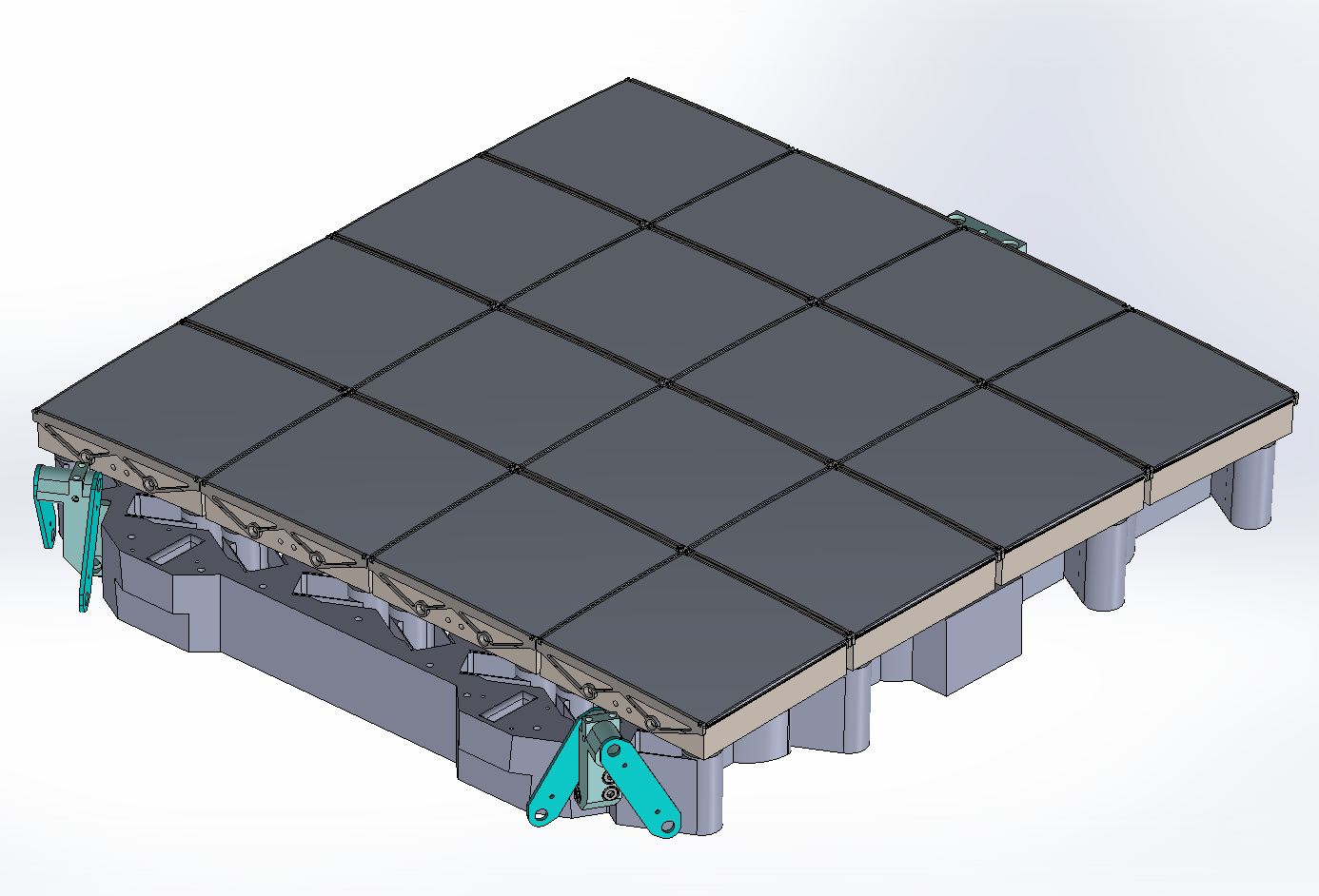
**Focal Plate Thermal-Structural Simulation**

**Andrew R. Lambert - 09/15/2014**

**Introduction**

The ZFT focal plate is an integral part of the ZTF camera, as it is responsible for holding and cooling the 16 CCDs that will be used for night sky imaging. The focal plate is constructed from aluminum (assumed to be 6061-T6 at this juncture) and has flexures machined into its body to accommodate the differential in thermal expansion between aluminum and silicon carbide. The focal plate assembly is shown in Figure 1.



Silicon Carbide CCDs x 16

Aluminum Focal Plate

Fused Silica Field Flatteners x 16

G10 Flexures

Figure 1: Focal plate assembly

The focal plate and CCD packaging will operate and cryogenic temperatures of approximately -100 oC to -120 oC, which is achieved by removing heat via two cryo-coolers attached to the back of the focal plate. In order to determine the thermal performance of the focal plate assembly, ANSYS simulation is utilized to solve the heat conduction and radiations equations that govern thermal transport. Material properties must be used that take these low temperatures into account. Material data properties at low temperature are taken from NIST databases and LBNL Advanced Light Source references.

In addition to thermal modeling, structural analysis is also completed to determine focal plate shrinkage and resulting thermal stress, as well as deflection due to both normal and lateral gravitational loading.

**FEA Modeling**

The focal plate is meshed with ~600,000 elements and 1.3 million nodes. The model mesh is shown in Figure 2 below.

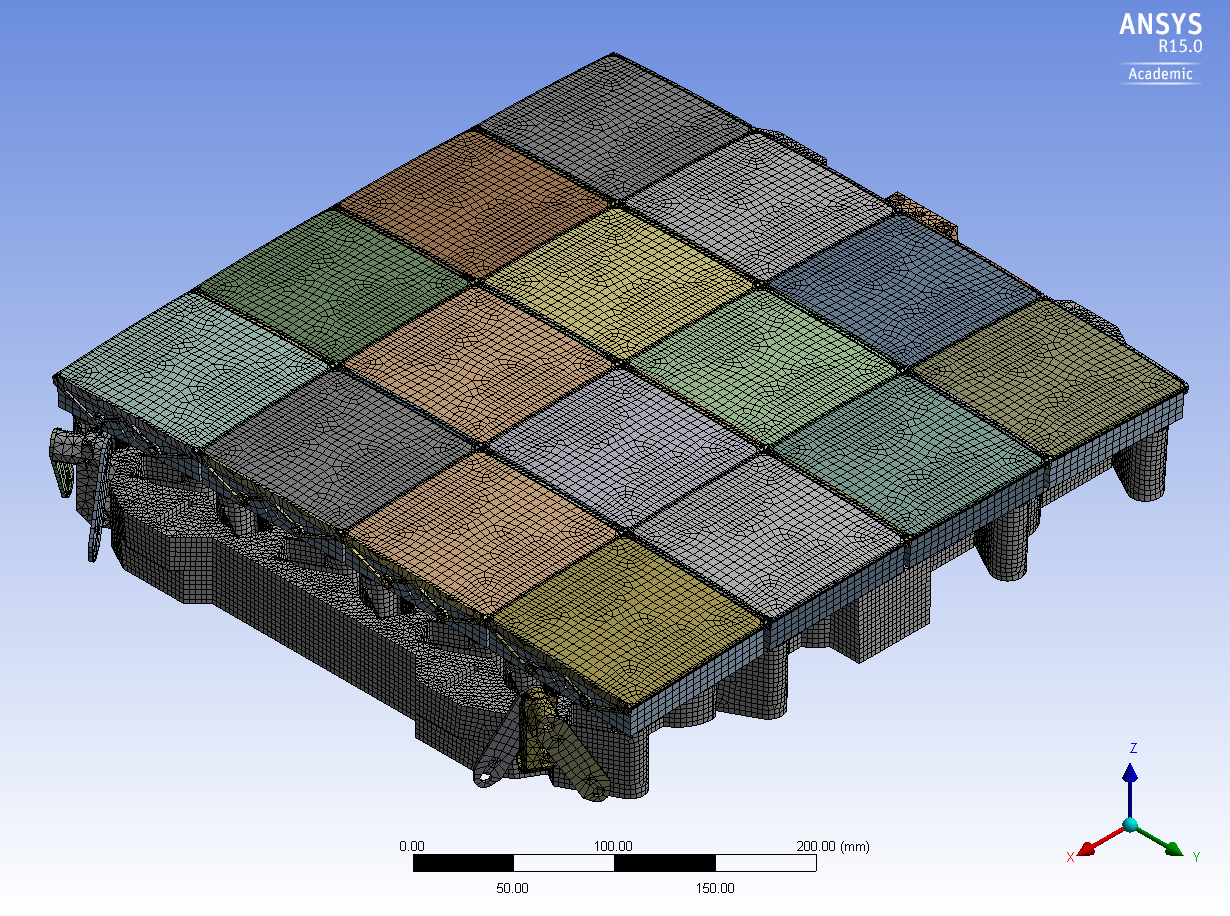


Figure 2: Focal plate mesh

The boundary conditions for the thermal model include both conductive and radiative components. The top surface of the field flatteners experience radiative heating, as they primarily “see” the fused silica window that seals the top of the dewar. The window temperature is conservatively assumed to be equal to a temperature of 0 oC. Radiative boundary conditions are used to also approximate the heat transfer from the field flatteners to the CCD surface via the enclosure setting in ANSYS mechanical. Use of the enclosure boundary condition does not over-constrain the temperatures on the field flatteners and CCDs. As mentioned, the focal plate is cooled via two cryo-coolers, which are connected to the focal plate by copper thermal links. The attachment points of these thermal links are “foot-printed” onto the back of the focal plate. These “foot-prints” on the back of the focal plate are approximated to be at -120 oC, which provides cooling to the rest of the assembly. Heat conduction from the CCDs to the focal plate occurs through the CCD to focal plate attachment pedestals, and are shimmed with invar spacers. Contact thermal conductance is taken into account, with the CCD to Invar shim conductance equal to 481 W/m2-K and the Invar shim to aluminum focal plate conductance equal to 1080 W/m2-K.

**Thermal Results**

The results of the thermal simulation for the focal plate assembly are shown in Figure 3.

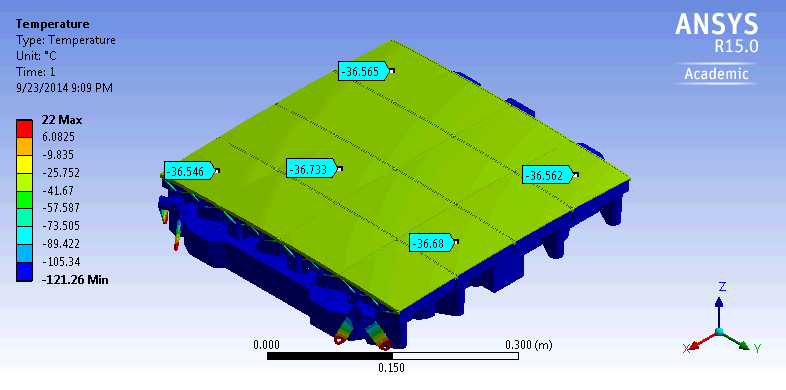


Figure 3: Focal plate assembly temperatures

As the figure shows, the field flatteners settle at approximately -36.5 oC and their temperatures are relatively uniform. The frames holding the field flatteners are made from stainless steel and serve to insulate them from the CCD, which cuts down on the total radiative heat load that must be managed by the cryo-coolers. The CCD temperatures are shown in Figure 4.

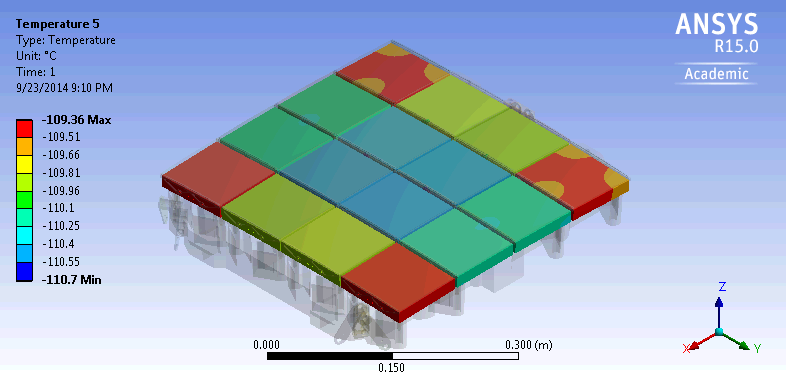


Figure 4: CCD temperatures

The CCDs operate at -110 oC and are very uniform in their temperatures. This shows that the stainless steel frame successfully isolates them from the fused silica flatteners. The thermal contact resistance does not significantly impede heat flow from the CCDs to the aluminum focal plate. The temperature on the aluminum focal plate is shown below in Figure 5.

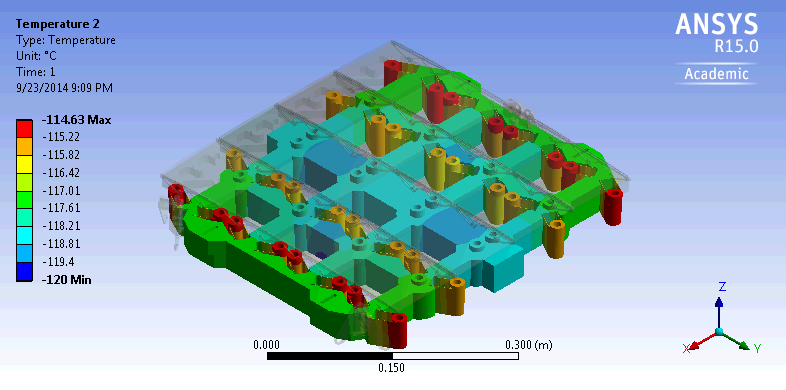
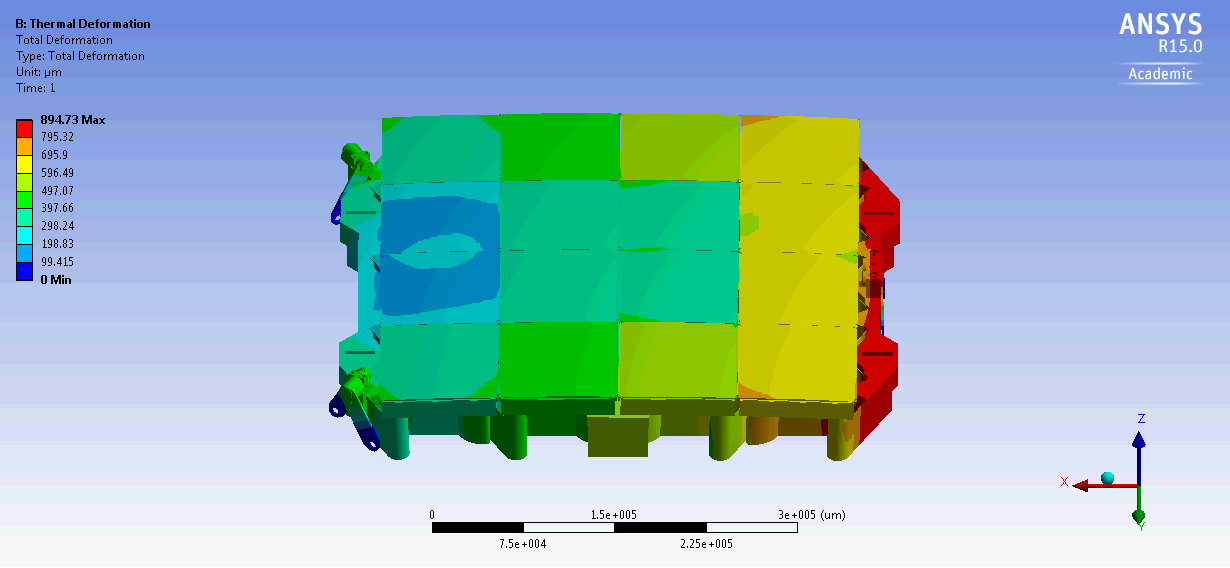


Figure 5: Aluminum focal plate temperatures

As Figure 5 shows, the aluminum focal plate temperature varies from -120 oC to -114.6 oC, with the warmer regions corresponding to the pedestals to which the CCDs attach. The parts stay warmer due to the limited heat transfer that may take place though the flexures. As evidenced by Figure 4 though, the heat path through the flexures is sufficient to keep the CCDs cold. The total heat removed through the cryo-cooler temperature connections is 23.8 W; approximately 88.5% of this heat load is due to radiative heat. Only 1.6% of this heat load is due to heat transfer through the G10 flexure struts, and the remaining heat load is due to the CCD electronics.

**Structural Results**

The thermal shrinkage of the focal plate assembly is shown in Figure 6. As the figure shows, one side of the focal plate shrinks more than the other, which is due to the configuration of the G10 struts.



These flexures are less compliant in x-direction

This G10 flexure is compliant in the x-direction

Figure 6: Total thermal shrinkage of the focal plate assembly

On the right side of the focal plate, as oriented in Figure 6, the flexure is parallel to the direction of shrinkage and is thus more compliant to motion in the x-direction than the flexures on the left side of the focal plate. Shrinkage in the x-direction only is shown in Figure 7.

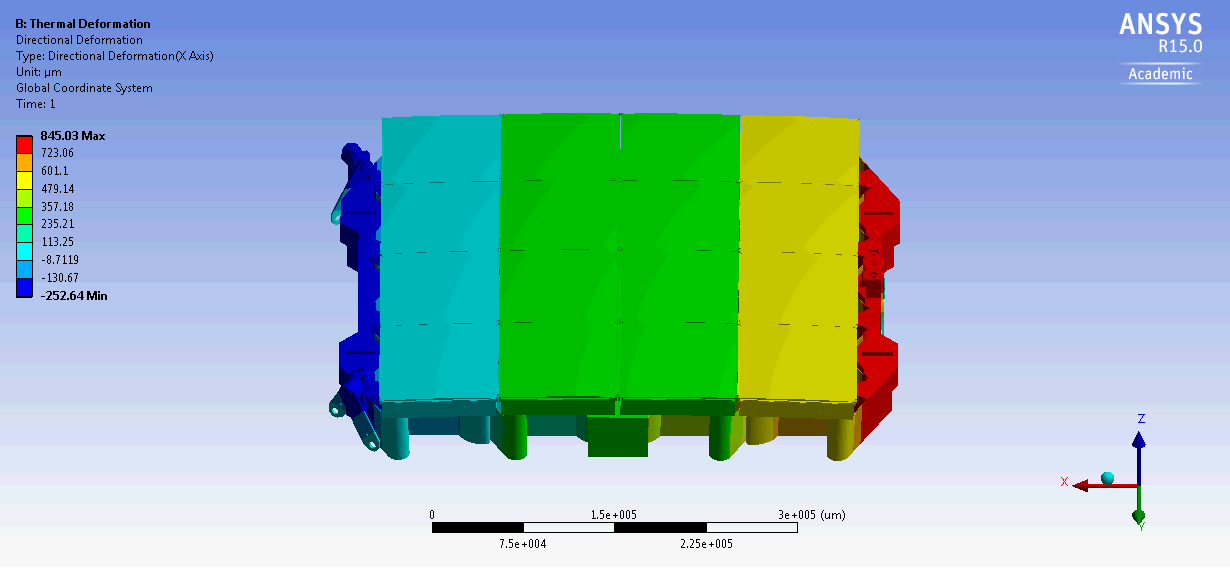


Figure 7: x-direction thermal shrinkage

This more clearly illustrates how the G10 struts orientation affects the thermal shrink in the x-direction, with a maximum of 854 µm on the right side of the focal plate and -247 µm on the left side of the focal plate, as oriented in Figure 7. Thermal deformation in the y-direction is shown in Figure 8.

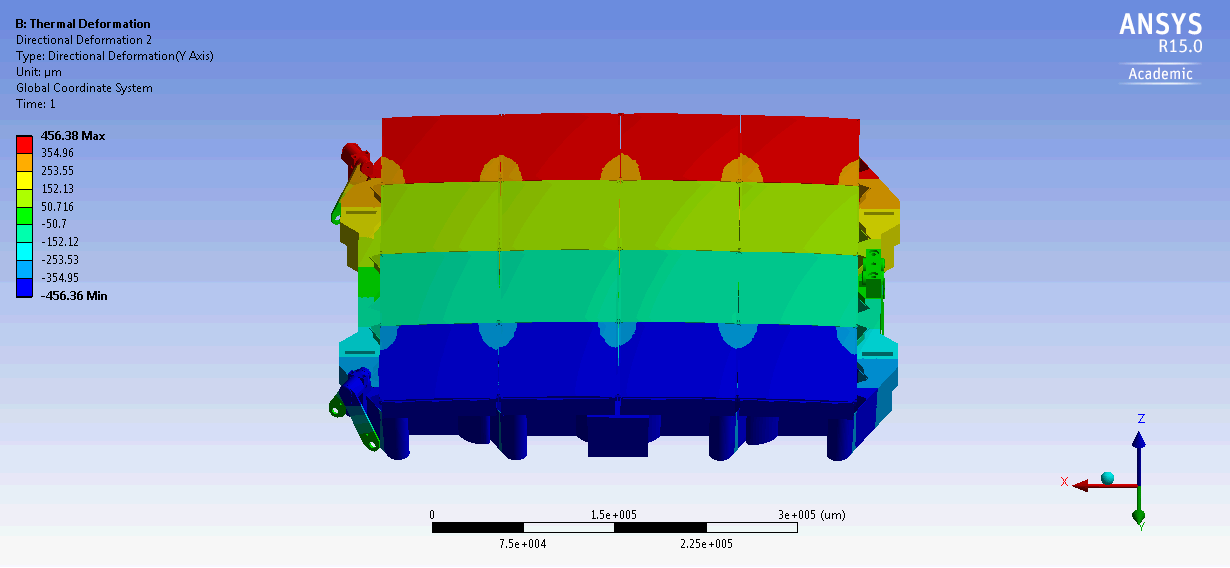


Figure 8: y-direction thermal shrinkage

The focal plate is symmetric about of the x-z plane, thus the thermal shrink in the y-direction is symmetric about the x-z mid-plane of the focal plate assembly. Both sides contract about 456 µm at maximum, with a total maximum shrink in the y-direction of 912 µm. Lastly, the contraction in the z-direction is shown in Figure 9.

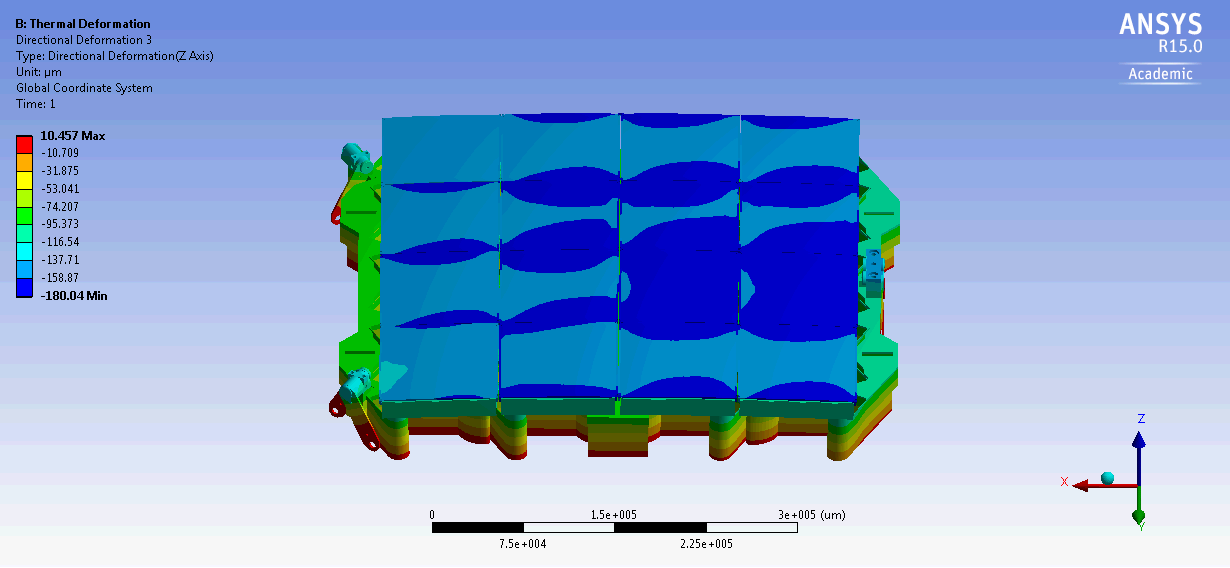


Figure 9: z-direction thermal shrinkage

Figure 9 shows the z-direction thermal shrinkage of the entire focal plate assembly; however we are more interested in the z-deflection of the focal surface, thus the z-direction shrinkage for the aluminum pedestals and CCD surfaces is shown in Figure 10.

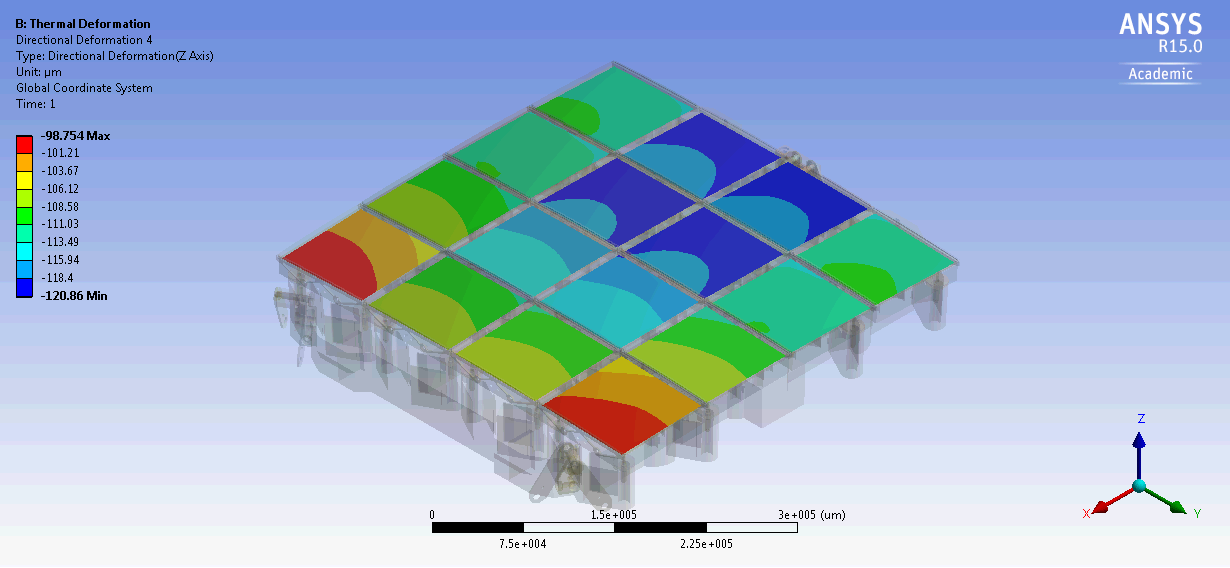
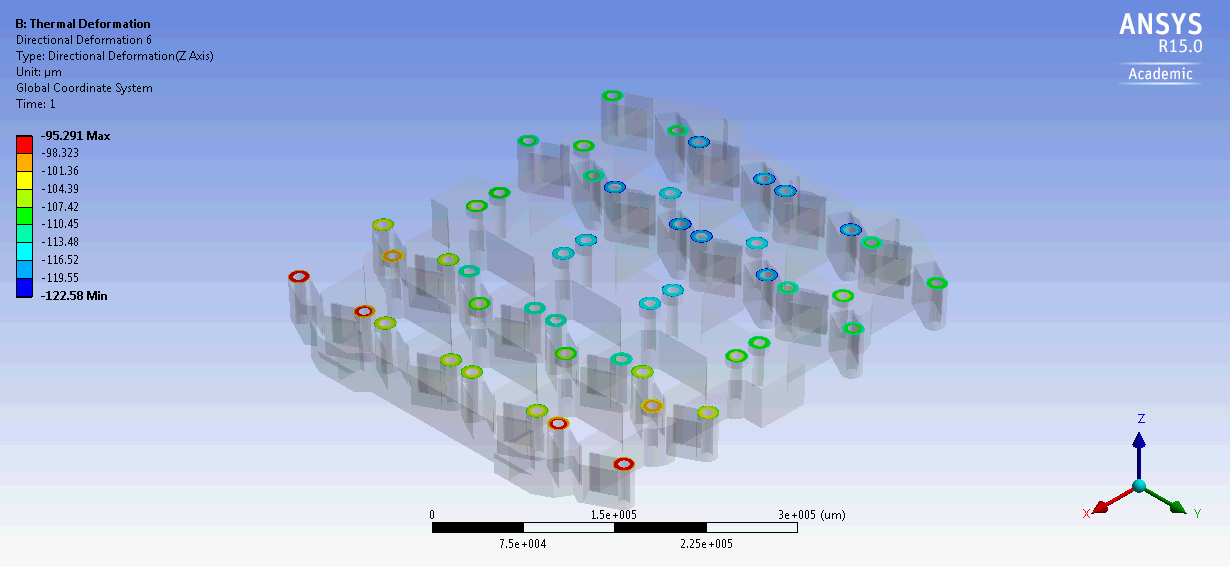


Figure 10: z-direction shrinkage of the aluminum pedestals and CCD surfaces

The CCD mating surfaces on the aluminum focal plate shrink from their initial positions by 95 µm to 123 µm; this translates to z-direction shrinkage of the CCD surfaces of 99 µm to 121 µm, thus the maximum delta, or change of CCD surface location w.r.t other CCD surfaces is 22 µm. Note that this is only due to thermal shrinkage and does not include the gravity vector, which will be examined shortly. Another important aspect of thermal shrinkage is the induced thermal stresses in focal plate components. In order to better investigate this, a sub-model of the focal plate was created and is shown in Figure 11.

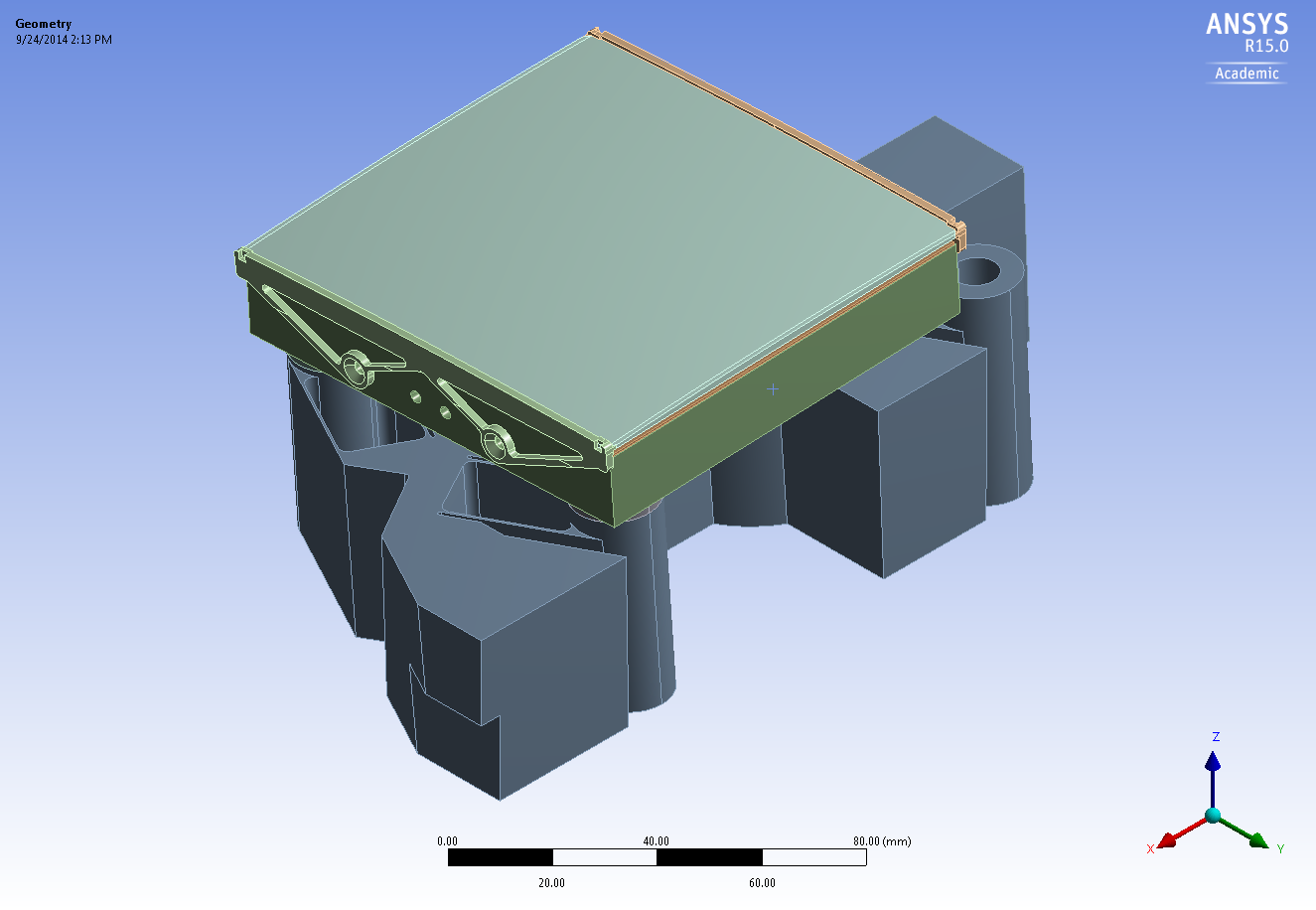


Figure 11: Sub-model for stress examination

The sub-model allows finer meshing to resolve the thin aluminum flexures, as well as inclusion of more complex connection conditions to better approximate surface stresses. Within the CCD, the maximum tensile stress is of primary concern due to their brittle nature. The connection from the Invar shims to the CCD is formulated as frictional, which helps to reduce inflated surfaces stresses due to a “bonded” contact formulation. The maximum principle stress in the CCD is shown in Figure 12.

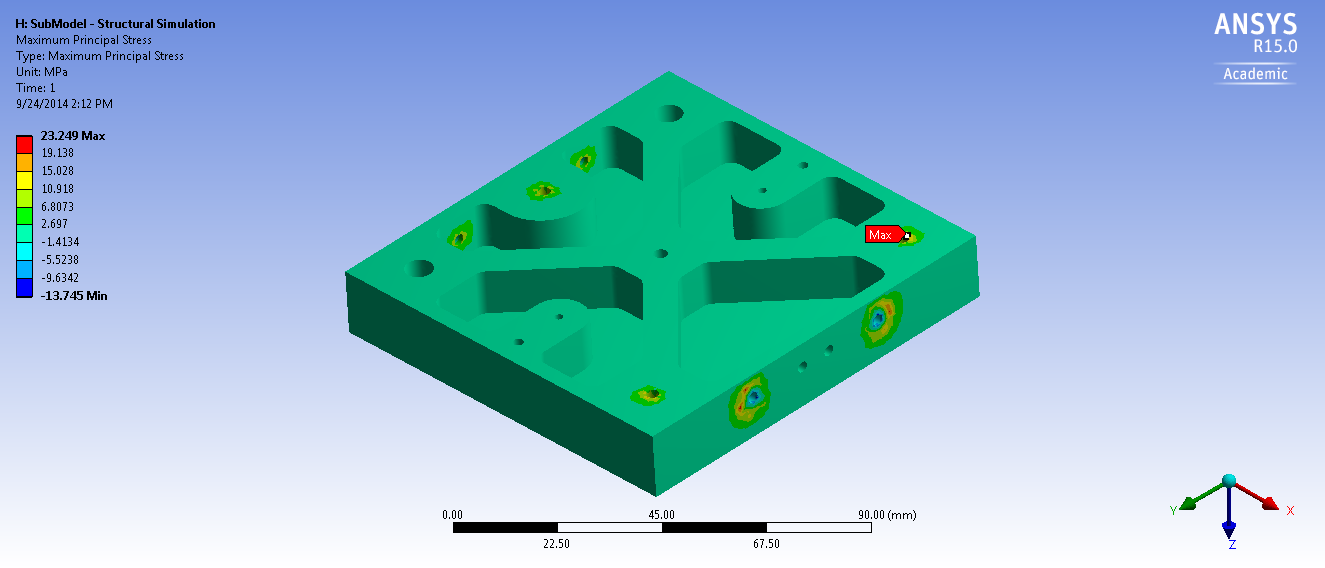


Figure 12: Maximum principle stress [MPa] in CCD

The maximum principle stress is 23.2 MPa and is located at one of the Invar shim attachment points. This is a localized stress, as overall the stress in the CCD is low. The stress in the aluminum flexures is shown in Figure 13.

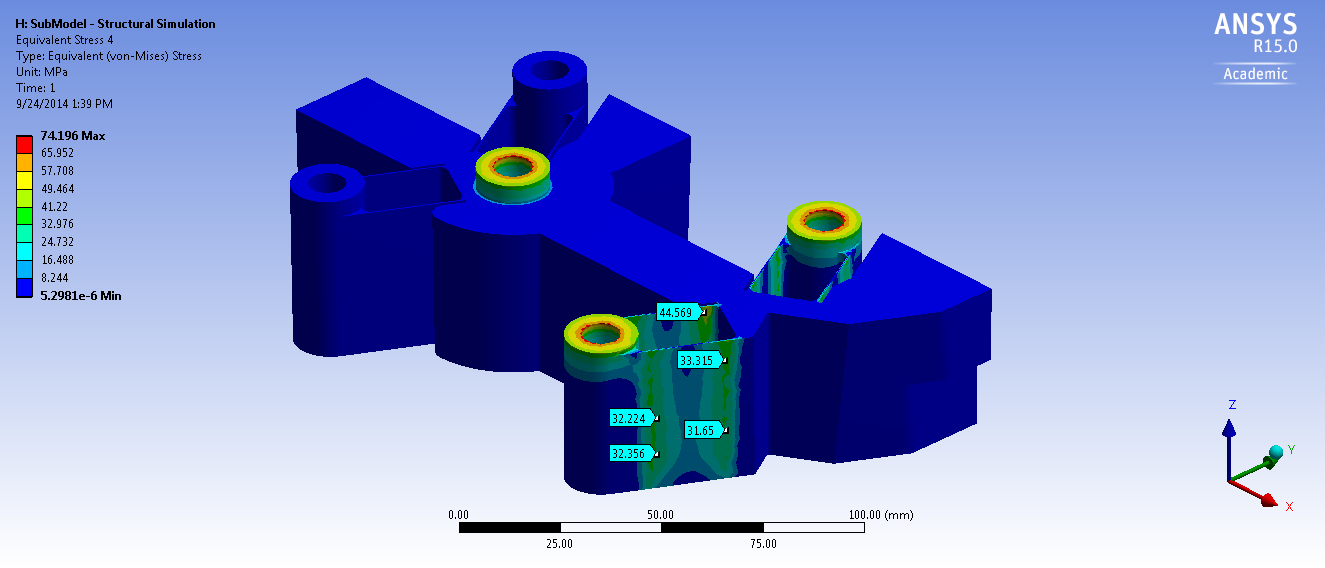


Figure 13: Aluminum flexure equivalent stress [MPa]

The stress in the aluminum flexures is roughly 45 MPa at maximum. The high stress seen at the pedestal is due to the bonded contact used here, which creates an artificially high surface stress. Overall, the aluminum flexures successfully accommodate the differential CTE between the aluminum focal plate and silicon carbide CCDs. An additional sub-model is constructed to examine the stresses in the stainless field flattener frame and fused silica field flattener. This sub-model is shown in Figure 14.

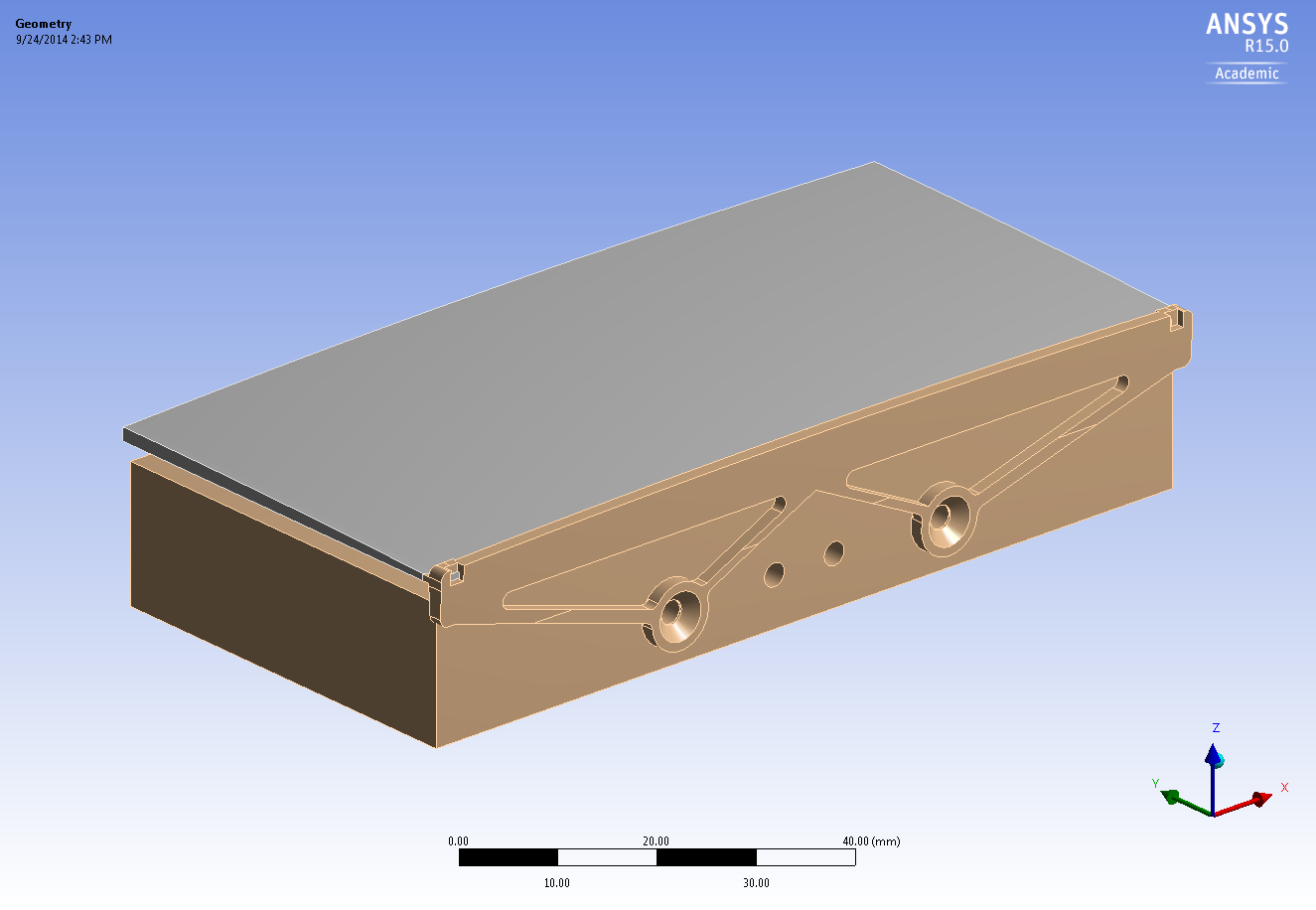


Figure 14: Sub-model for frame and flattener stress examination

This sub-model takes advantage of symmetry about the x-z mid-plane. The CCD body is cooled to -120 oC and the field flattener experiences radiative heating due to viewing the “warm” fused silica window at 0 oC.

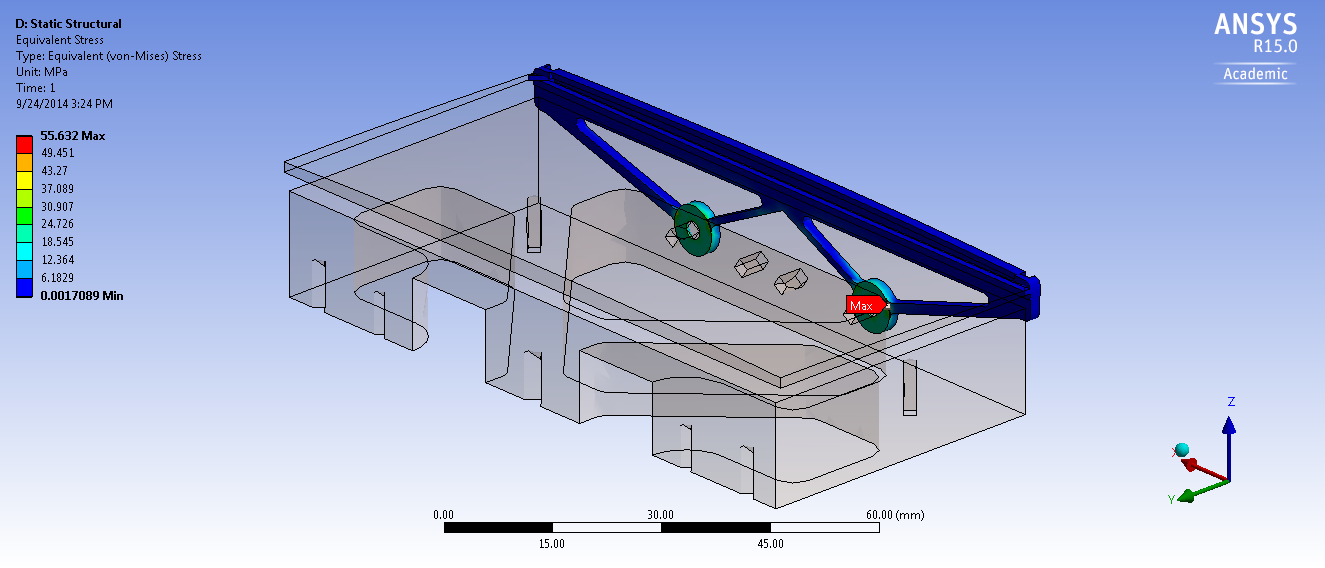


Figure 15: Flattener frame equivalent stress [MPa]

Figure 15 shows the equivalent stress in the stainless steel field flattener frames, with a maximum of 55.6 MPa. This stress is an edge concentration due to the bonded contact. Actual stresses in the frame are lower than this, with stresses at the attachment points of roughly 20 MPa and stresses in the thin legs ranging from 2.5 MPa to 5 MPa. The maximum principle stress in the fused silica field flattener is shown in Figure 16.

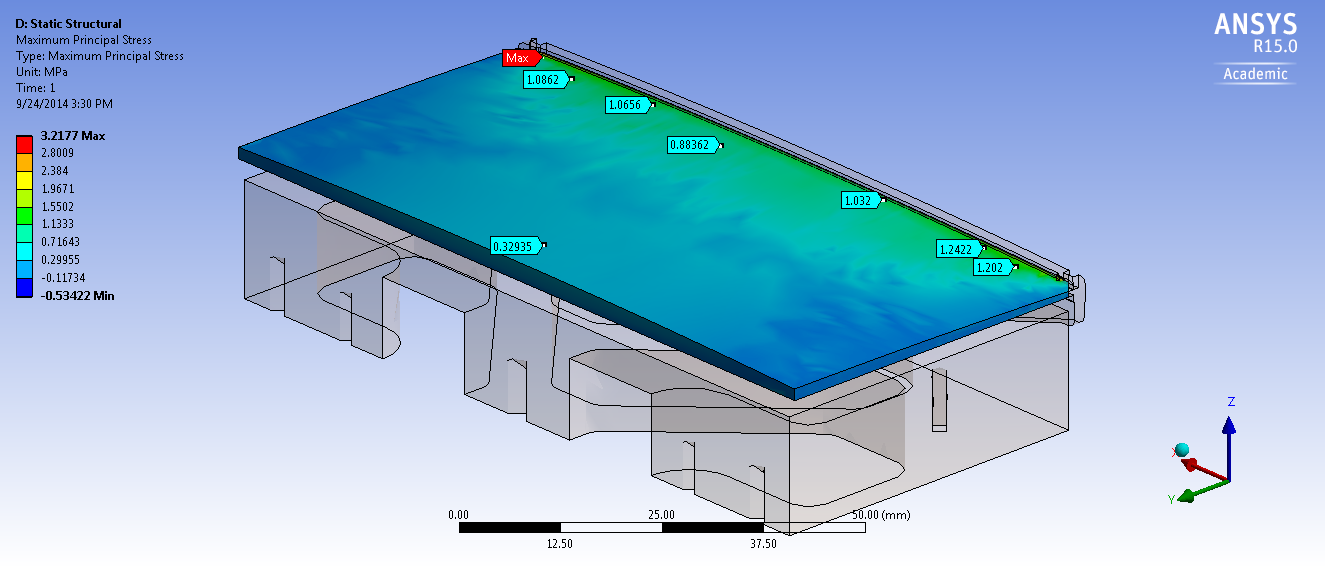


Figure 16: Flattener maximum principle stress [MPa]

The maximum principle (tensile) stress in the glass is 3.2 MPa, and average stresses at the frame equal to ~ 1MPa.

In addition to thermal deformations of the focal plate and its components, gravitational deflections are of upmost importance. Simulation is carried out for three different gravity vector orientations, with the subsequent deformations plotted. Figure 17 shows the total deformation of the focal plate assembly when gravity is oriented in the x-direction. The maximum deflection is roughly 32 µm and is primarily rigid body motion of the focal plate assembly.

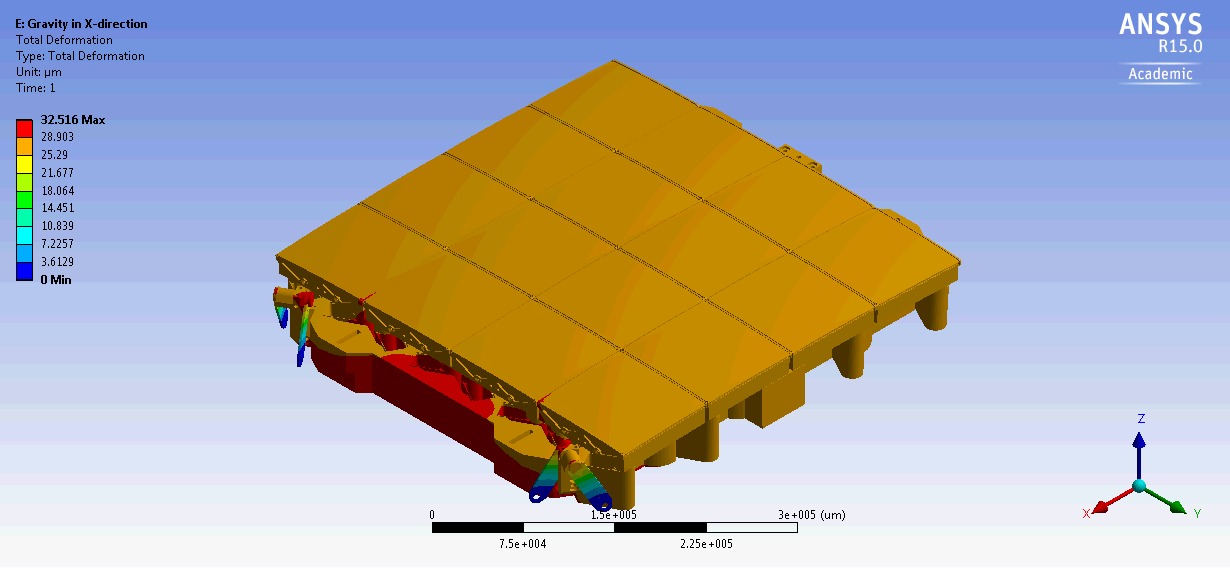


Figure 17: Total deformation for gravity in x-direction

Figure 18 shows the total deformation when gravity is oriented in the y-direction. The maximum deflection is 28 µm and is again primarily due to rigid body motion of the focal plate assembly on the flexures.

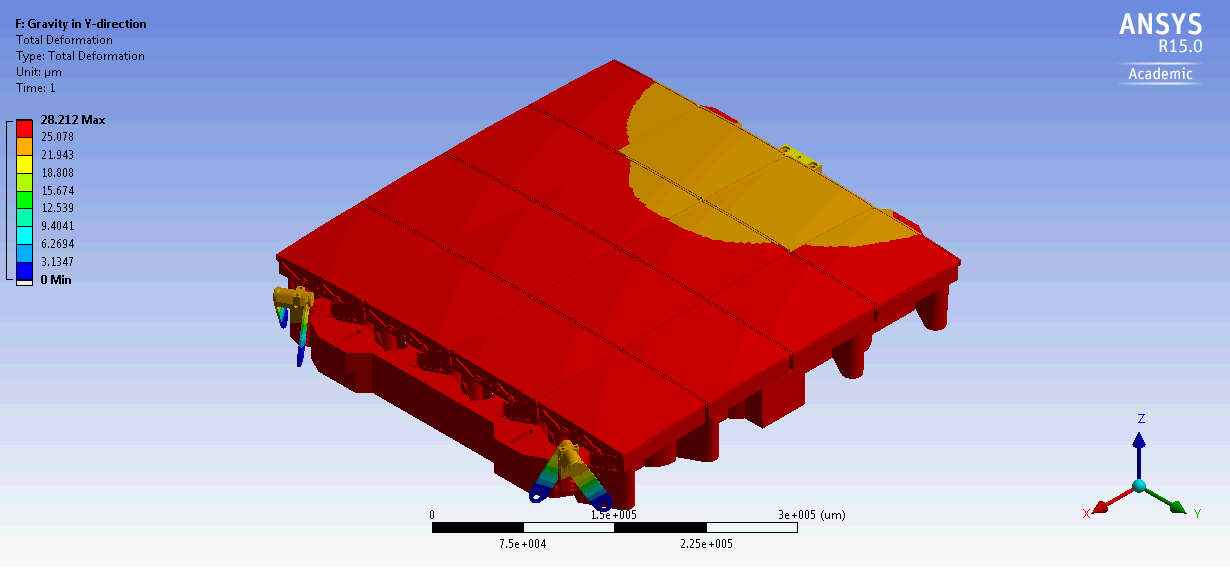
5

Figure 18: Total deformation for gravity in y-direction

The deflection when gravity is oriented in the z-direction is shown in Figure 19.

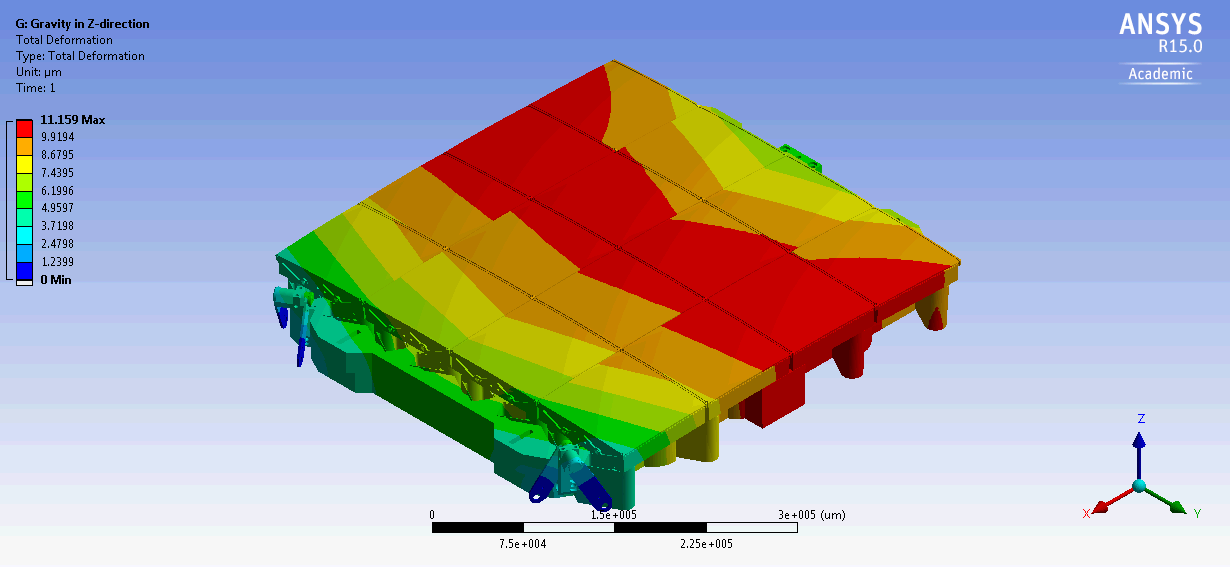


Figure 19: Total deformation for gravity in z-direction

Figure 19 shows that the deflection in the z-direction due to gravity in z is quite small, with maximum of 11 µm. The direction deflection of the CCD sensor surfaces are tabulated for all three loading conditions in Table 1.

Table 1: CCD sensor surface deflections for all gravitational loading conditions

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Gravity Vector** | **Displacement Maximum [µm]** | | | **Displacement Minimum [µm]** | | |
|  | x | y | z | x | y | z |
| **X-direction** | 28.7 | 1.7 | 5.1 | 27.8 | -1.7 | -0.4 |
| **Y-direction** | 1.9 | 26.3 | 9.7 | -1.9 | 23.2 | -9.7 |
| **Z-direction** | 3.1 | 0.6 | 11.0 | 0.02 | -0.7 | 3.6 |

As the above table shows, the deformations experienced by the focal plate are minor, with maximum peak-to-valley of 19.4 µm in the z-direction occurring for y-directional gravity loading; this is due to tilting cause by the placement of the G10 struts that support the focal plate. Further investigation of the structural characteristics of the focal plate can be completed in the ANSYS file “FocalPlateZTFFinal.wbpj”.

Modal analysis of the ZTF focal plate yields the resonant frequencies for the structure, which are shown in Figure 20.

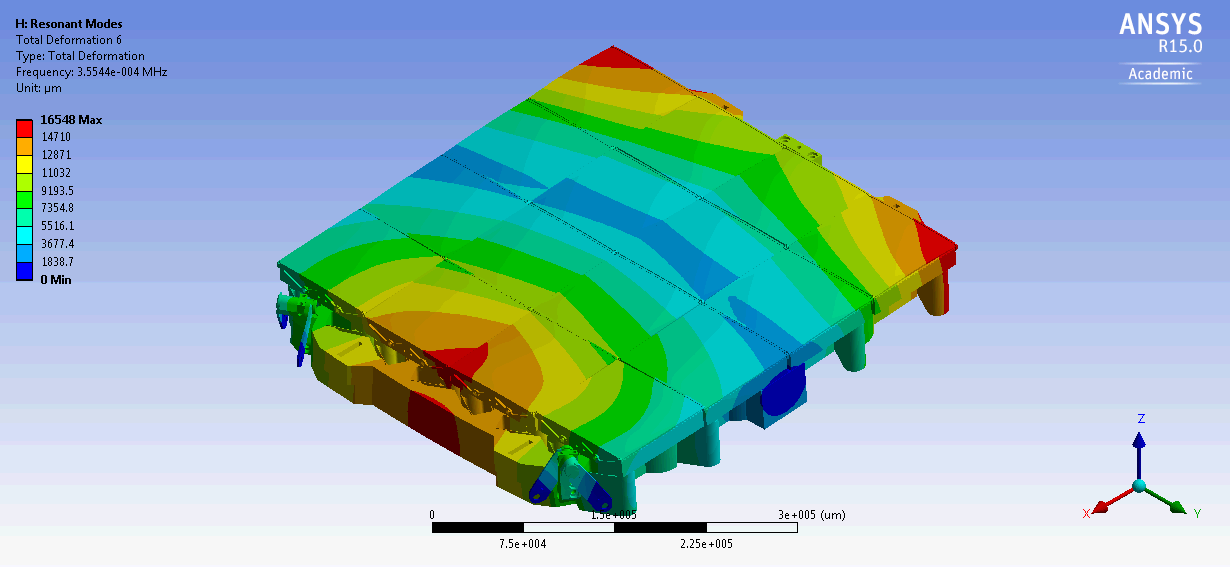
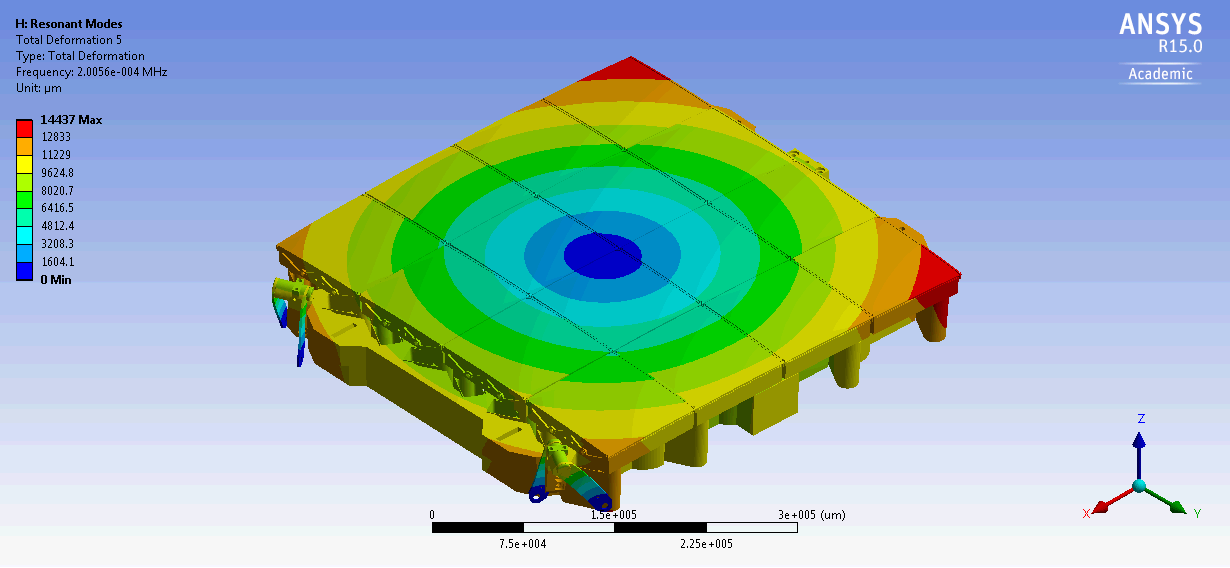
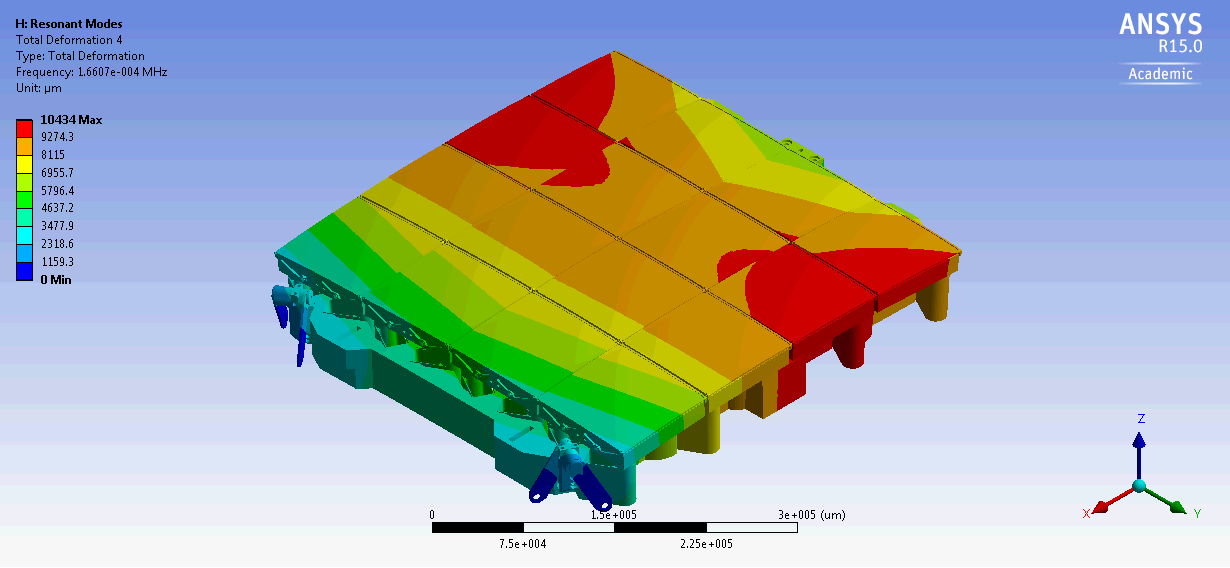
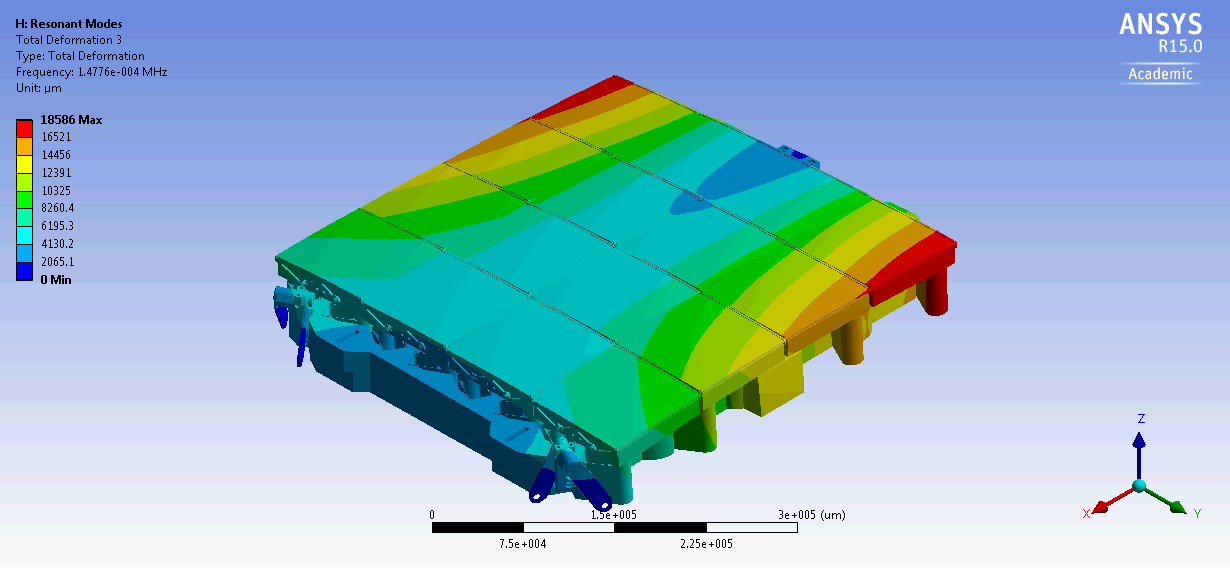
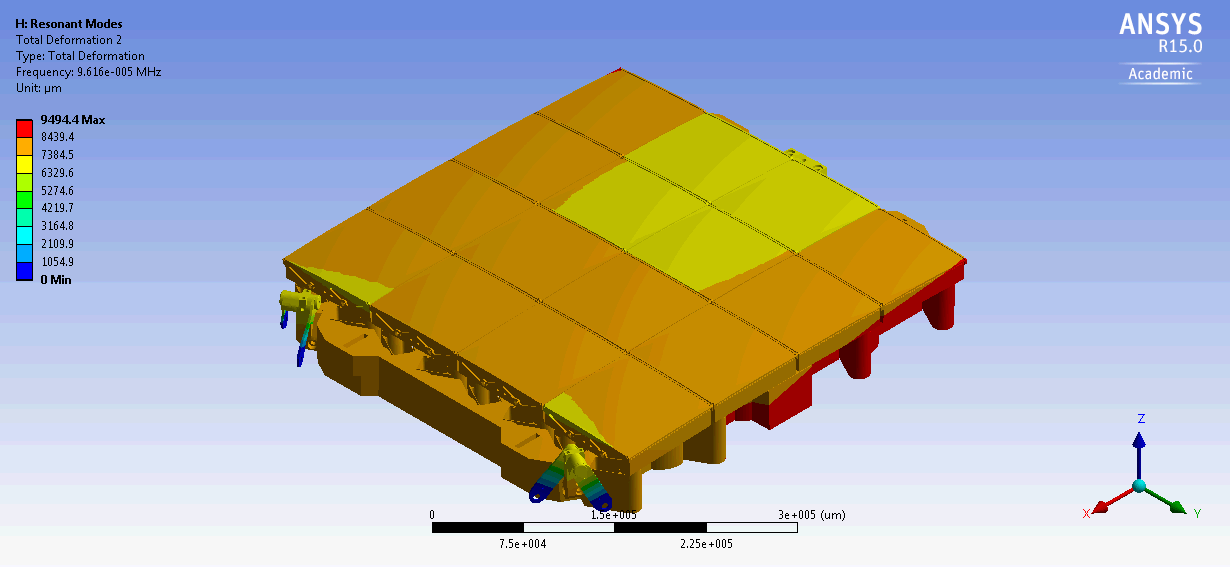
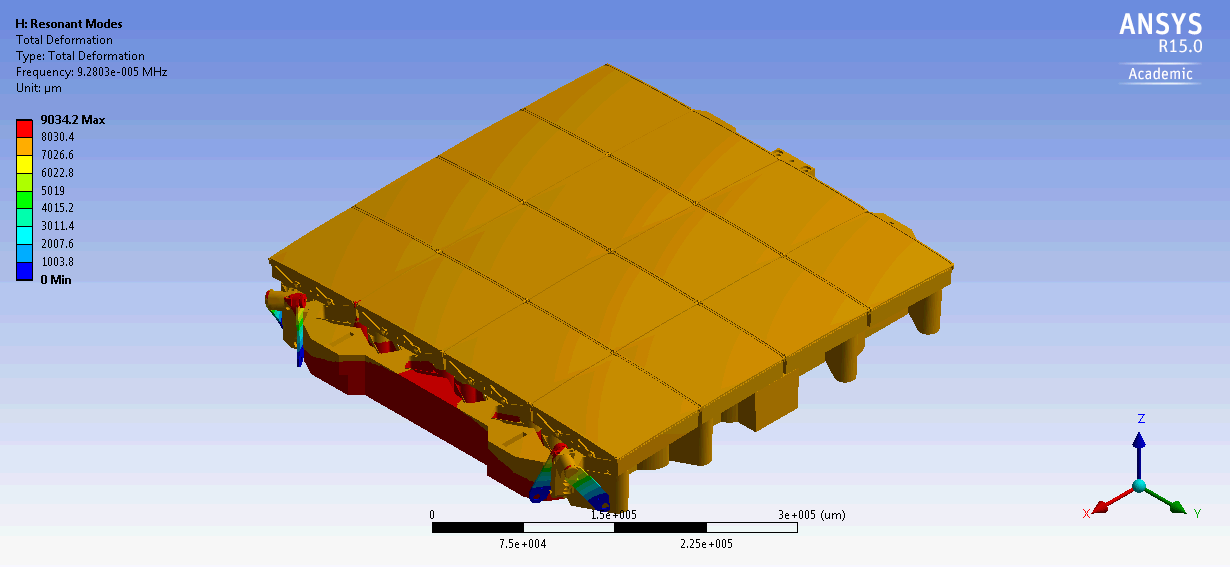


Figure 20: First six mode shapes for ZTF focal plate

The modal resonant frequencies are tabulated in Table 2.

Table 2: First six resonant frequencies

|  |  |
| --- | --- |
| **Mode** | **Frequency [Hz]** |
| 1 | 92.803 |
| 2 | 96.16 |
| 3 | 147.76 |
| 4 | 166.07 |
| 5 | 200.56 |
| 6 | 355.44 |

The resonant frequencies shown in Table 2 indicate that the assembly is sufficiently stiff to resist harmonic oscillations. It should be noted that the “weak” point in the assembly is the G10 struts, and resonant movement occurs there. Exported .avi files are made available in order to visualize the harmonic deformations.

**Conclusion**

The focal plate assembly performs well both thermally and structurally. Comprehensive FEA models of the focal plate assembly have been built and archived for future investigation. In addition, a workable sub-model has been constructed for examination of component stresses. All of these models may be found in the ANSYS Workbench archive file “FocalPlateZTFFinal.wbpj”.