LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T1900258 *LIGO A+* 09 May 2019

A+ Beam Splitter Optical Surface Deformation due to Gravity

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Distribution of this document:
LIGO Scientific Collaboration

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1 Introduction

The Beam Splitter Optic design currently in work in Advanced LIGO (d=370mm) needed to be redesigned for A+ with a larger diameter (d=450mm) and thus reanalyzed to observe its deformation under gravitational load (body force). In order to have some sort of control system to compare new results to, the Static Structural Analysis of the Advanced LIGO optic was replicated and reworked in ANSYS Workbench 2019 R1 with the goal being to get as close to the original analysis results (documented in D080233) as possible creating a baseline design before making any A+ changes. These results compared to the original results, as well as the analysis results for the larger A+ optic, are discussed in this document.

2 Model

The Beam Splitter Optic in all of these analysis is fused silica with a nominal thickness of 60 mm. The aLIGO optic and the A+ optic differences are their diameters of 370 mm and 450 mm respectively. All of the data inputs kept constant among all analyses is as follows:

- Mesh
  - Body sizing of entire optic (element size = 0.01 m)
  - Face sizing of just split lines and clocking line (element size 0.001 m)
- Boundary Conditions
  - Cylindrical Support on just split lines (radial: fixed, axial: fixed, tangential: free)
  - Displacement Support on clocking center line (X: 0, Y: free, Z: 0)
  - Standard Earth Gravity (-Y Direction)
- Suprasil 3001 Material Properties
  - Density = 2.2 g/cm^3 = 2200 kg/m^3
  - Young's Modulus = 7.0x10^4 N/mm^2 = 7x10^{10} Pa
  - Thermal Conductivity = 1.38 W/m·K = 1.38 W/m·°C
  - Specific Heat = 772 J/kg·K = 772 J/kg·°C
  - Tensile Yield Strength = 50 N/mm^2 = 5x10^7 Pa
- Relevant Structural Steel Properties (from ANSYS Materials Library)
  - Density = 7850 kg/m^3
  - Young's Modulus = 2x10^{11} Pa
  - Thermal Conductivity = 60.5 W/m·°C
  - Specific Heat = 434 J/kg·°C
  - Tensile Yield Strength = 2.5x10^8 Pa
  - Tensile Ultimate Strength = 4.6x10^8 Pa
- Solution
  - Directional Deformation in the Z Axis (for front and back faces)
    - Front face (S1) normal vector has the same direction as the global Z axis
  - Total Deformation in the Z Axis (for entire body)

The wire loops that support the suspended weight of the optic are modeled in this analysis as split lines distanced 10mm apart from each other centered about the geometric origin of the optic. It is important to note that this geometric center is not always be the same as the optic's center of gravity. This greatly depends on the presence of a wedge angle and how that angle is modeled (1 of 3 wedge angle designs)

**See Figures 12-14 in Appendix 1 for the selections of the necessary Boundary Conditions

3 Advanced LIGO Optic Analysis Replication

The purpose of these replication ANSYS analyses is to try to get as close as possible to reproducing the findings from a previous ANSYS analysis done on this same optic a while ago (see LIGO-T080233). To make sure I ruled out all possible result affecting factors, I used 8 different geometries to narrow down which geometry fit the closest to the initial geometry used in the previous analysis.

The 6 geometries I tested are:

1) Incorrect wedge and Structural Steel (SS) material
2) No wedge and SS material
3) Correct wedge and SS material
4) Incorrect wedge and correct (Suprasil 3001) material
5) No wedge and correct material
6) Correct wedge and correct material
7) Real Life Wedge and correct material
8) Incorrect Wedge, correct material, and skewed split lines

I started my analyses with structural steel to see how large of a difference the material made on the overall results. Also, because the previous analysis that I was attempting to replicate didn't have defined material properties. I had to later obtain these Suprasil 3001 properties from a different source.

The different wedge types listed are to cover an array of different wedge angles that were communicated to me in different ways. Although the previous analysis used an optic model without a wedge angle, I wanted to get a realistic view of how the wedge angle actually affected the analysis results. But in order to do this, I had to correctly model the optic with an angle. How the wedge angle was directly explained to me is what I deemed the "correct" wedge angle while the CAD model of the optic in the LIGO vault, which was modeled differently, I deemed the "incorrect" wedge angle. The third "real life wedge" angle is what I found upon further investigation of how the optics currently in use today were manufactured (See related documents in Q1100083 relevant to BS Fiducial Line Measurements). Figure 1 below gives a visual of how these wedge angles differ.

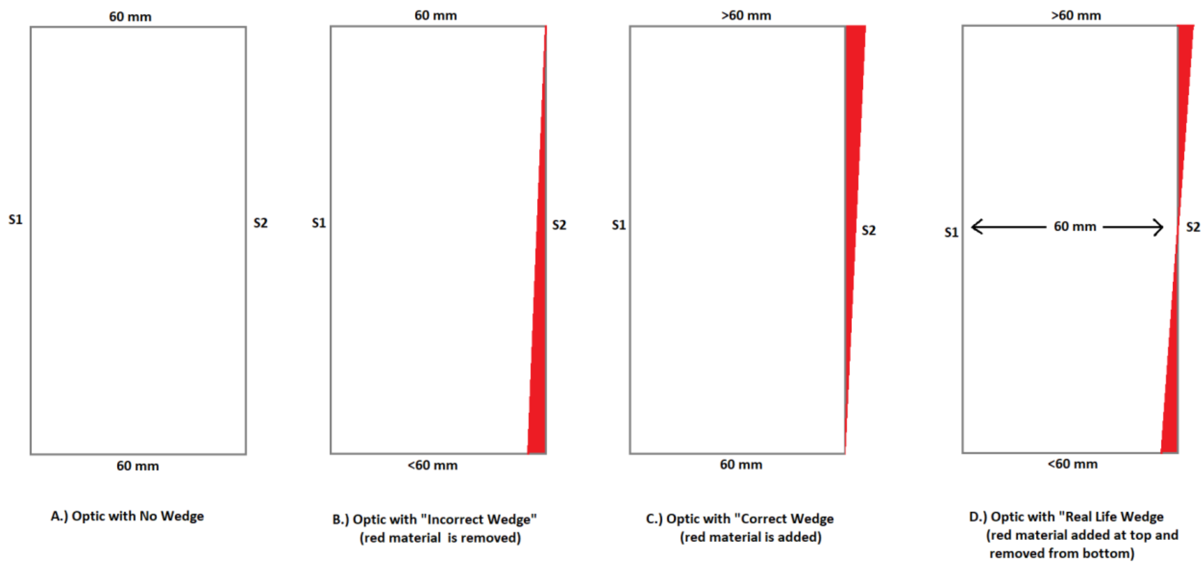

Figure 1: Wedge angle differences top view (wedge angles over exaggerated for reference)

For clarification, S1 is the front face of the optic while S2 is the back face. The "incorrect" wedge optic has a maximum thickness of 60mm, the "correct" wedge optic has a minimum thickness of 60mm, and the "real life" wedge has a central thickness of 60mm. So although one design was deemed as "correct" it may not be correct after all. This will take further investigation, but in the meantime, the no wedge angle optic is the one that most closely reproduced the analyses of before so that is the one that was used in the model of the larger diameter A+ optic (d=450mm) described further in a sections.

The results of all 8 models are described in Table 1 below. Note that case 8 was just an experiment to see if skewing the split lines boundary conditions (making each line parallel to the surface it was closest to instead of both parallel to S1) would reduce the pitching affect the wedge seemed to have on the optic. The results of these weren't found to be that significantly different.

Table 1: ANSYS static structural analysis findings for the 370x60mm optic

370 x 60 mm Optic		Mesh		Directional Deformation Front Face (nm)			Directional Deformation Back Face (nm)			Directional Deformation Entire Body (nm)		
Geometry Info	Weight (kg)	Nodes	Elements	Max	Min	Sag	Max	Min	Sag	Max	Min	Sag
Original Analysis (by Calum Torrie)	**14**	**100000**	**62000**	**1.9958**	**-0.9114**	**2.9**	**0.93537**	**-1.9908**	**2.9**	**2.1259**	**-2.1021**	**4.2**
1 - Incorrect Wedge + SS	50.5	95,896	64,817	12.423	0	12.4	12.42	-3.7437	16.2	12.42	-3.7437	16.2
2 - No Wedge + SS	50.6	95,854	64,846	4.3258	-0.95961	5.3	0	-4.445	4.4	4.3258	-4.445	8.8
3 - Correct Wedge + SS	50.8	95,656	64,678	3.7683	-12.54	16.3	0	-12.538	12.5	3.7653	-12.54	16.3
4 - Incorrect Wedge + S3001	14.2	95,896	64,817	9.9229	-1.2317	11.2	9.9238	-1.9315	11.9	9.924	-2.6567	12.6
5 - No Wedge + S3001	**14.2**	**95,854**	**64,846**	**2.3946**	**-1.2108**	**3.6**	**1.1975**	**-2.4644**	**3.7**	**2.6367**	**-2.6753**	**5.3**
6 - Correct Wedge + S3001	14.2	95,656	64,678	1.9367	-10.042	12	1.1945	-10.041	11.2	2.665	-1.004	3.7
7 - Real Life Wedge + S3001	**14.2**	**96,264**	**65,093**	**2.4018**	**-1.2051**	**3.6**	**1.1884**	**-2.4575**	**3.6**	**2.6832**	**-2.6818**	**5.4**
8 - Incorrect Wedge + skewed split lines	14.2	91,345	61,972	8.4949	-1.2044	9.7	8.4958	-1.9822	10.5	8.4961	-2.626	11.1

Since case 5 produced the closest results to the original analysis (with case 7 being the second closest) this optic design was used to create and analyze the optic at the larger A+ diameter. The results from case 5 (no wedge and Suprasil 3001 material) are further revealed in Figures 2-6 below.

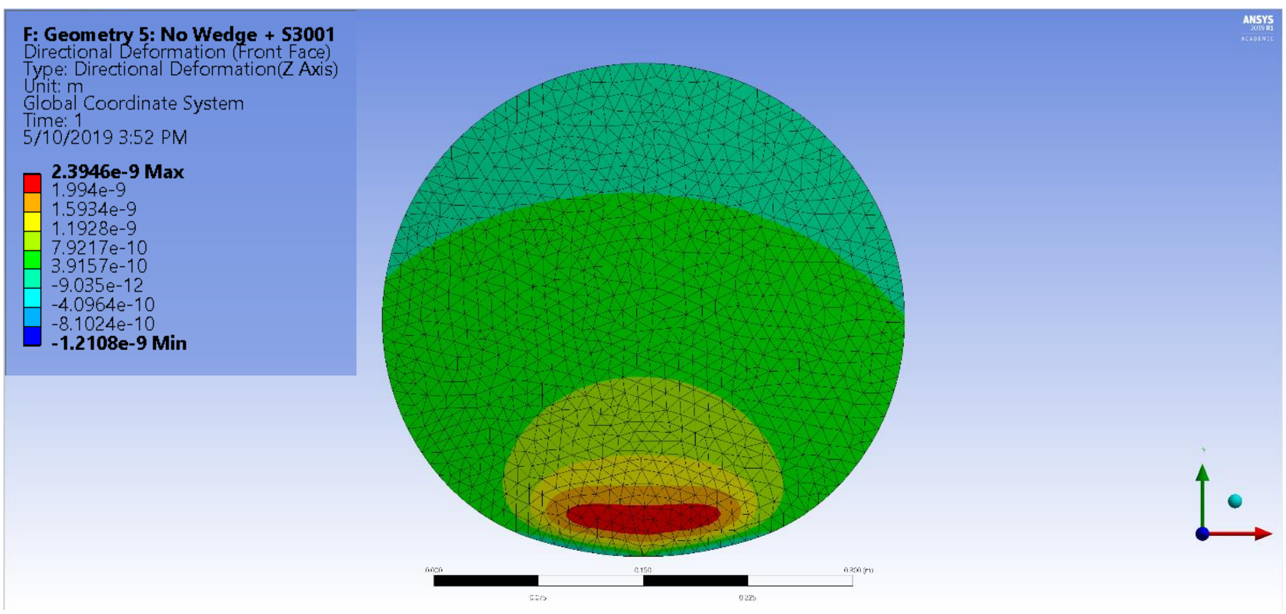

Figure 2: Front face normal displacement of replicated 370x60mm optic with no wedge

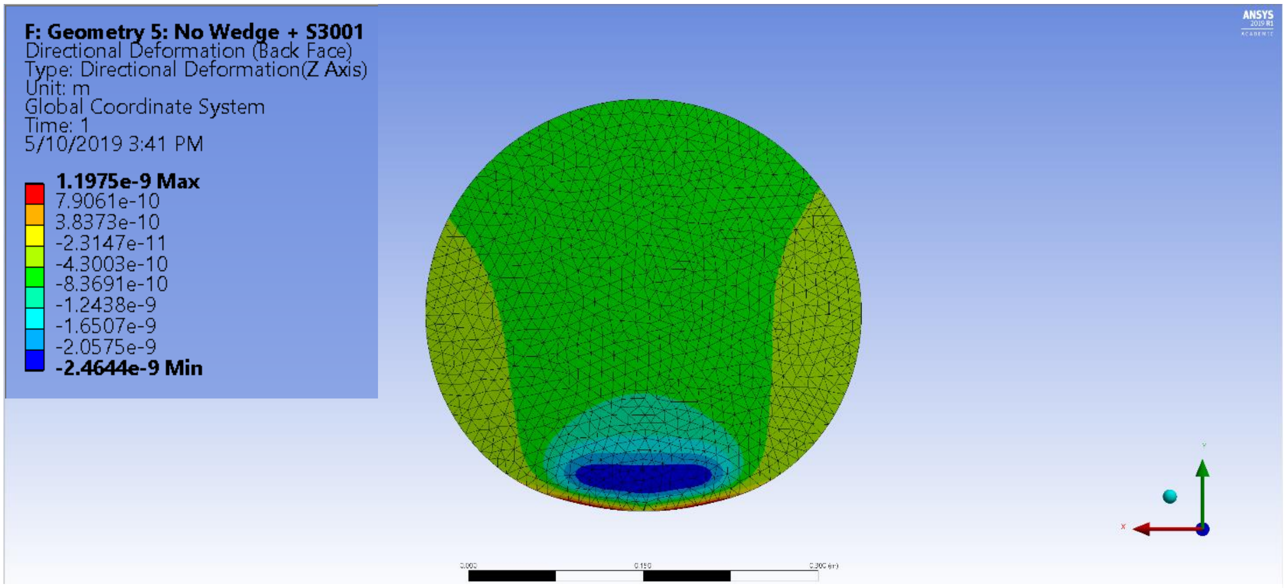

Figure 3: Back face normal displacement of replicated 370x60mm optic with no wedge

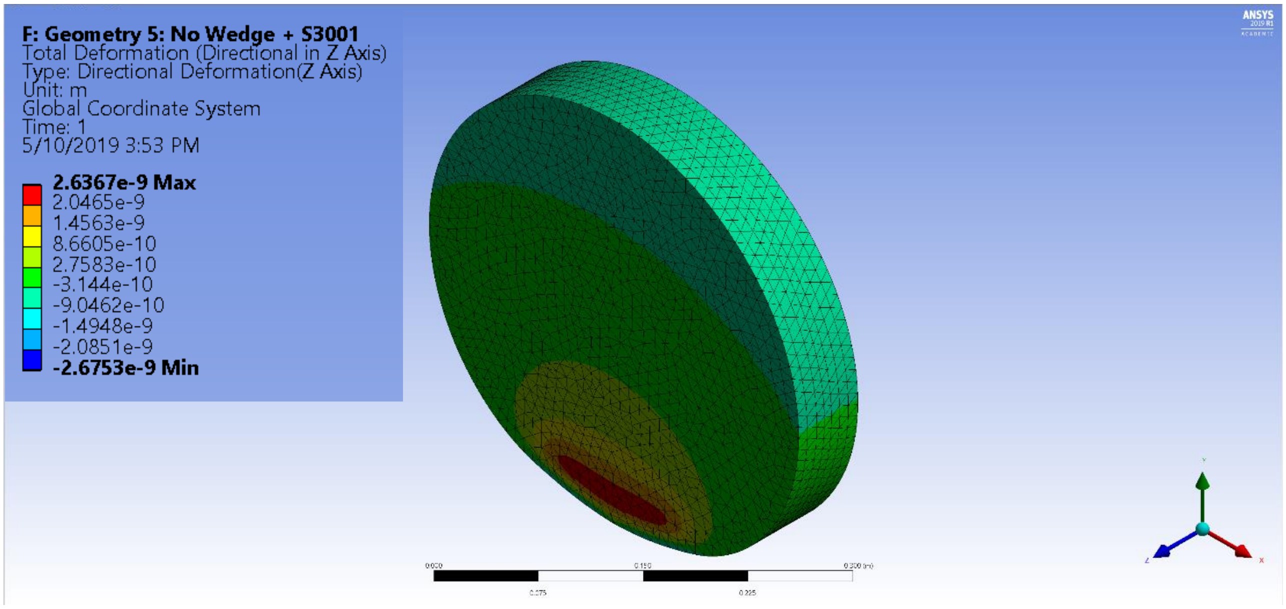

Figure 4: Isometric front view of replicated 370x60mm optic with no angle

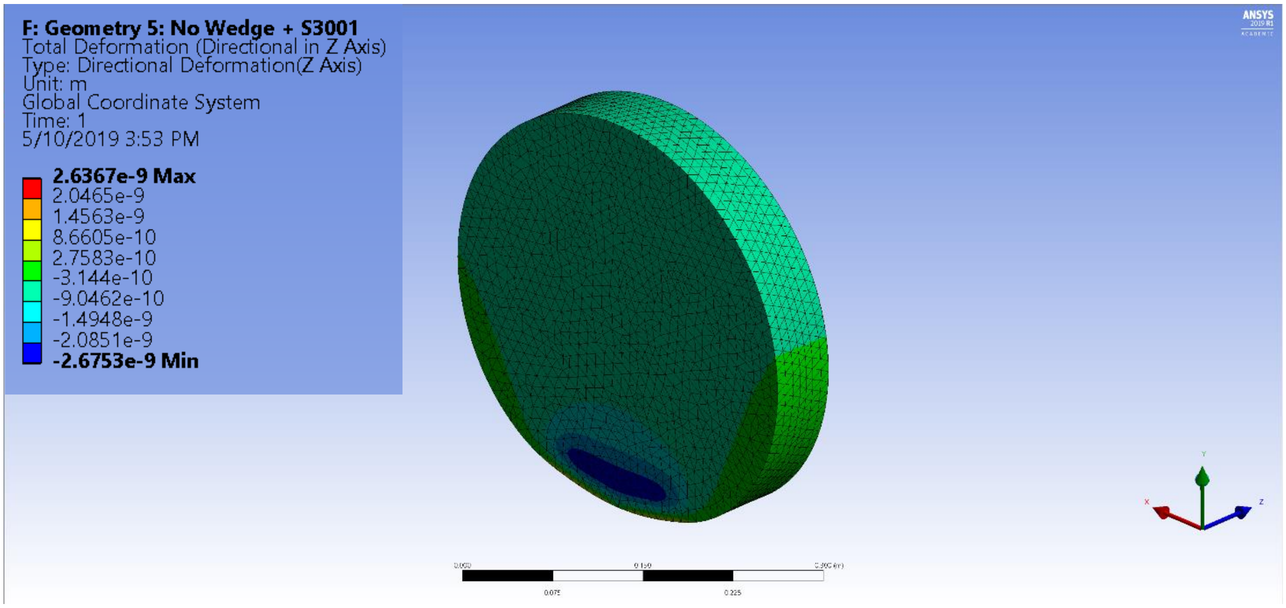

Figure 5: Isometric back view of replicated 370x60mm optic with no wedge

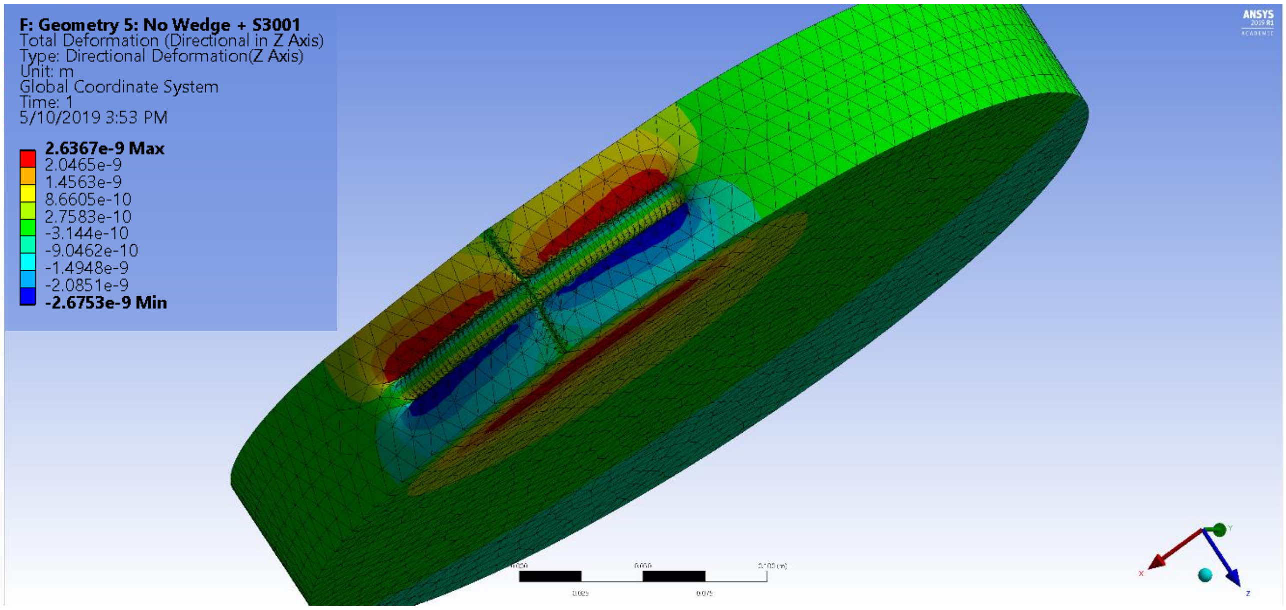

Figure 6: Location of wires on 370x60mm optic with no wedge

4 A+ Optic Analysis

As mentioned in the previous section, the analysis of the "real life wedge" optic, I found that the numbers weren't much different from the "no wedge" scenario because material was taken out of one side and added back to the other side of the optic symmetrically, which ended up pretty much canceling out the wedge entirely. So because of this and the fact that the "no wedge" optic results were slightly closer to the original results, I decided to use the no wedge design as my base for the larger diameter A+ optic. Analysis of the 450x60mm optic with no wedge is described in Table 2 and Figures 7-11 below.

Table 2: ANSYS static structural analysis findings for the 450x60mm optic

450 x 60 mm Optic		Mesh		Directional Deformation Front Face (nm)			Directional Deformation Back Face (nm)			Directional Deformation Entire Body (nm)		
Geometry Info	Weight (kg)	Nodes	Elements	Max	Min	Sag	Max	Min	Sag	Max	Min	Sag
9 - No Wedge + S3001	20.994	133877	91315	3.5294	-1.7241	5.3	1.6775	-3.4552	5.1	4.0205	-4.0507	8.1

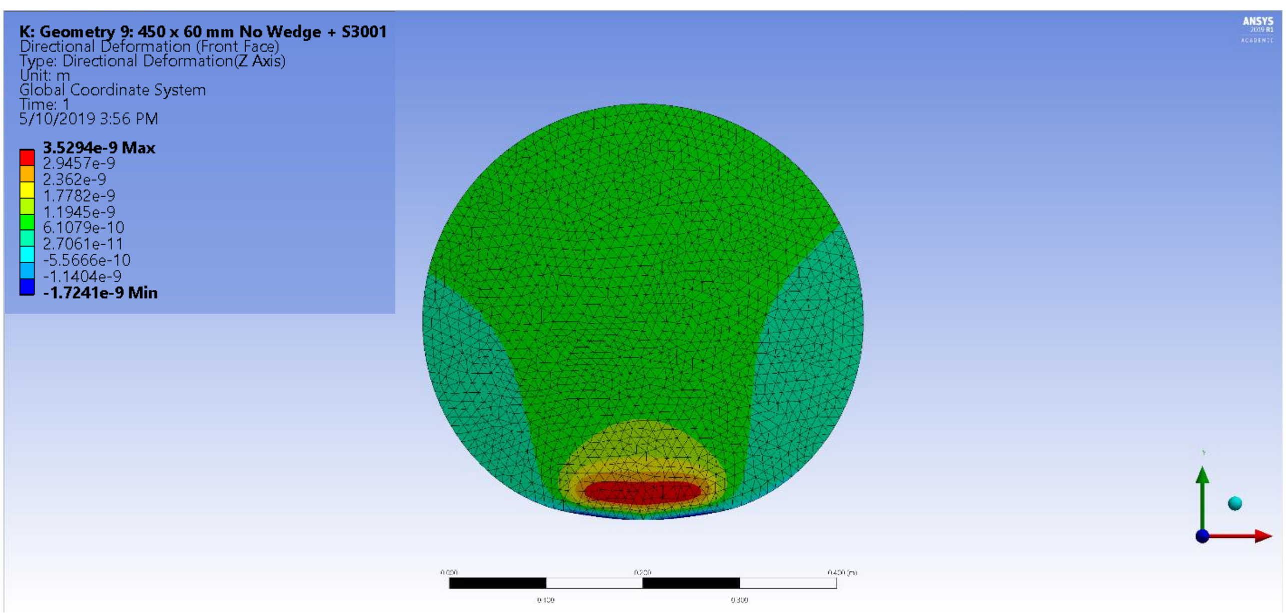

Figure 7: Front face normal displacement of A+ 450x60mm optic with no wedge

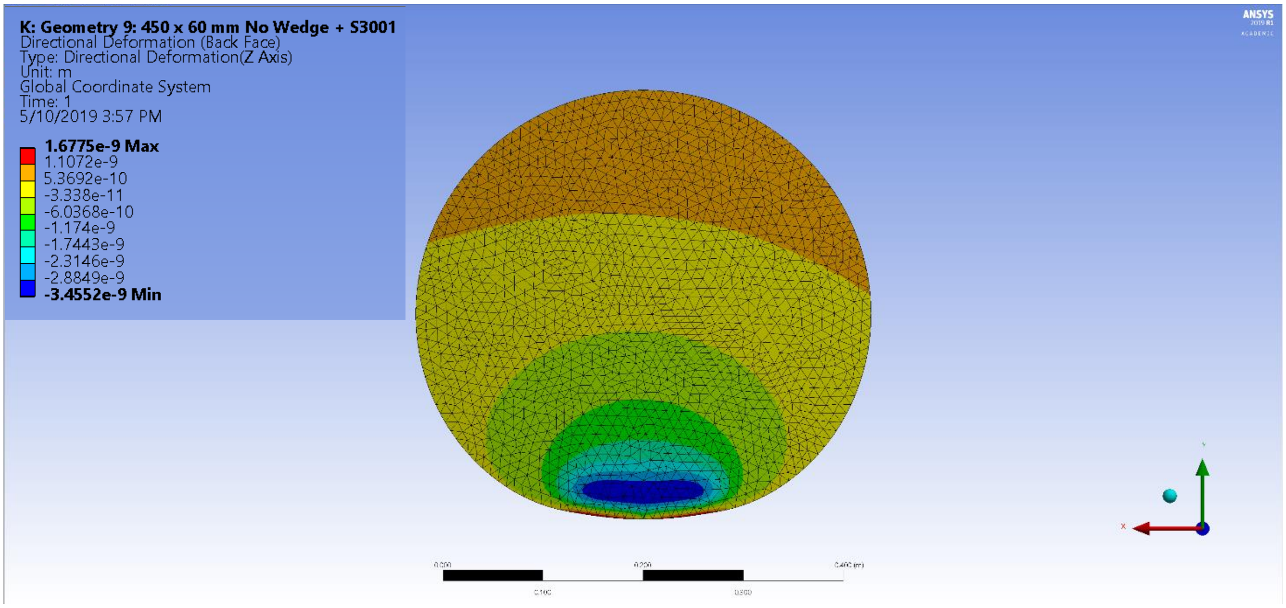

Figure 8: Back face normal displacement of A+ 450x60mm optic with no wedge

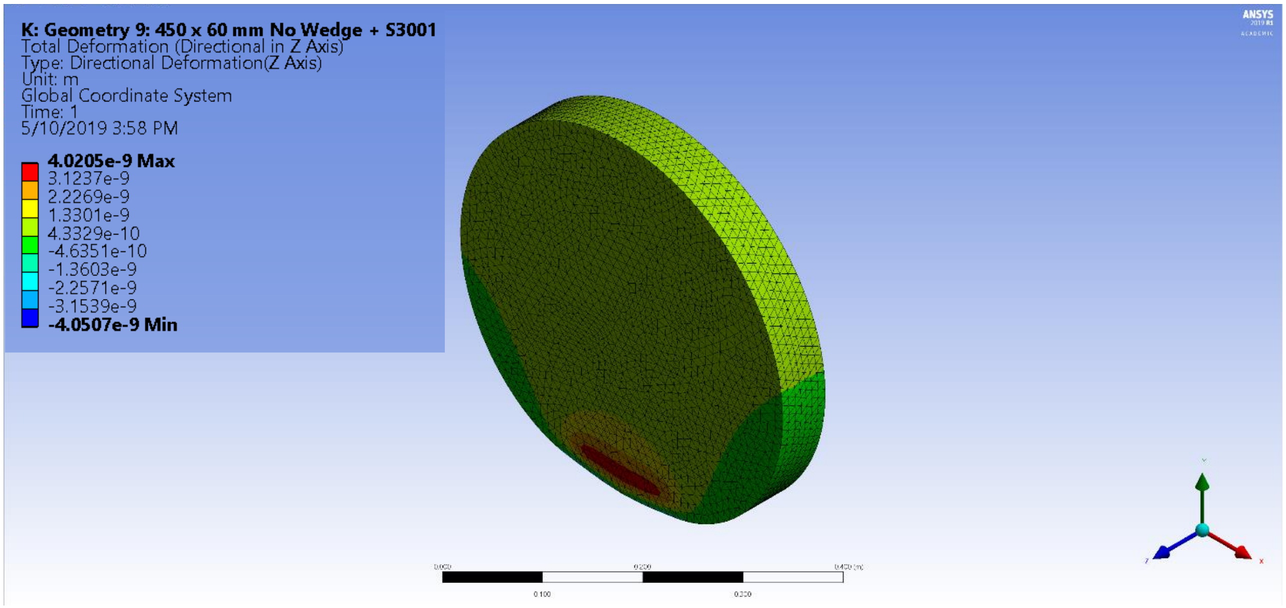

Figure 9: Front isometric view of A+ 450x60mm optic with no wedge

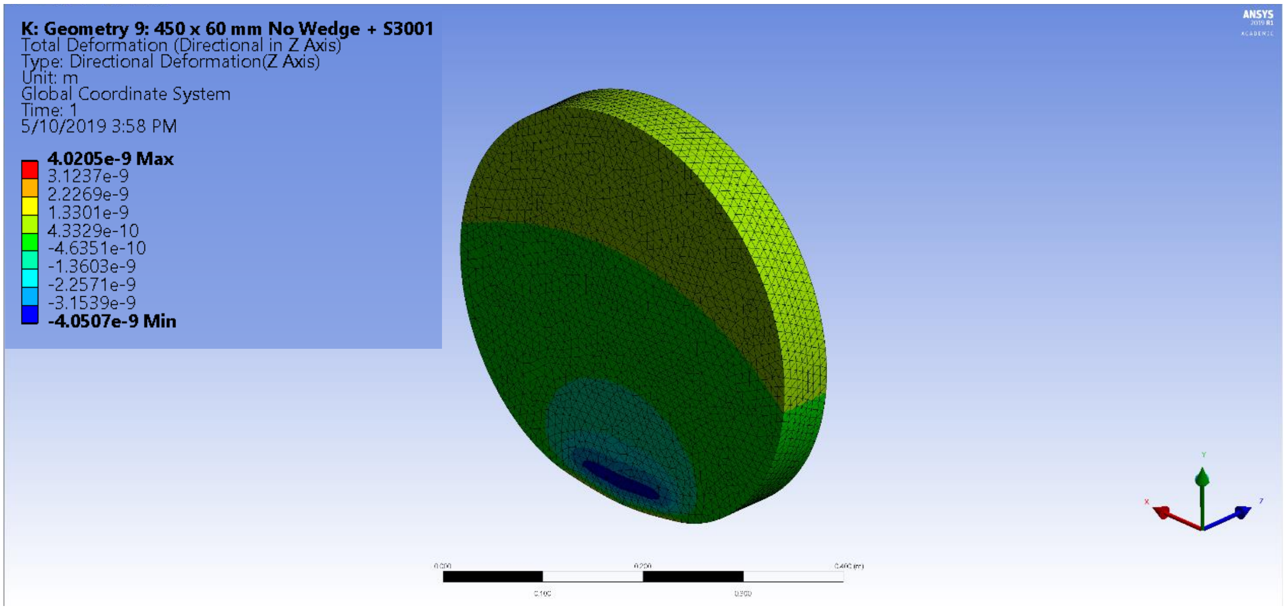

Figure 10: Back isometric view of A+ 450x60mm optic with no wedge

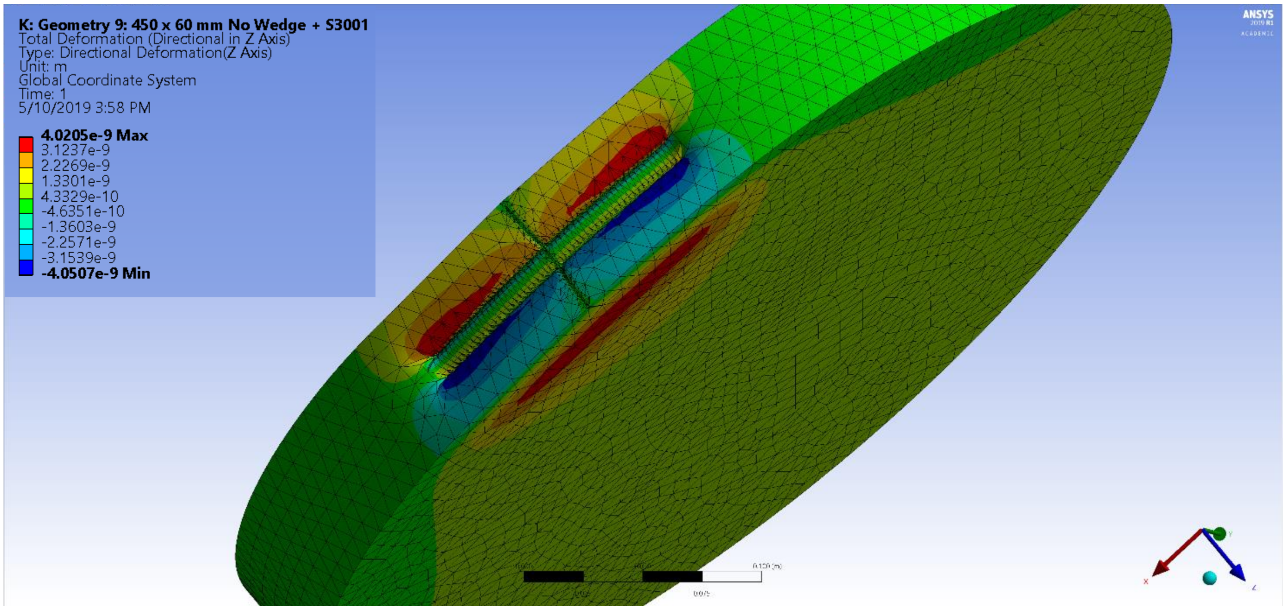

Figure 11: Location of wires on A+ 450x60mm optic with no wedge

5 Going Forward

After thorough static structural analysis of the optic and its many design options, we got close to the original analysis results but not an exact replication. There are many possible explanations for why we could not replicate these results exactly including issues with mesh sizing, the size and positions of the split lines, the upgrade differences between ANSYS Workbench version-11.1 to version 2019 R1, etc. The main thing to discuss now is whether these discrepancies are significant enough to be investigate further or minor enough to be considered a successful replication of results. Once that decision has been made, the larger optic design can be assessed and put into work for A+.

6 Appendices

Appendix 1

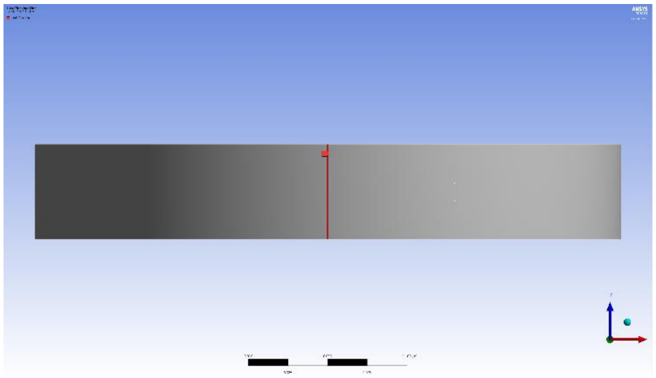

Figure 42: Clocking Line for Displacement Support

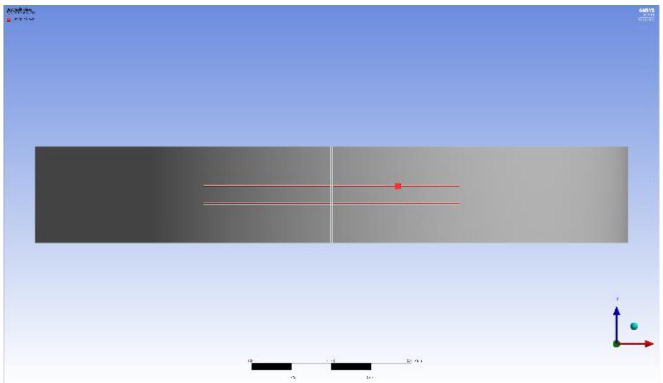

Figure 13: Split Lines for Cylindrical Support

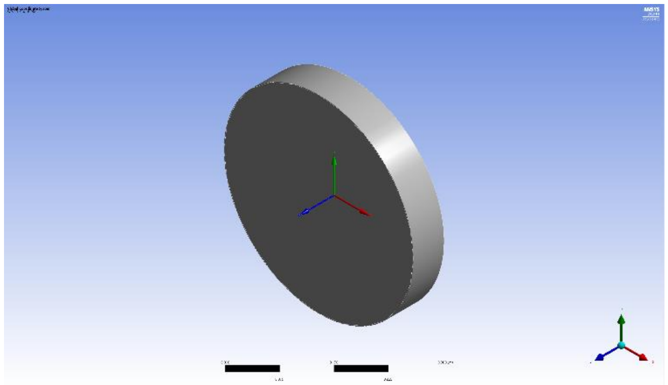

Figure 14: Global Coordinate System (Normal to S1)