Modeling optical deformations due to laser heat flux on a flat mirror

Eduardo Marin
December 13, 2016
Given as part of OPTI 521

Laser Heat flux

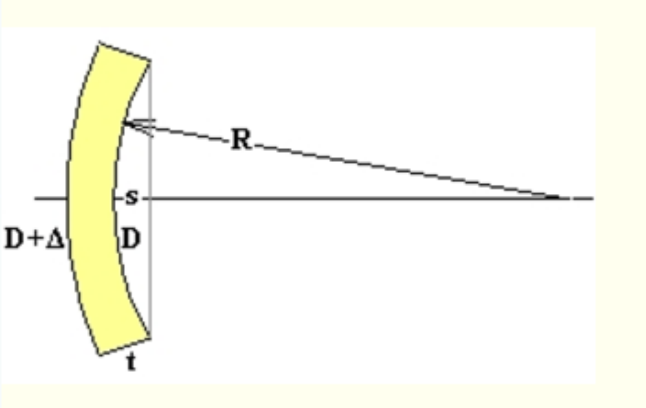
- As a laser beam contacts a mirror it will heat up the surface.
- This heat flux will cause a thermal expansion on the mirror based on its material

Thermal Expansion

- As a material undergoes a change in temperature it deforms.
- Every material has a coefficient of thermal expansion that defines this deformation α.
- Typical units are in ppm/K
- The higher the coefficient the larger the deformation
- The equation for linear thermal expansion is given as $\Delta L = L \alpha \Delta T$

Expected Deformation due to a liner temperature gradient

- In a liner case you expect a temperature gradient to cause a bending of the surface causing focus and spherical aberrations.



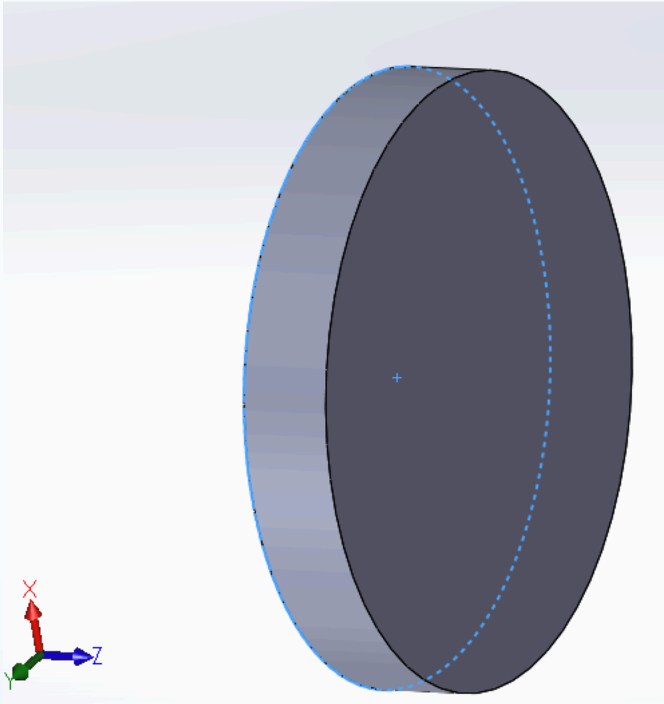
- The Radius of the sag is $R=(D \cdot t/\Delta)$
- Sag = $R-\sqrt{(R^2-(D/2)^2)}$

How to Model deformation

- Create a solid model
- Introduce the thermal gradient and use FEA to model the temperature
- Constrain your solid model
- Model deformation due to thermal load
- Process data into Zernike polynomials

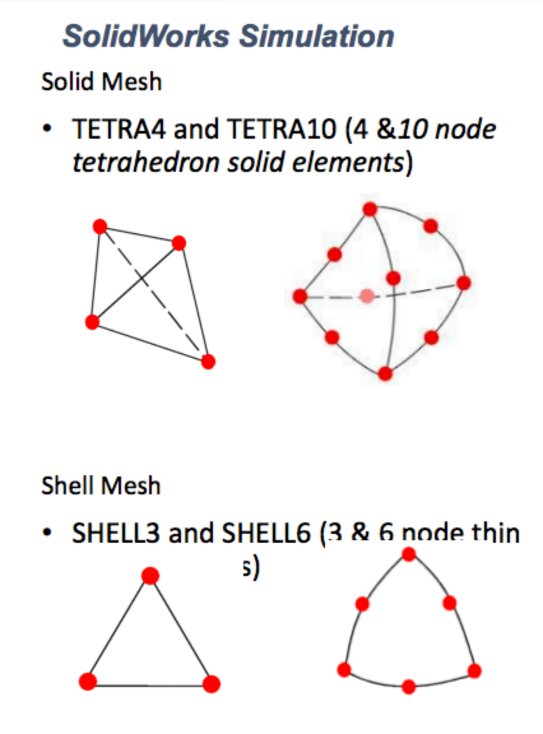
Making the solid model

- Use Solidworks or similar program.
- For this presentation a 100 mm diameter 15 mm thick Fused Silica mirror is made
- Transmission: 0.18 – 2.5 microns
- Young Modulus = 75.8 GPa
- α =3.25 ppm
- Thermal conductivity = 1.2 W/m/K



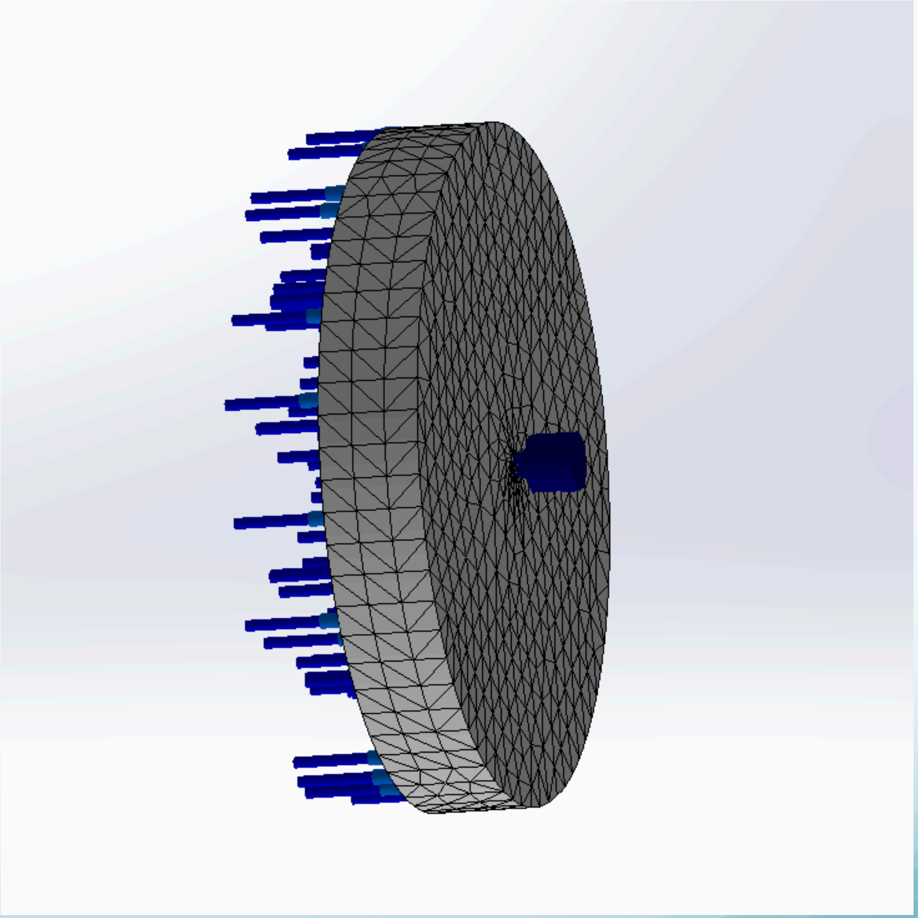
Brief overview of FEA

- FEA = Finite Element Analysis
- Turns one large problem into a series of smaller ones.
- Divide the solid body in elements connected by nodes.
- Solve in the form of a matrix
- $[K]\{u\}=\{F\}$
- => $\{u\}=[K]^{-1}\bullet\{F\}$



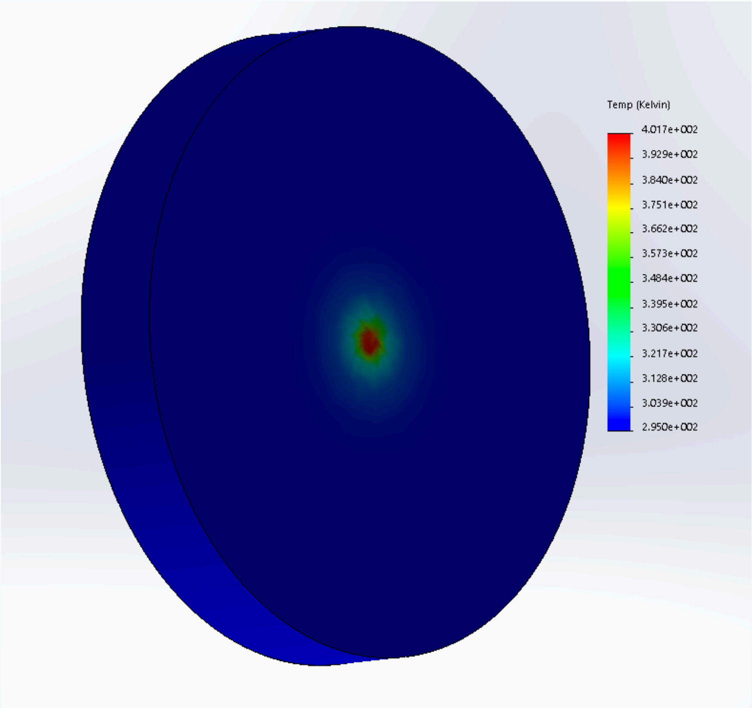
Prepare FEA

- Now we need to run a FEA to find a temperature solution.
- First we add loads to the solid model. In this case we add 1W of heat power in a 3mm diameter beam at the front surface. We set the back of the mirror to ambient temperature of 295K
- We create the mesh of elements and nodes



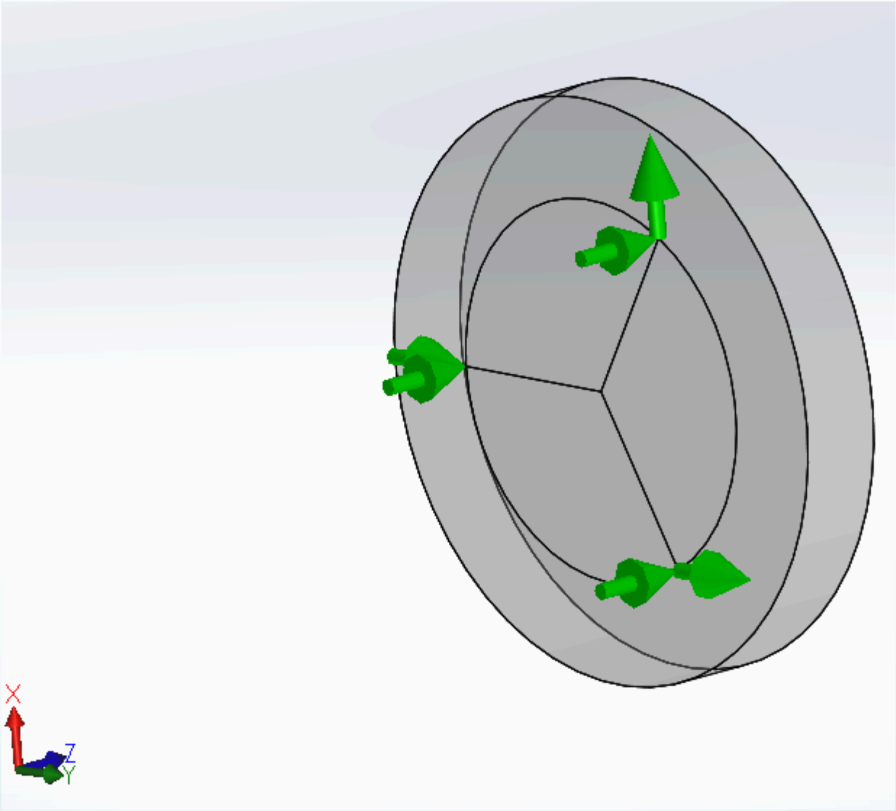
Run the thermal analysis

- Now we run the thermal analysis to get a temperature solution
- Temperature goes up to ~407 K at beam center



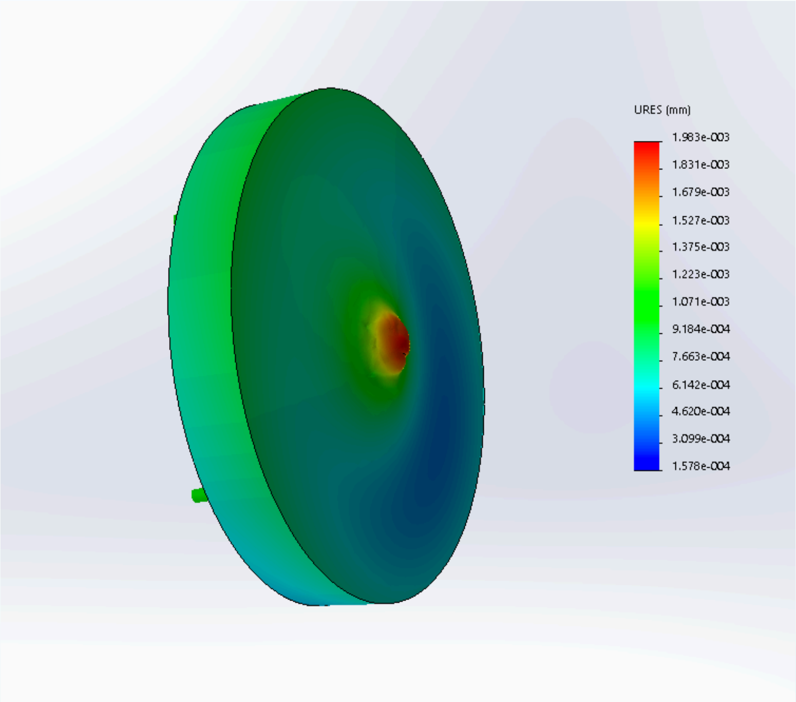
Mirror mounting

- With the thermal information in hand we move on the modeling the displacement caused by the thermal load. First we have to mount the mirror. We will use a standard 3 point mount on the back and set up the needed constraints in soildworks.



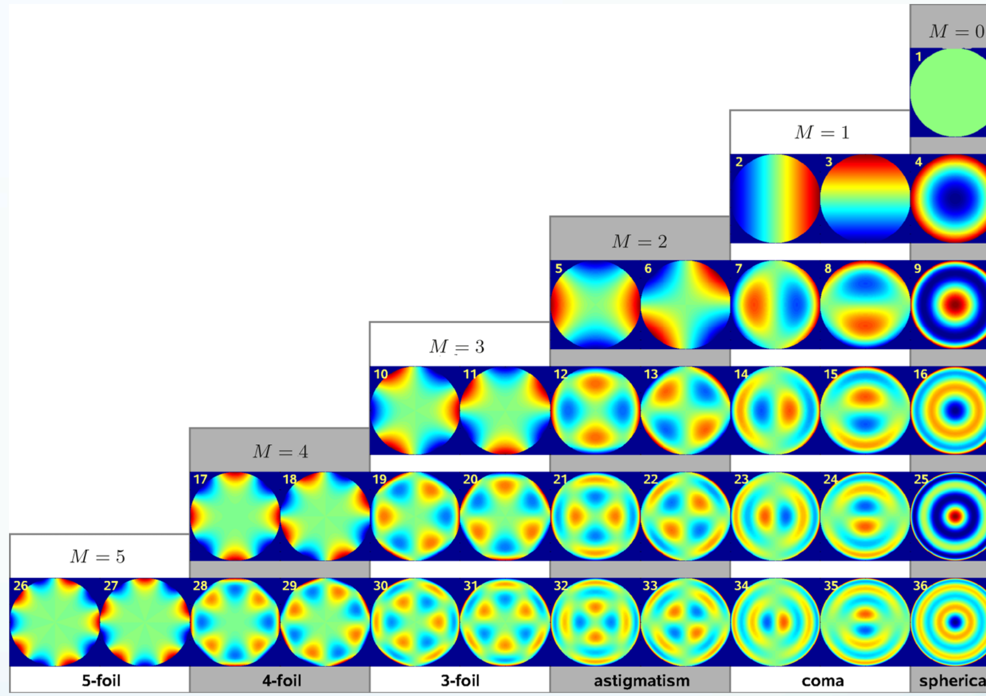
Create new mesh and run FEA to find displacement

- We make a new mesh considering the mounting.
- Using the thermal study as our load we can find the displacement, the center is displace almost 2 microns



Zernike Polynomials

- A series of polynomials that are orthogonal to the unit disk. Used to describe optical aberration.



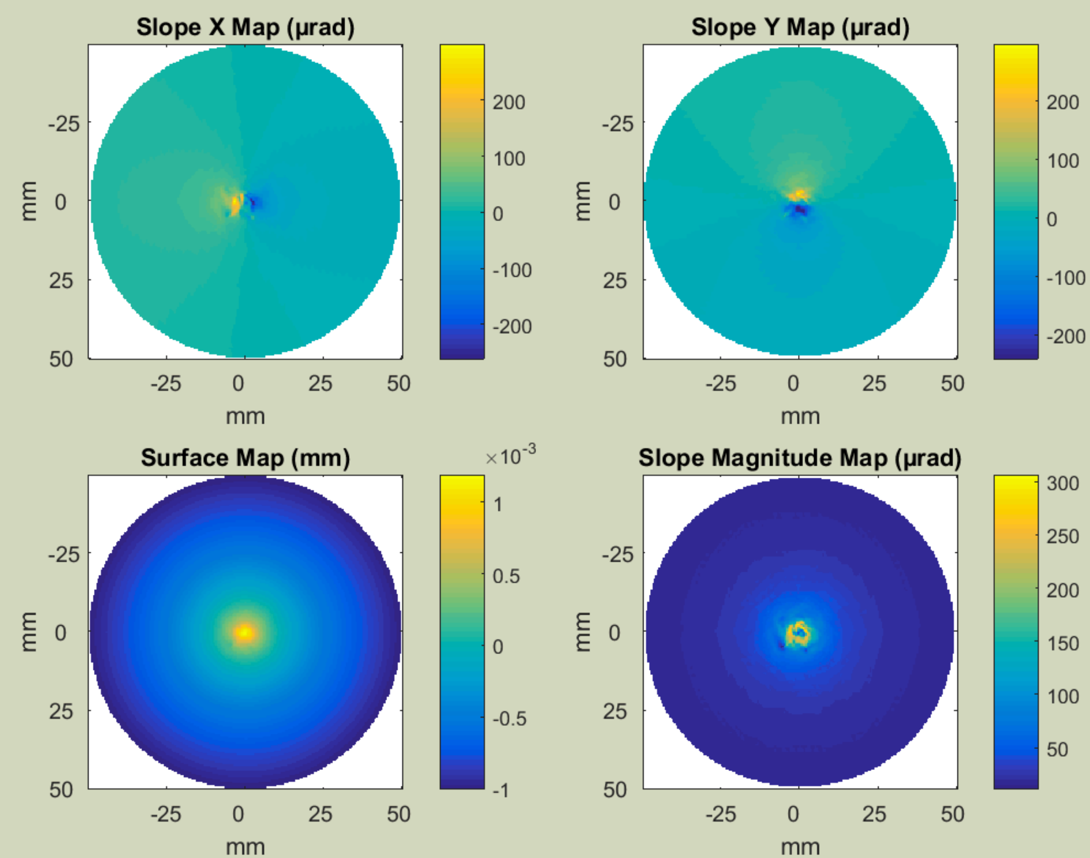
$$Z_n^m(\rho, \varphi) = R_n^m(\rho)\cos(m\,\varphi)$$

$$Z_n^{-m}(\rho, \varphi) = R_n^m(\rho)\sin(m\,\varphi)$$

$$R_n^m(\rho) = \sum_{k=0}^{\frac{n-m}{2}} \frac{(-1)^k\,(n-k)!}{k!\left(\frac{n+m}{2}-k\right)!\left(\frac{n-m}{2}-k\right)!}\,\rho^{n-2\,k}$$

Use data processing software

- I used the SAGUARO data processing package and was able to reconstruct the mirror surface shape.
- 0.7 microns RMS



Measure	Value	Units
Surface RMS	7.1721e-04	mm
Surface StdDev	3.1497e-04	mm
Surface P-V	0.0022	mm
Surface Min	-0.0010	mm
Surface Max	0.0012	mm
Slope Mag RMS	32.6046	µrad
Slope Mag Min	10.7321	µrad
Slope Mag Max	306.4390	µrad
Slope X RMS	22.7008	µrad
Slope X Min	-261.1852	µrad
Slope X Max	299.8044	µrad
Slope Y RMS	23.2895	µrad
Slope Y Min	-240.9378	µrad
Slope Y Max	297.1687	µrad

Show Slope X and Slope Y
Show Radial and Tangential Slope
Show Slope Magnitude only

Discard outliers from map
Limit = 3 × std.dev.

Conclusions

- Thermal effects due to laser beams can be large
- Need to be careful when selecting materials and coatings
- Not only must the material survive the power of the laser it can not deform too much due to the heat induced by the laser.