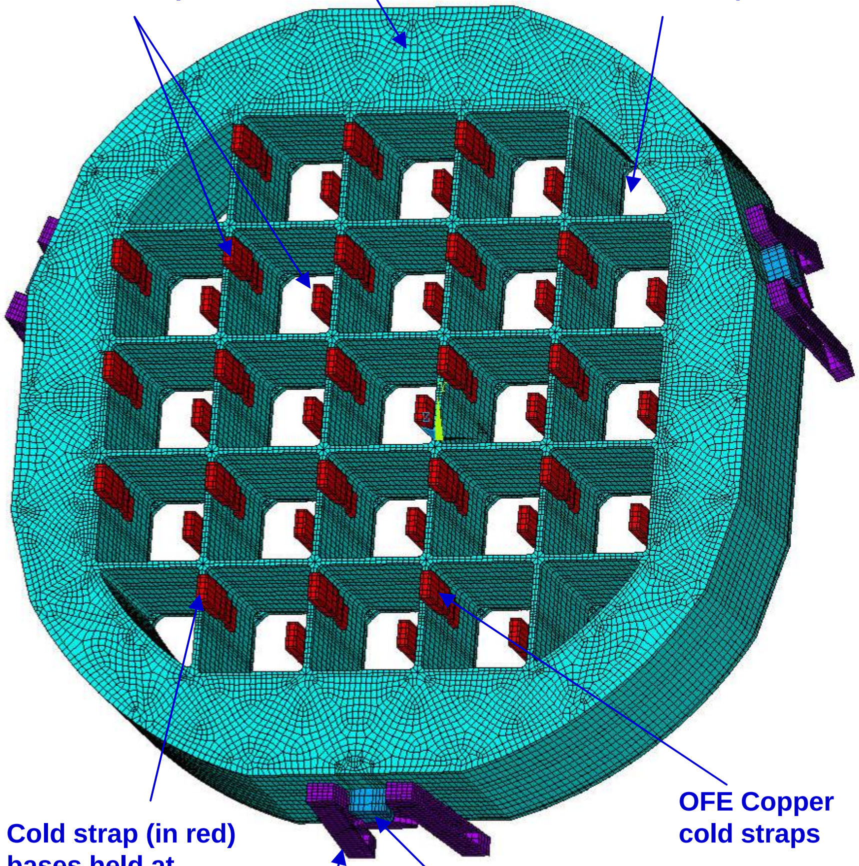
Cold straps sink Grid to Cryo Plate at 2 diagonal locations in each square bay





Grid Thermal-Mechanical Finite Element Analysis

- Thermal load cases
  - Each thermal load case is analyzed separately
  - Results are linearly superimposed
  - Results can also be individually scaled to investigate sensitivities
- Load cases and thermal boundary conditions
  - Load case 1: support flexure heat leak
    - Heat load: no applied heating
    - Boundary conditions: flexure base held at 293 K and cold strap bases held at 167 K
  - Load case 2: radiation on Grid perimeter
    - Heat load: 1 W/m^2 applied to Grid perimeter
    - Boundary conditions: cold strap bases held at 0 K
  - Load case 3: radiation on front face of Grid perimeter picture frame
    - Heat load: 1 W/m^2 applied to Grid picture frame front face
    - Boundary conditions: cold strap bases held at 0 K
  - Load case 4: radiation and conduction heating from Rafts
    - Heat load: 0.15 W/bay on front face of Grid around each bay + 0.16 W/ball
    - Boundary conditions: cold strap bases held at 0 K



View from Cryo Plate side

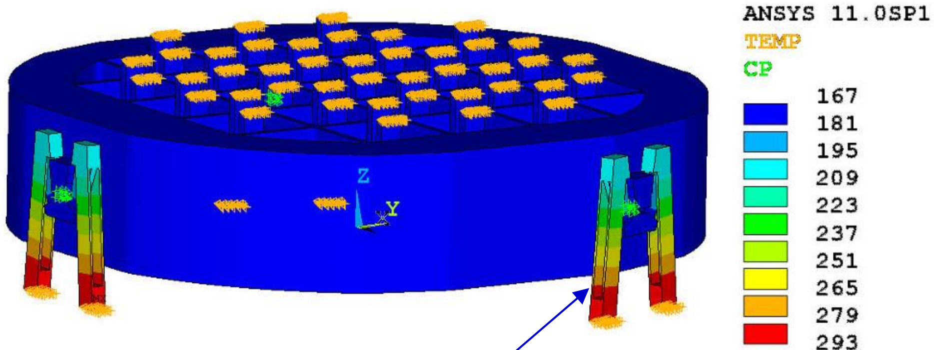
Load Case 1: Thermal B.C.'s and Temperature Distributions

FEA Model Parameters

Load case 1: heat leak through flexures

Heat load: no applied heating

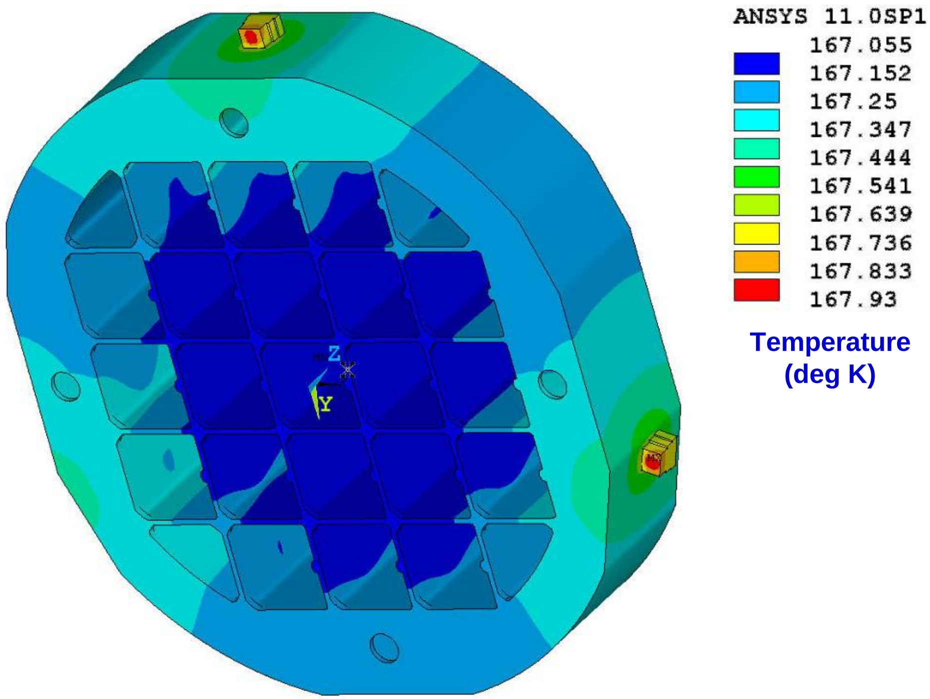
Boundary conditions: flexure base held at 293 K; cold strap bases held at 167 K



116 K temperature gradient up the flexures to the Grid mount

Temperature (deg K)

Grid and Flexure temperatures

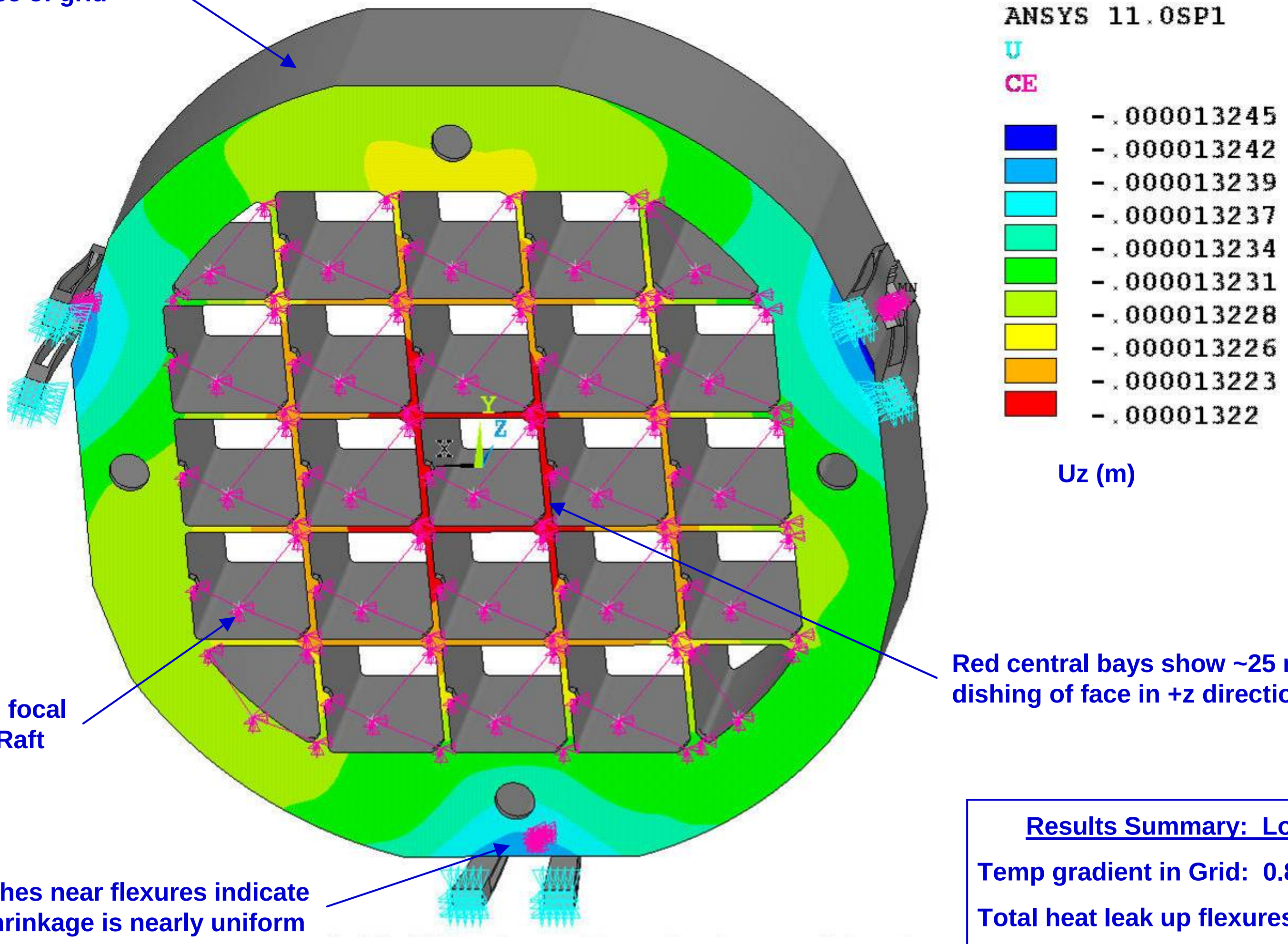


Temperature (deg K)

Grid temperatures (flexures not shown)

Load Case 1: Thermal Distortion

Limiting contour legend range highlights axial deflection, Uz, of forward face of grid



RBE3 elements on focal plane at center of Raft

Red central bays show ~25 nm dishing of face in +z direction

Blue patches near flexures indicate flexure shrinkage is nearly uniform

Grid front face Z-deflection

Results Summary: Load Case 1
Temp gradient in Grid: 0.875 K
Total heat leak up flexures: 3.98 W
Flexure contraction: 13.2 microns
Grid distortion: 0.025 microns

Load Case 2: Thermal B.C.'s and Temperature Distributions

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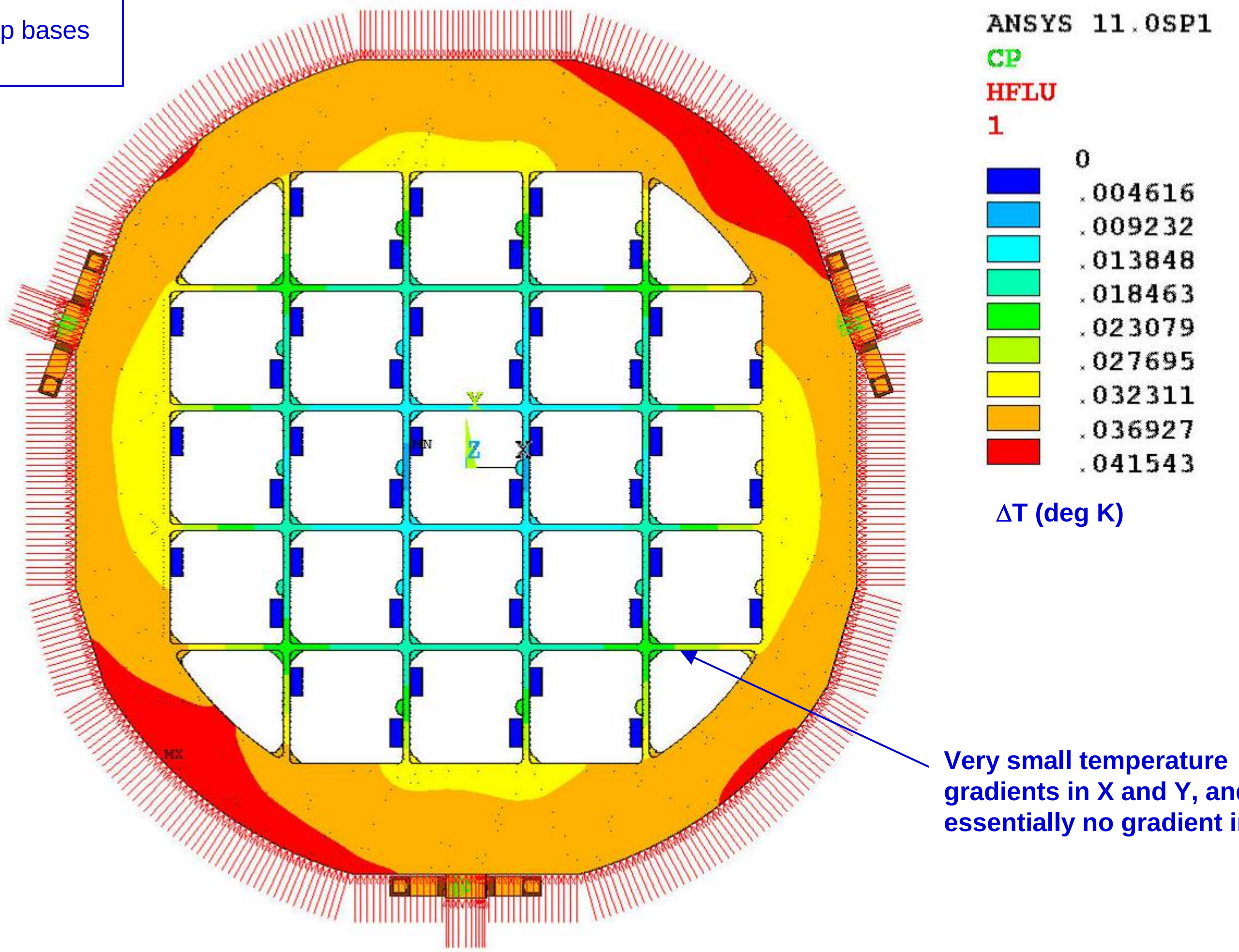
FEA Model Parameters

Load case 2: radiation on Grid perimeter

Heat load: 1 W/m^2

Boundary conditions: cold strap bases held at 0 K

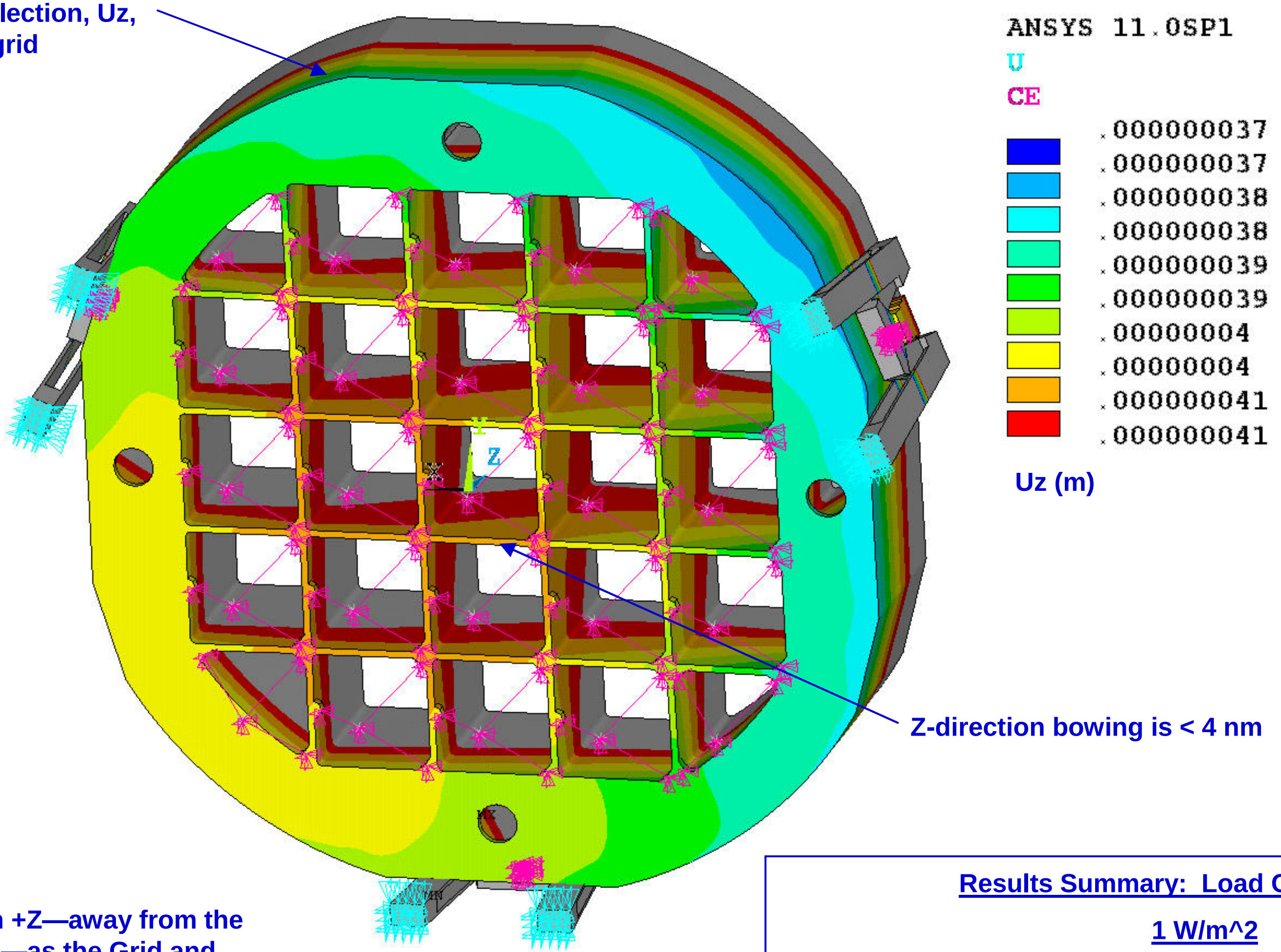


Very small temperature gradients in X and Y, and essentially no gradient in Z

Grid temperatures

Load Case 2: Thermal Distortion

Limiting contour legend range highlights axial deflection, Uz, of forward face of grid



Z-direction bowing is < 4 nm

Average motion is in +Z—away from the flexure base mounts—as the Grid and flexures heat up and expand

Grid front face Z-deflection

(1 W/m^2 heat flux)

Results Summary: Load Case 2

	1 W/m^2	16 W/m^2
Temp gradient in Grid:	0.04 K	0.64 K
Total heat load out Straps:	0.5 W	8 W
Grid distortion:	0.004 microns	0.064 microns

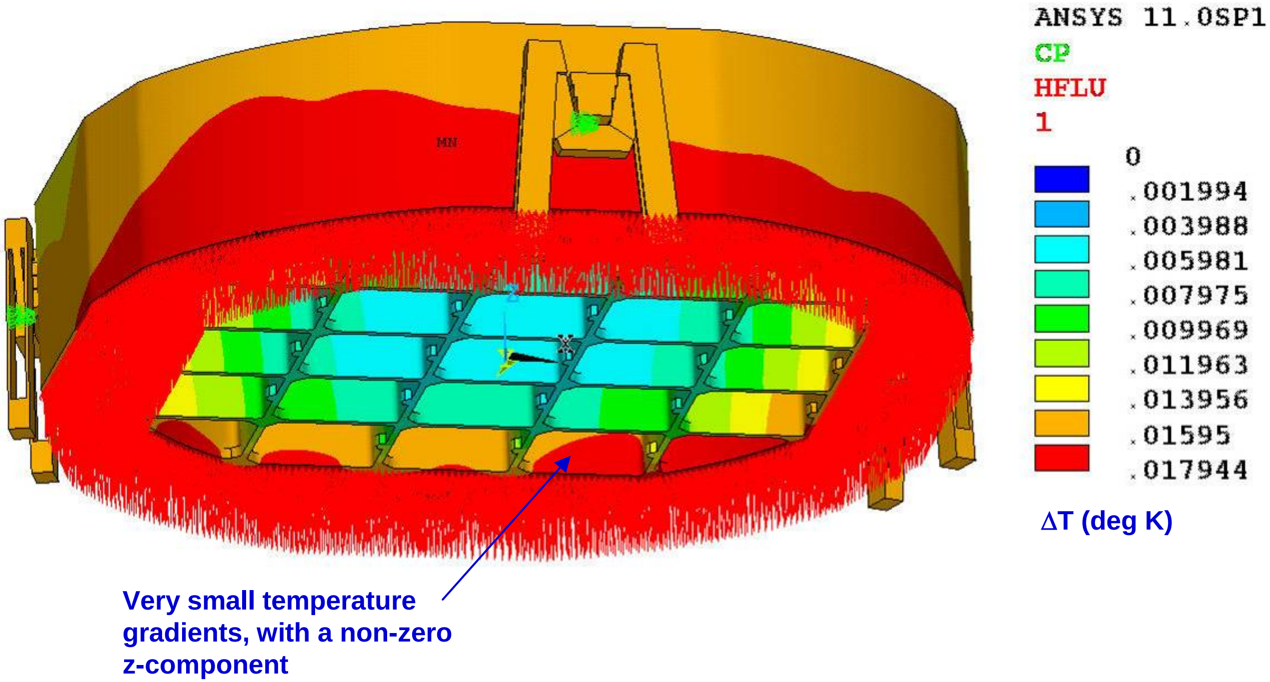
Load Case 3: Thermal B.C.'s and Temperature Distributions

FEA Model Parameters

Load case 3: radiation on Grid perimeter picture frame

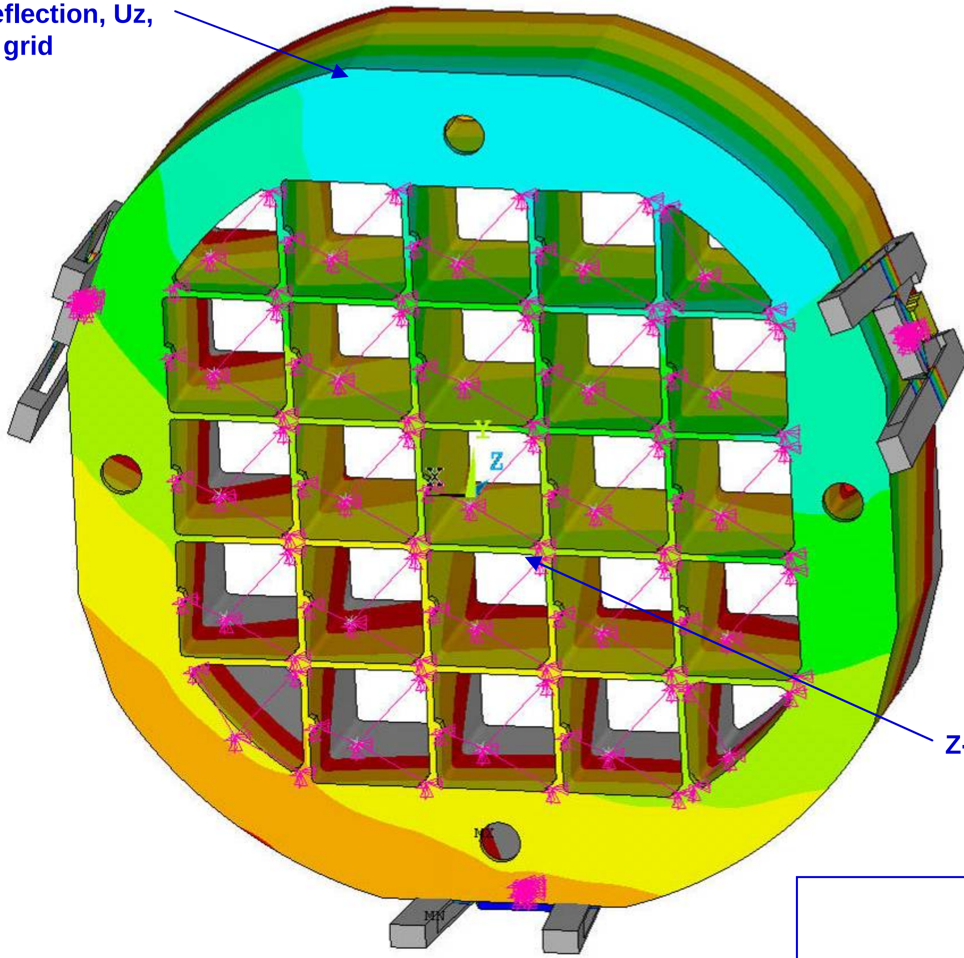
Heat load: 1 W/m^2

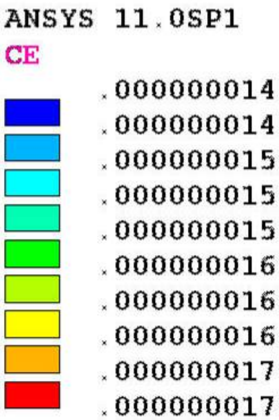
Boundary conditions: cold strap bases held at 0 K



Load Case 3: Thermal Distortion

Limiting contour legend range highlights axial deflection, Uz, of forward face of grid





Uz (m)

Z-direction bowing is < 3 nm

Grid front face Z-deflection

(1 W/m^2 heat flux)

Results Summary: Load Case 3

	1 W/m^2	16 W/m^2
Temp gradient in Grid:	0.016 K	0.26 K
Total heat load out Straps:	0.23 W	3.7 W
Grid distortion:	0.003 microns	0.048 microns

Load Case 4: Thermal B.C.'s and Temperature Distributions

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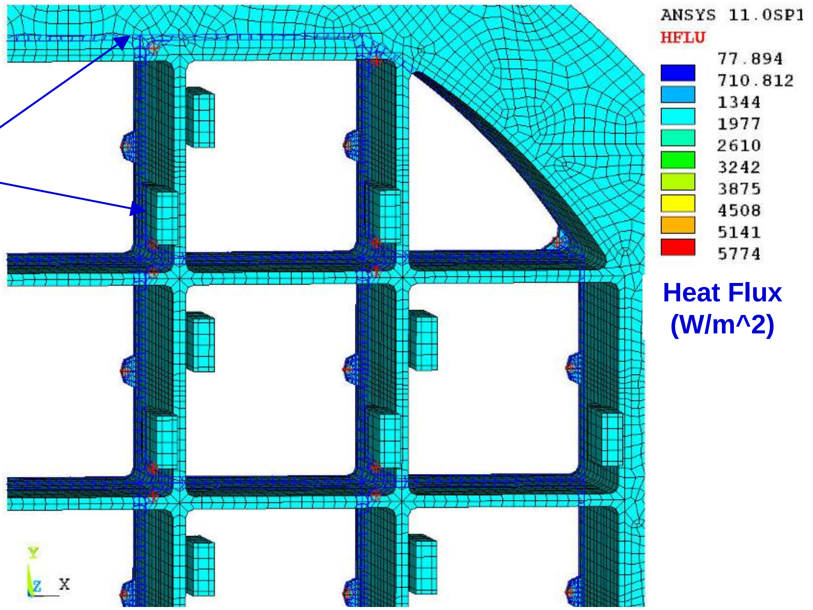
FEA Model Parameters

Load case 4: radiation and conduction heating from Rafts

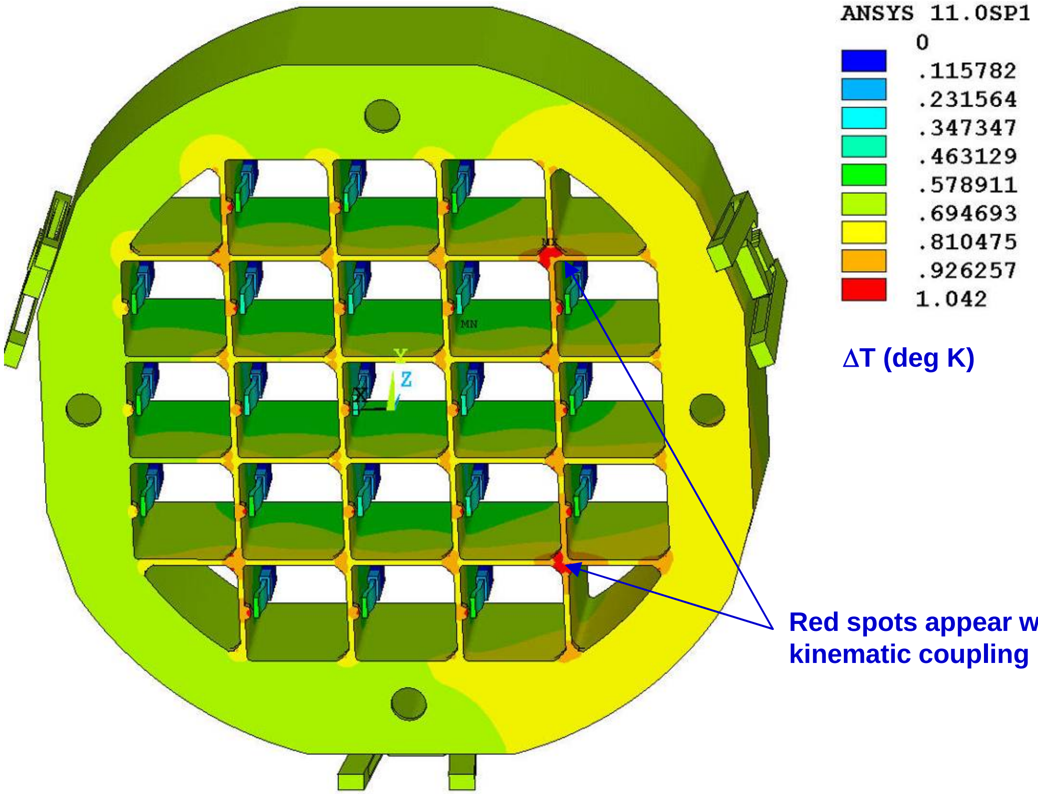
Heat load: 0.15 W/bay on front face of Grid around each bay + 0.16 W/ball

Boundary conditions: cold strap bases held at 0 K

0.15 W/bay distributed heat load is highlighted with dark blue element faces



Heat Flux (W/m^2)



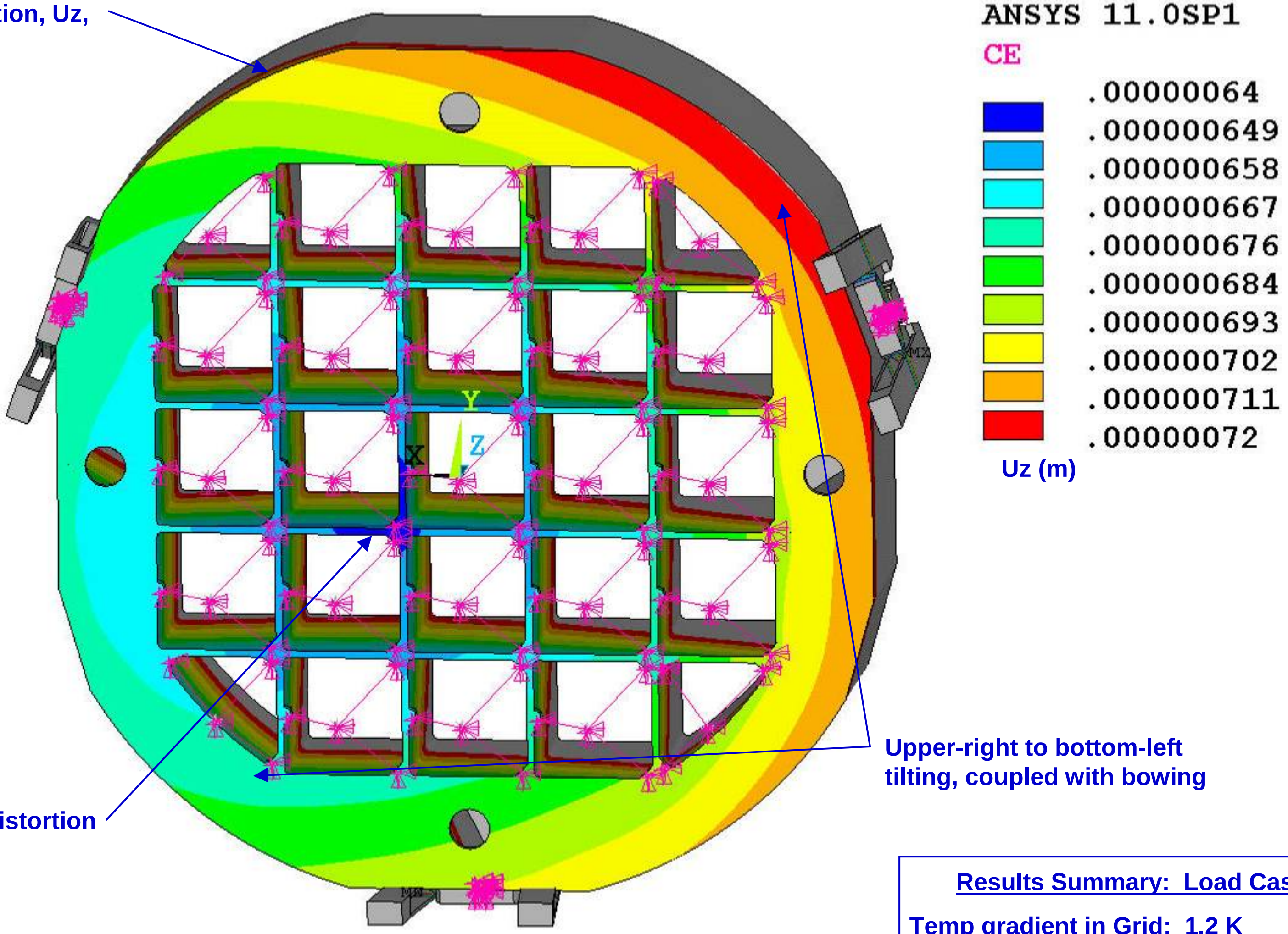
ΔT (deg K)

Red spots appear where 3 kinematic coupling balls cluster

Grid temperatures

Load Case 4: Thermal Distortion

Limiting contour legend range highlights axial deflection, Uz, of forward face of grid



Upper-right to bottom-left tilting, coupled with bowing

80 nm total z-distortion

Grid front face Z-deflection

Results Summary: Load Case 4

Temp gradient in Grid: 1.2 K

Total heat flux out Straps: 15.7 W

Grid distortion: 0.080 microns

Grid Thermal Distortion Summary

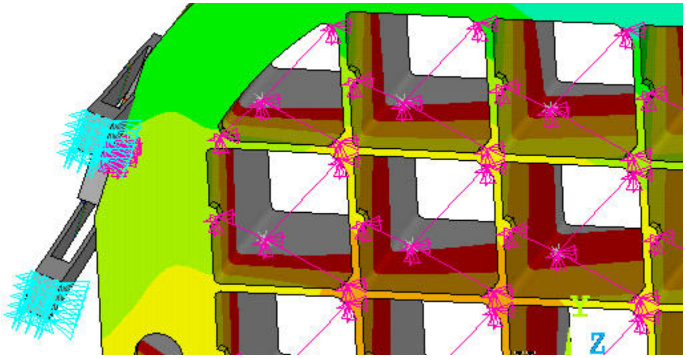
- **Total heat load = 31.4 W**
  - **Compare with ~100 W I.R. heating through L3 and ~600 W process heat load from FEE**
  - **With no MLI radiation barriers**
- **Worst-case Grid distortion = 0.22 microns**
  - **This assumes all sources of distortion are fully correlated**
  - **Radiation heat loading shown in table is based on no MLI radiation barriers, but just the Shroud cone and front plate**
    - Distortions due to this higher radiative heat load account for 50% of the total
    - However, the reduction in surface area is significant, and likely worth the increased heat load
  - **Conclusion: as related to the Grid distortion, MLI radiation barriers are not needed → the Shroud provides adequate thermal isolation for the Grid on its own**

- **While there is no focal plane distortion budget yet, the Grid thermal design appears to provide a suitably stable thermal environment which results in adequately small thermally-induced distortions of the Grid**

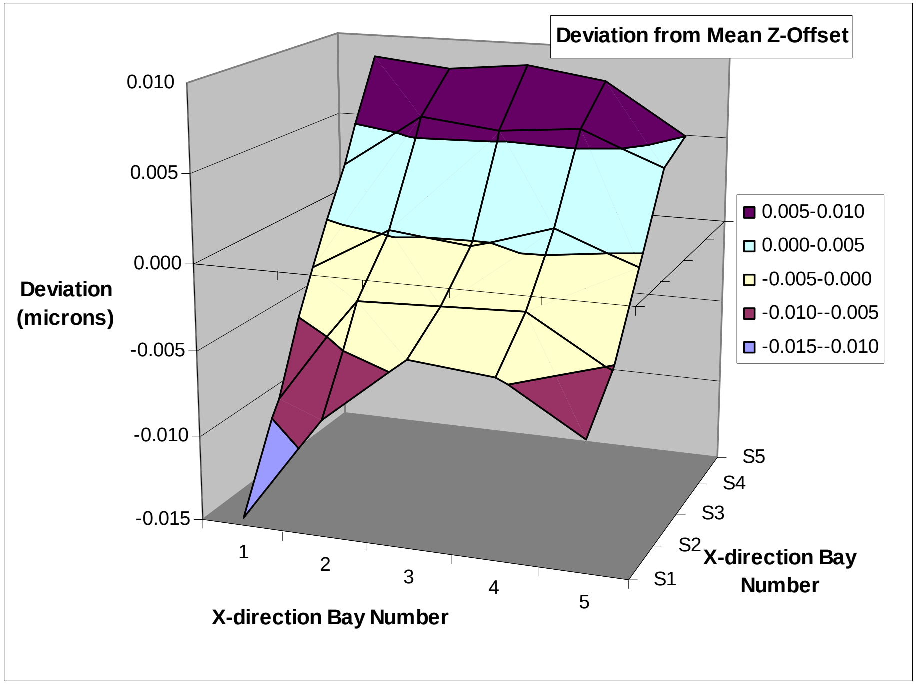
Load Case	Description	Heat Load	Grid ΔT (K)	Total Heating (W)	Grid Distortion (microns)
1	Heat leak through flexures	293K-167K temp gradient	0.875	3.98	0.025
2	Radiation around Grid perimeter	16 W/m^2	0.64	8	0.064
3	Radiation on front face of Grid perimeter picture frame	16 W/m^2	0.26	3.7	0.048
4	Radiation and conduction heating from Rafts	0.15 W/bay + 0.16 W/ball	1.2	15.7	0.080
			Total:	31.38	0.217

Focal Plane Distortion

- While Grid distortions provide insight into the heat transfer mechanisms, what we actually care about are the sensors on the focal plane
- The Grid FEA model includes RBE3 elements that average out grid motions through the kinematic coupling balls, and up to the center of each Grid bay on the focal plane
  - These simulate the average motion of each raft, and simulate changes to the flatness of the focal plane
- RBE3 element Z-positions were exported to MS Excel:
  - Average focal plane motion: indicates uniform motion or dilation
  - Deviation from average: indicates tipping or out-of-plane distortion
- The graph shows that much of the F.P. deviation is due to tipping, which can be compensated for, if needed



Load Case	Description	Average F.P. Z-motion (microns)	Deviation from Average (microns)
1	Heat leak through flexures	-13.227	0.010
2	Radiation around Grid perimeter	0.634	0.034
3	Radiation on front face of Grid perimeter picture frame	0.251	0.022
4	Radiation and conduction heating from Rafts	0.668	0.051
	Total:	-12.199	0.023



Transients Due to Changes in Cryostat Temperature

- **Camera ambient air and the cryostat temperature affect**
  - **I.R. heat load on sensors through L3—which produces second-order change in heat leak from Raft to Grid**
  - **Temperature of the cryostat structure—which affects the overall length off its mounting flange**
  - **Temperature gradient up the flexure—which affects the length of the flexure**

- **Flexure length and sensor position as a function of flexure base temperature**
  - **As the cryostat temperature changes, the temperature gradient up the flexure also changes, which affects its overall length**
  - **Cryostat operating temperature range is 0-25 degC (assumption)**
  - **For this range, the flexure length changes by 2.6 microns**
  - **This indicates that we will need to monitor the cryostat temperature and correct for changes**

Conclusions and Next Steps

- **Conclusions**
  - **The cryostat front end design does a very good job in thermally isolating the Grid**
  - **F.P. raft motions are small relative to the flatness goal, indicating that the thermal design philosophy and SiC Grid material are effective in supporting the sensor rafts stably**

- **Next steps**
  - **Add a real Cryo Plate model**
    - This analysis assumed that cold straps were grounded at the same temperature
    - However, hand calculations of the Cryo Plate suggest that there will temperature gradients with the Cryo Plate on the order of 2-5 degC, which will impact temperatures and gradients in the Grid
    - We are currently developing a combined Cryo Plate / Grid thermal FEA model to analyze the thermal performance of the combined assemblies
  - **Add Raft Tower thermal models to the FEA model**
    - This is needed for the radiation heat transfer analysis
    - It will also be needed for cool-down and other transient analyses
  - **Include radiation heat transfer from L3 lens**
    - Add L3 lens assembly and develop view factor elements to calculate radiation heat transfer network
    - Incorporate radiation elements into overall FEA model
  - **Run cooldown and other transient analyses**
    - Update FEA model to include temperature-dependent material properties
    - Analyze cool-down and warm-up transients to develop a time estimate for cycling the cryostat
    - Analyze failure scenarios to understand sensitivities to failed states and determine heater and instrumentation requirements and positioning

Supporting Information

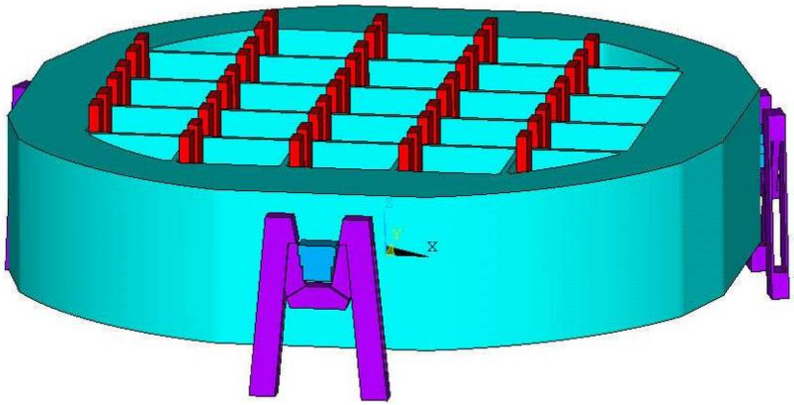
- Grid material properties
- Heat load derivations

Grid Material Properties

- **Only three materials were modeled**
  - **CeSiC silicon carbide for the Grid**
  - **Pure OFE copper for the cold straps**
  - **Titanium TI-6AL-4V for the flexures**

	CeSiC ® Silicon carbide	OFE Copper	Titanium Ti-6AL-4V	Unit
Thermal conductivity	121	400	6.7	W/m^2-K
Elastic modulus	249		114	Gpa
Poisson's ratio	0.17		0.33	---
Coefficient of thermal expansion	0.63		8.6	micron/m/K

- **CeSiC silicon-carbide expansion coefficient**
  - **Varies significantly from room- down to operating-temperature**
  - **The CTE at 150 K was used for this analysis**
  - **This provides accurate thermal distortions relative to a no-heat-load state**
  - **However, it does NOT accurately predict absolute position relative to a room temperature baseline**
  - **To do this, temperature-dependent material properties will need to be added to the thermal model—this is planned for future work**



Heat Load Derivation

- Heat load derivations: emissivities and hand calc's
- Load case 1: support flexure heat leak
  - Boundary conditions: flexure base held at 293 K and cold strap bases held at 167 K
- Load case 2: radiation on Grid perimeter
  - 1 W/m^2 applied to Grid perimeter
    - View factor = 1
    - Assumed emissivity of metal surfaces and MLI: 0.07 (worst-case spec for SC MLI: 0.03)
    - Total radiative heat load scales with 1 / (N+1), where N = number of intermediate radiation barriers
    - 1 W/m^2 heat flux applies for 15 layers of MLI between warm cryostat wall (300 K) and cold shroud (140 K)
- Load case 3: radiation on front face of Grid perimeter picture frame
  - 1 W/m^2 applied to Grid picture frame front face
    - View factor = 1
    - Heat flux parameters are identical to perimeter shroud
    - Shiny, low-emissivity surfaces will likely not be used since they will reflect incoming light
    - Option: use 15 layers of high-emissivity, matte surface (E ~ 1) → flux = 16 W/m^2
- Load case 4: radiation and conduction heating from Rafts
  - 0.15 W/bay on front face of Grid around each bay
    - Assumes emissivity = 1, which may not be far off for SiC material
    - Assumes raft temp = 173 K and grid = 143 K
  - 0.16 W/ball
    - Contact resistance ~ 10x conservative (scaled off of TRW test data for satellites)
    - Assumes 30 degC temp gradient from raft to grid
    - This is likely 50x conservative, overall