VOPO Suspension Final Design

LIGO MIT Lab

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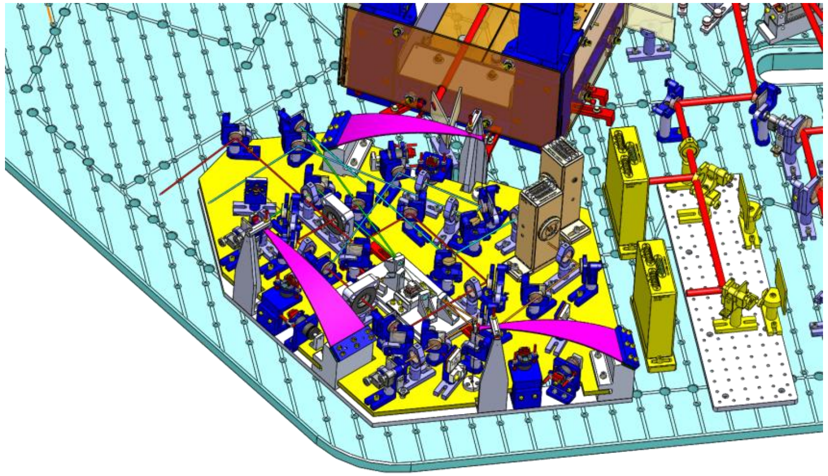
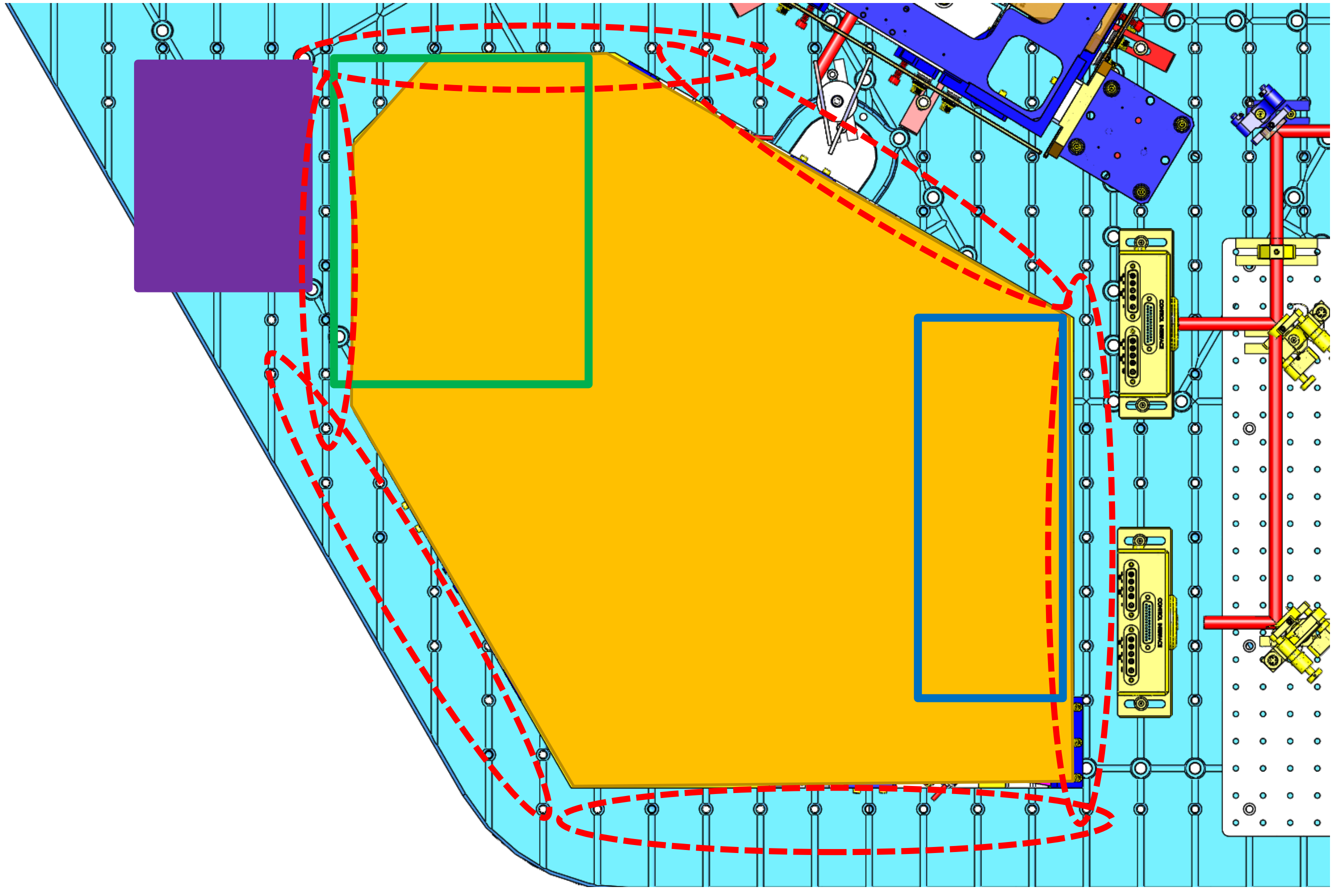
VOPO Suspension

- Design based on HAM 6



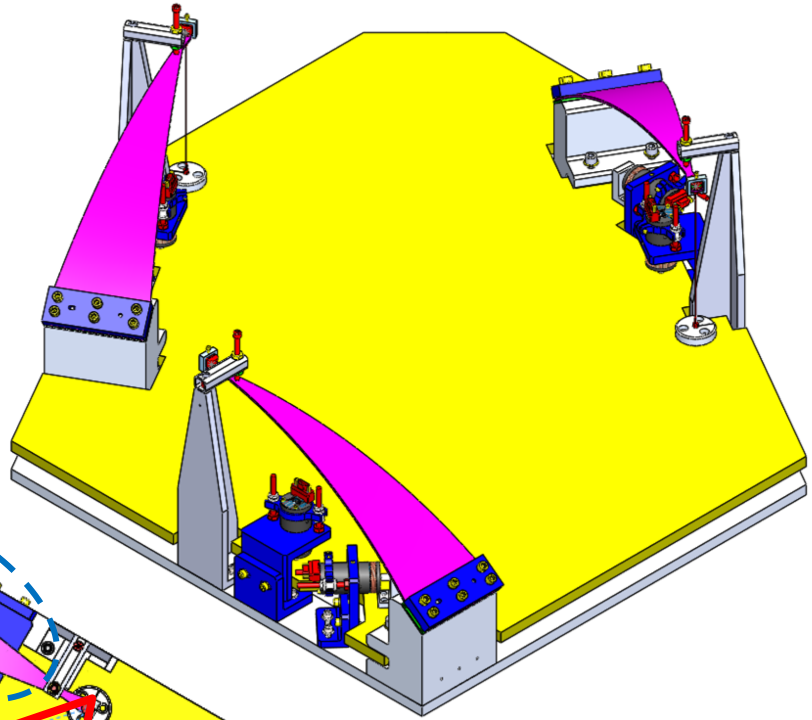
- Holes availability (Dog Clamps)
- “Shooting” Area (for the outcome beam)
- In Vacuum RFPD Area
- Space for Tip Tilt



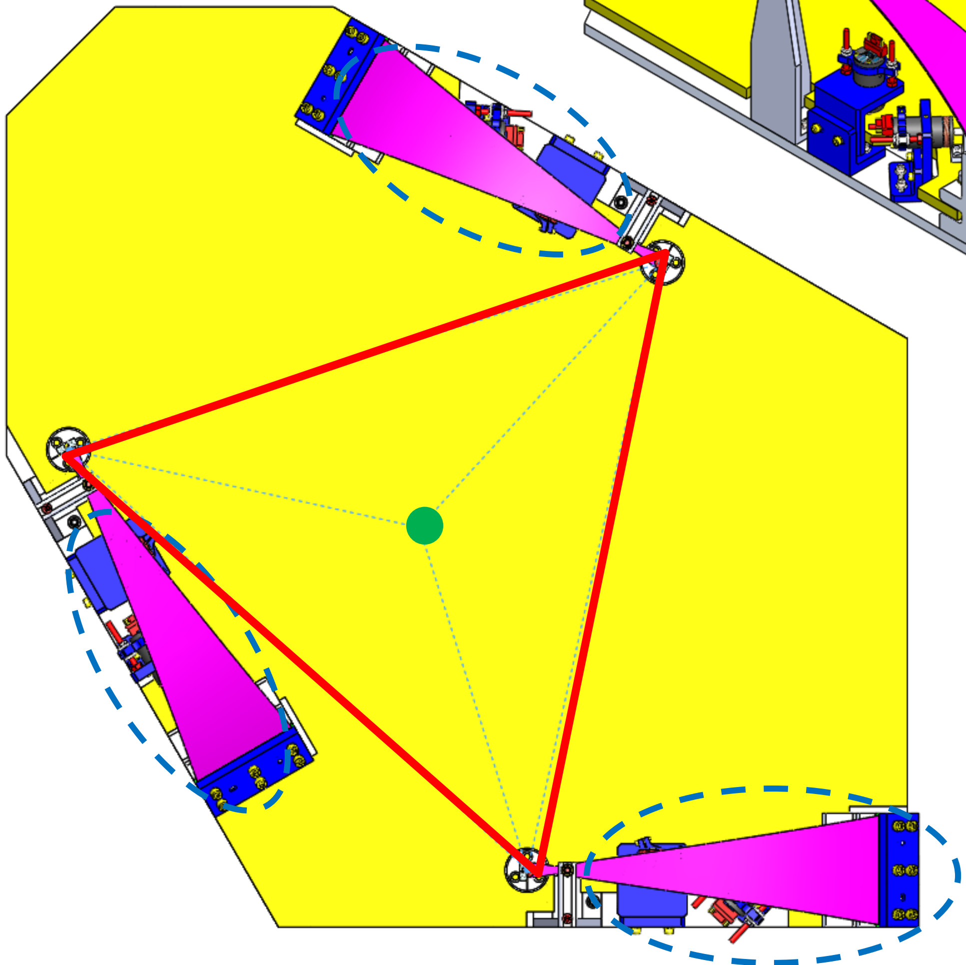
Maximizing Bench Surface: 3.64 ft^2

VOPO Suspension

- Blade with 3-axial symmetry



- Blades clamps form equilateral triangle
- Triangle center close to “Geometric Center” (easy to balance)
- Stops separated enough



VOPO Suspension

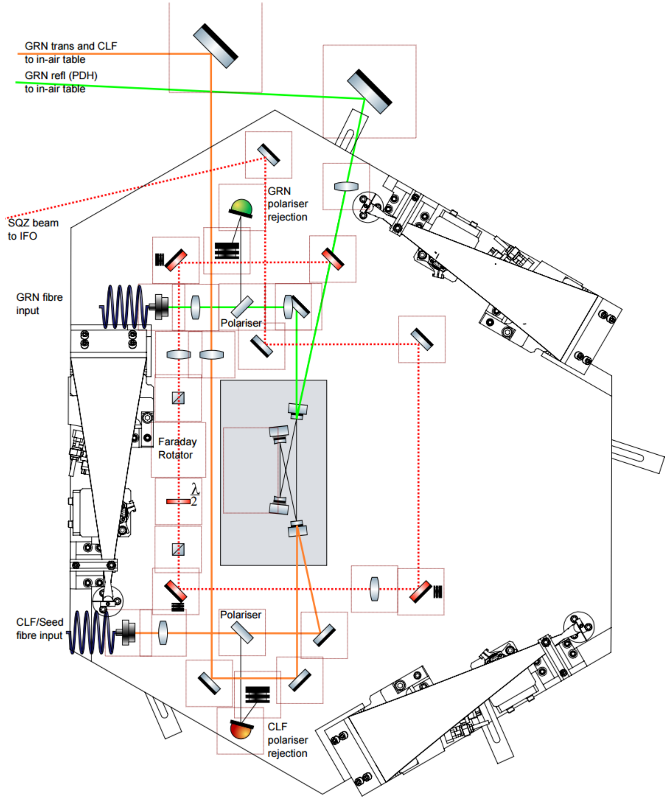
- Conclusions:

- Questions:
  - Is it enough space for the Tip Tilt?
  - Do we need a Tip Tilt?
  - Is it enough shooting space?

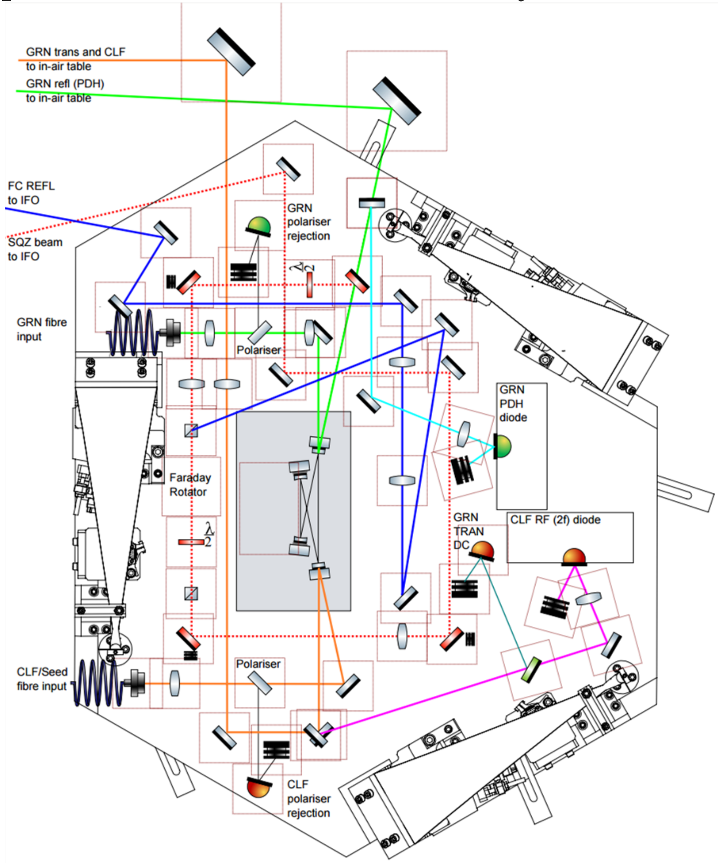
Optical Layout

- 2 different layouts:

- O2 Squeezer model (*early* squeezing)



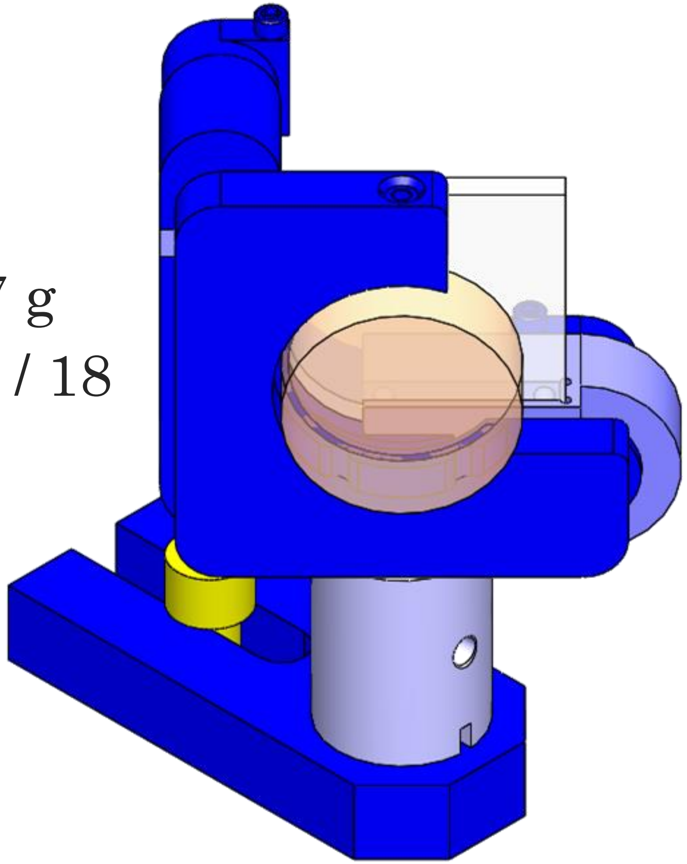
- O3 Squeezer model with filter cavity + RFPD in Vacuum

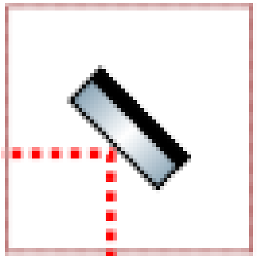


Optical Layout

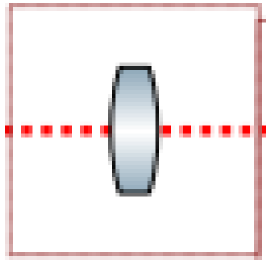
- Solid Works Optical Layout

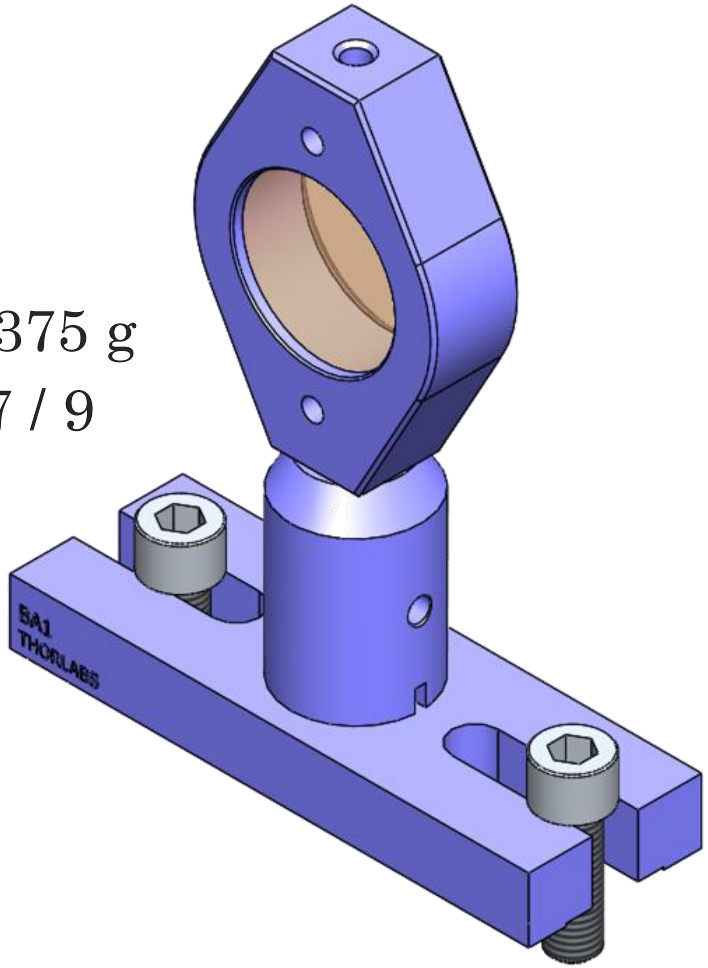
- Mirror:
  - Mass: 205.87 g
  - Quantity: 11 / 18





- Lens:
  - Mass: 121.375 g
  - Quantity: 7 / 9

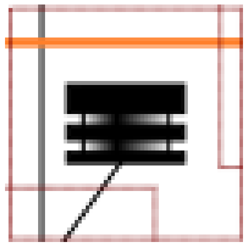


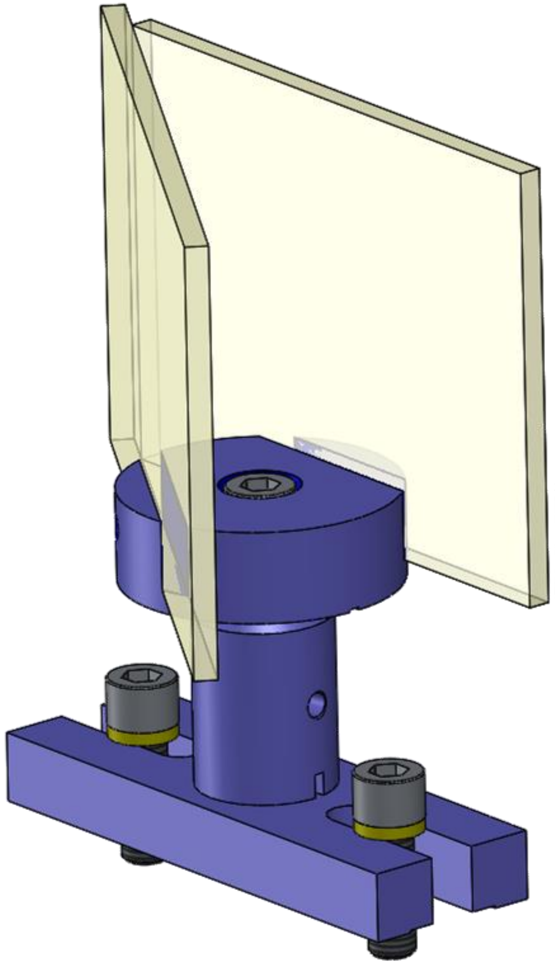


Optical Layout

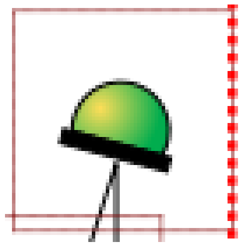
- Solid Works Optical Layout

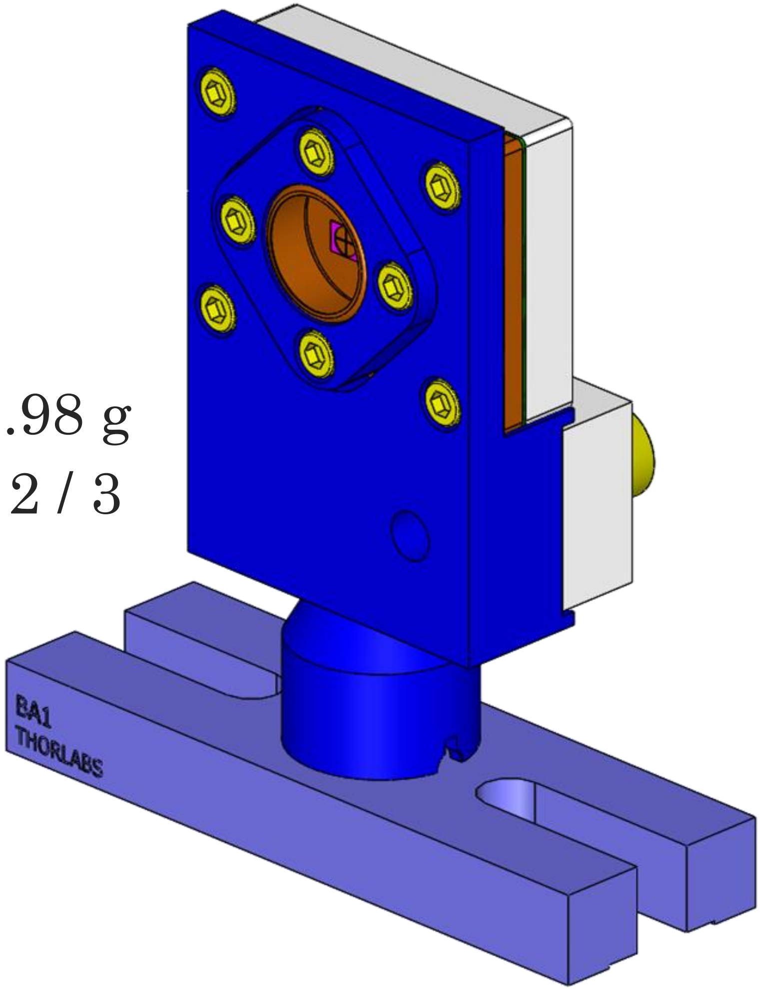
- Beam Dump:
  - Mass: 164.61 g
  - Quantity: 2 / 5





- QPD:
  - Mass: 142.98 g
  - Quantity: 2 / 3

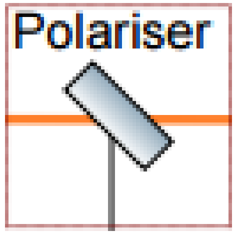


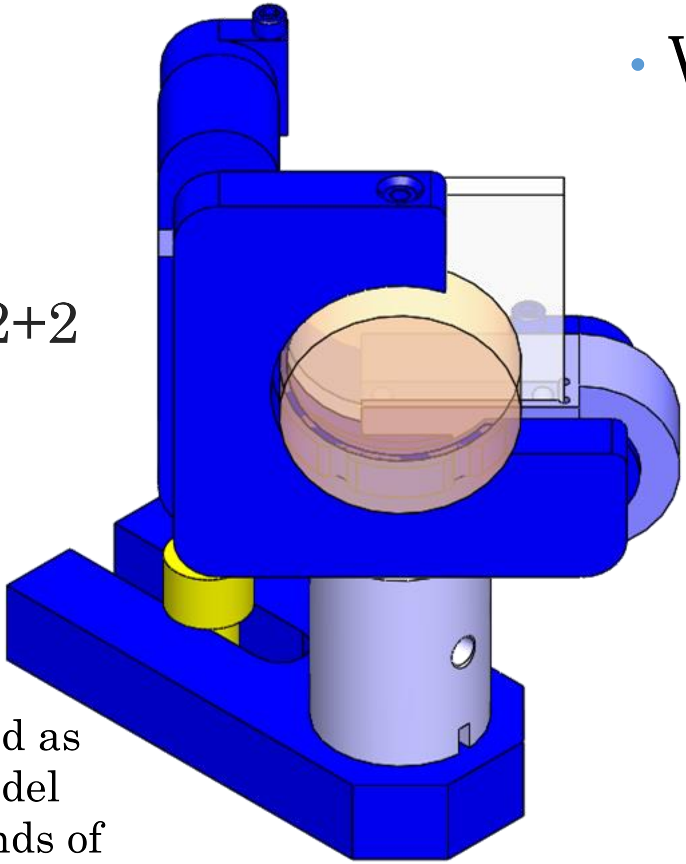


Optical Layout

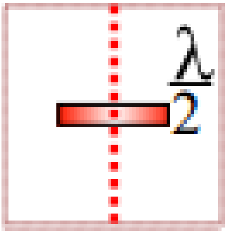
- Solid Works Optical Layout

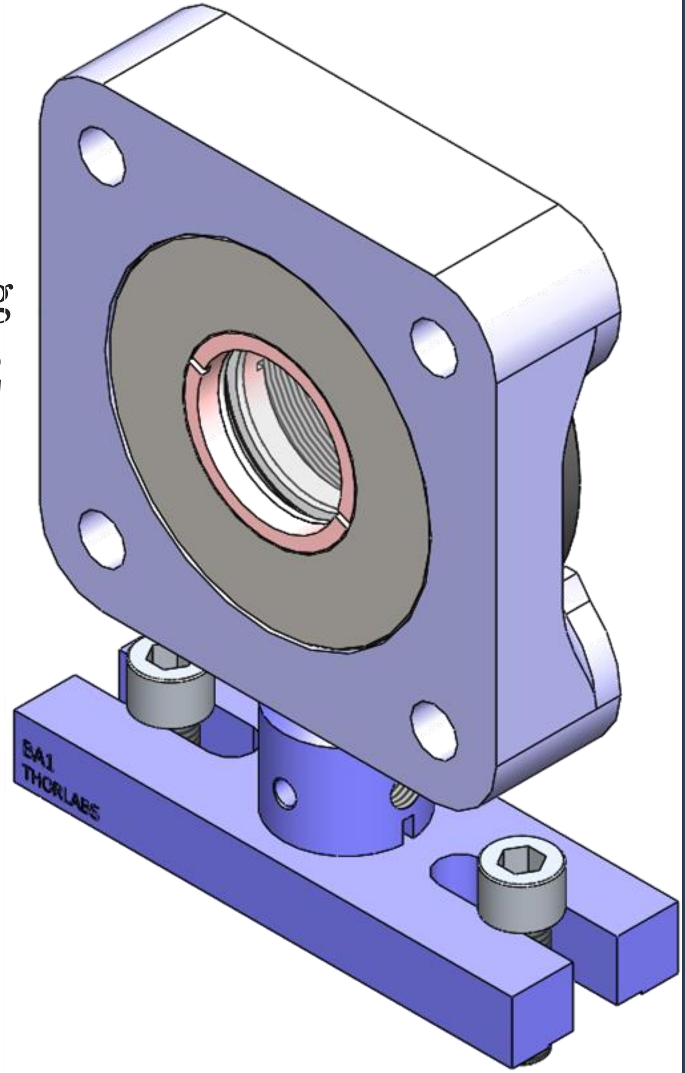
- Polarizers:
  - Mass: 206.71 g
  - Quantity: 2+2 / 2+2





- Wave Plate:
  - Mass: 299.69 g
  - Quantity: 1 / 2



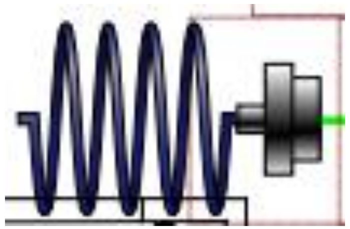


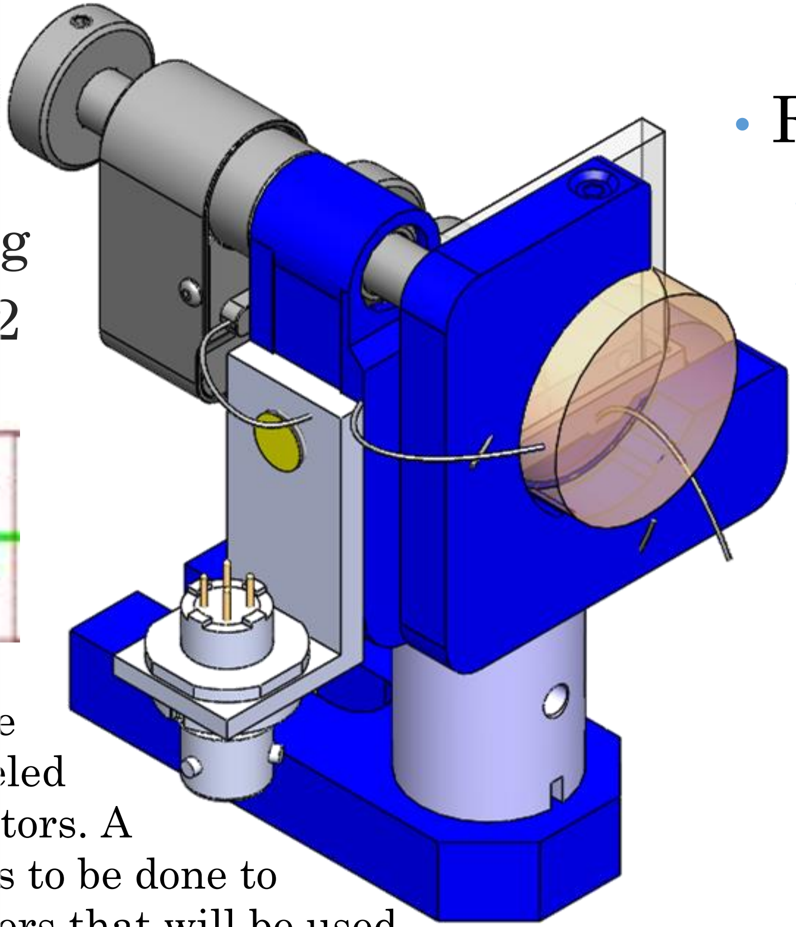
NOTE: At this point the polarizers have been modeled as mirrors. A more realistic model has to be done to the two kinds of polarizers that will be used.

Optical Layout

- Solid Works Optical Layout

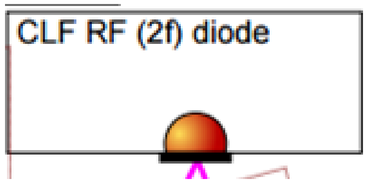
- Fibers In:
  - Mass: 252.01 g
  - Quantity: 2 / 2

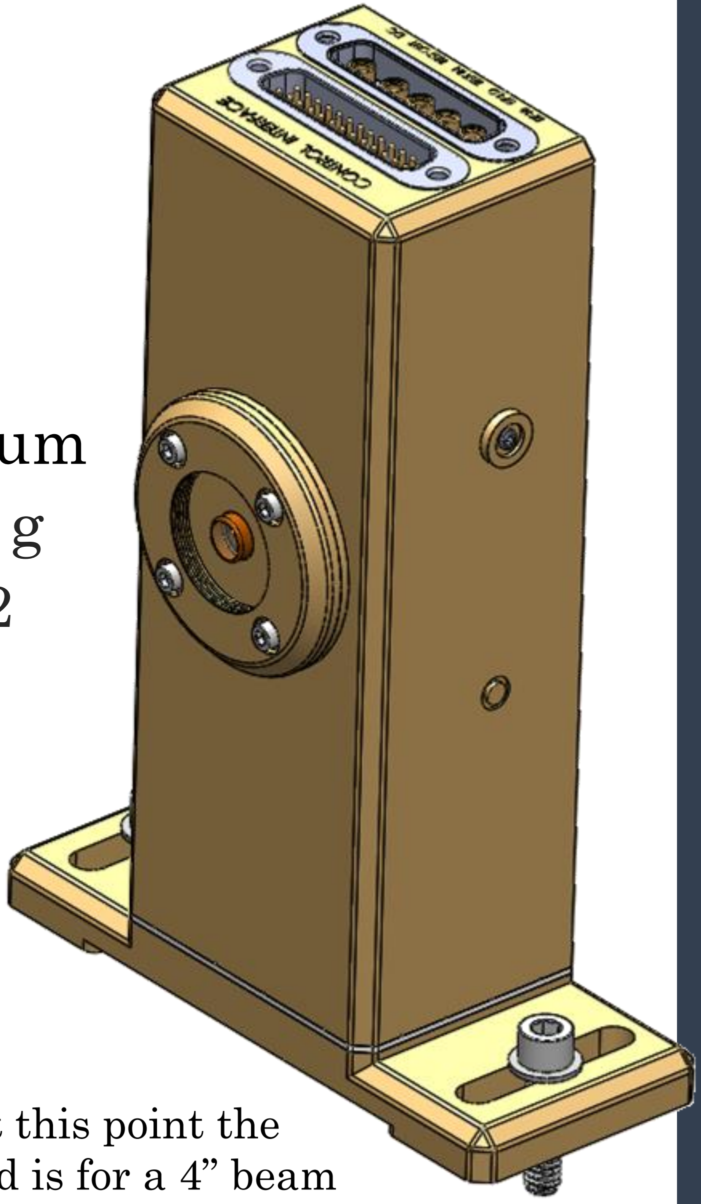




NOTE: At this point the fiber In have been modeled as mirrors with pico motors. A more realistic model has to be done to the two kinds of polarizers that will be used.

- RFPD in Vacuum
  - Mass: 270.41 g
  - Quantity: 0 / 2



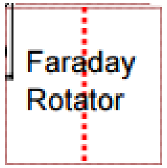


NOTE: At this point the model used is for a 4” beam height while the real one will be at 2.5”

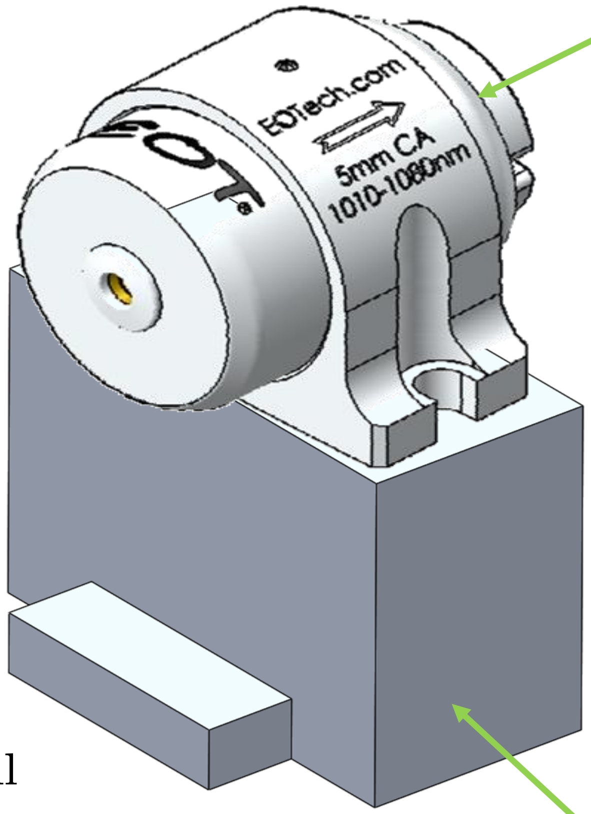
Optical Layout

- Solid Works Optical Layout

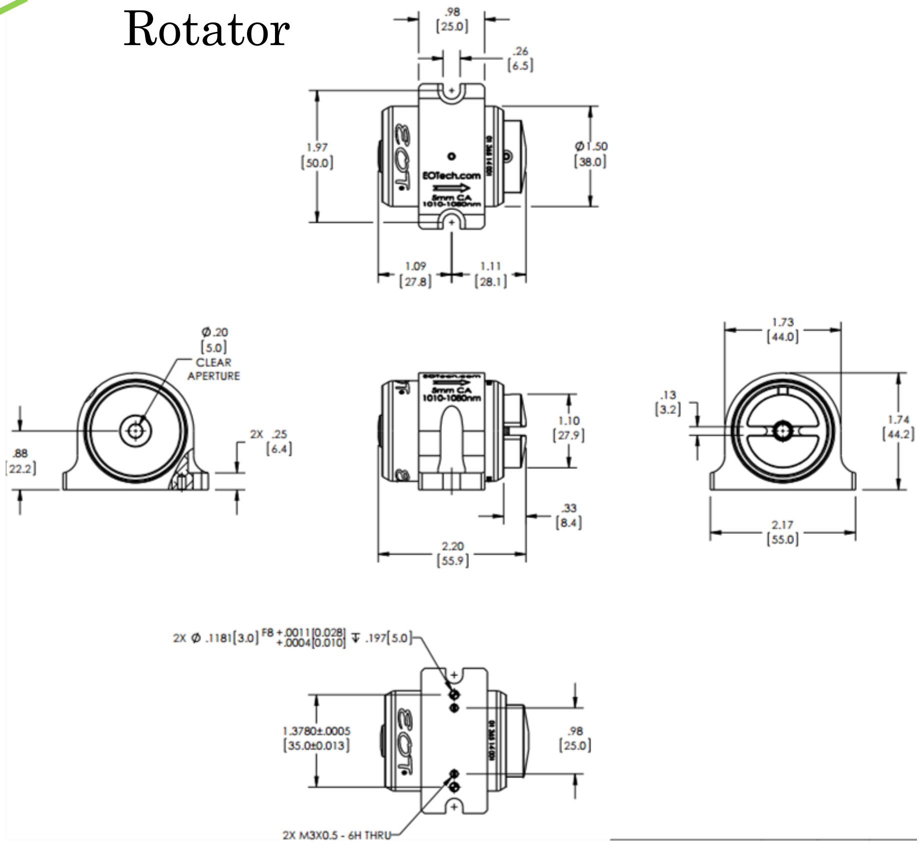
- Faraday Rotator:
  - Mass:
    - Base: 170.43 g
    - Rotator: X g
  - Quantity: 1 / 1



NOTE: At this point the Faraday Rotator has been modeled as just its base and with a rough design that will be improved once the Faraday rotator model will be obtained.



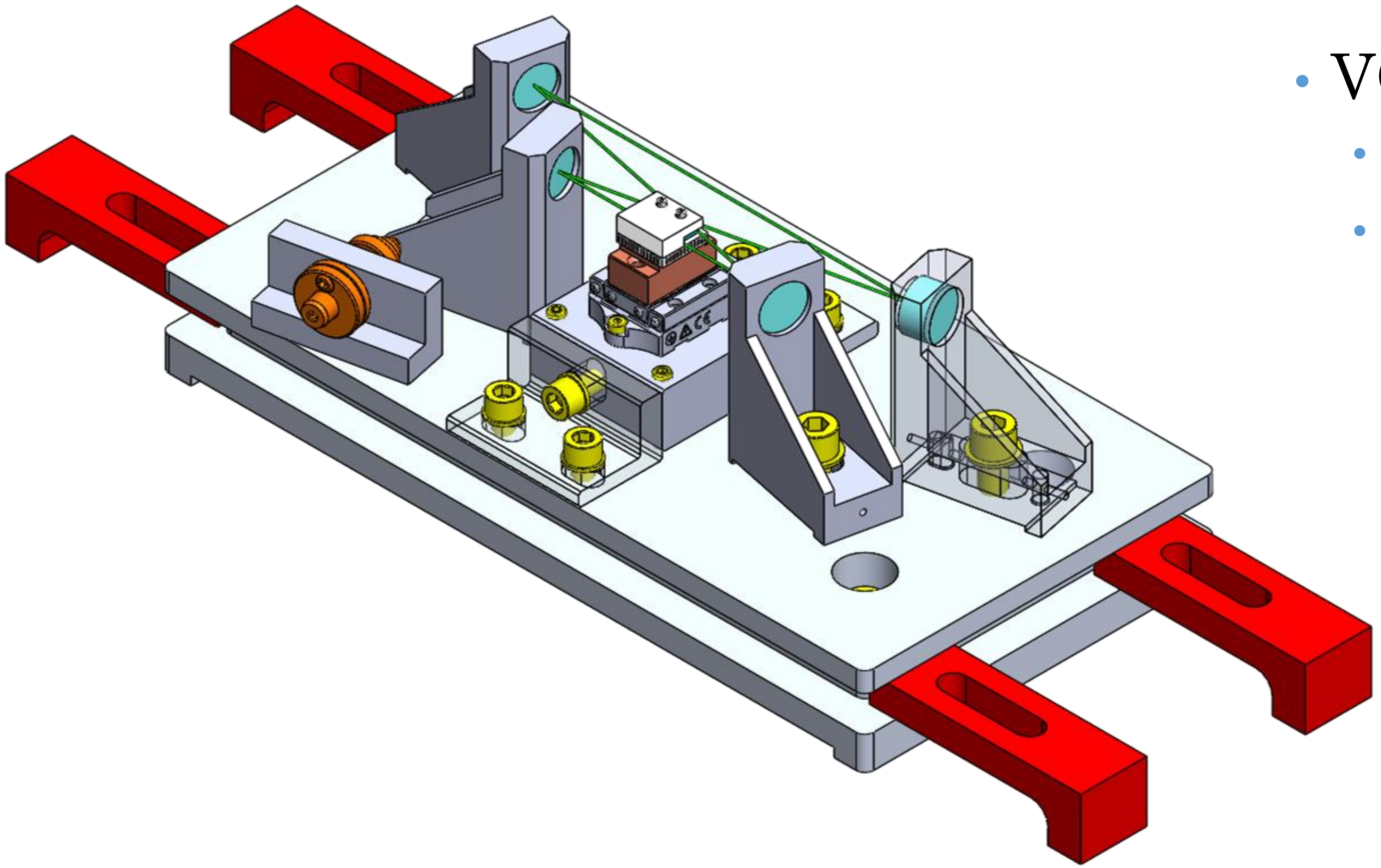
EOT Faraday Rotator



Base (6061-T6 Al)

Optical Layout

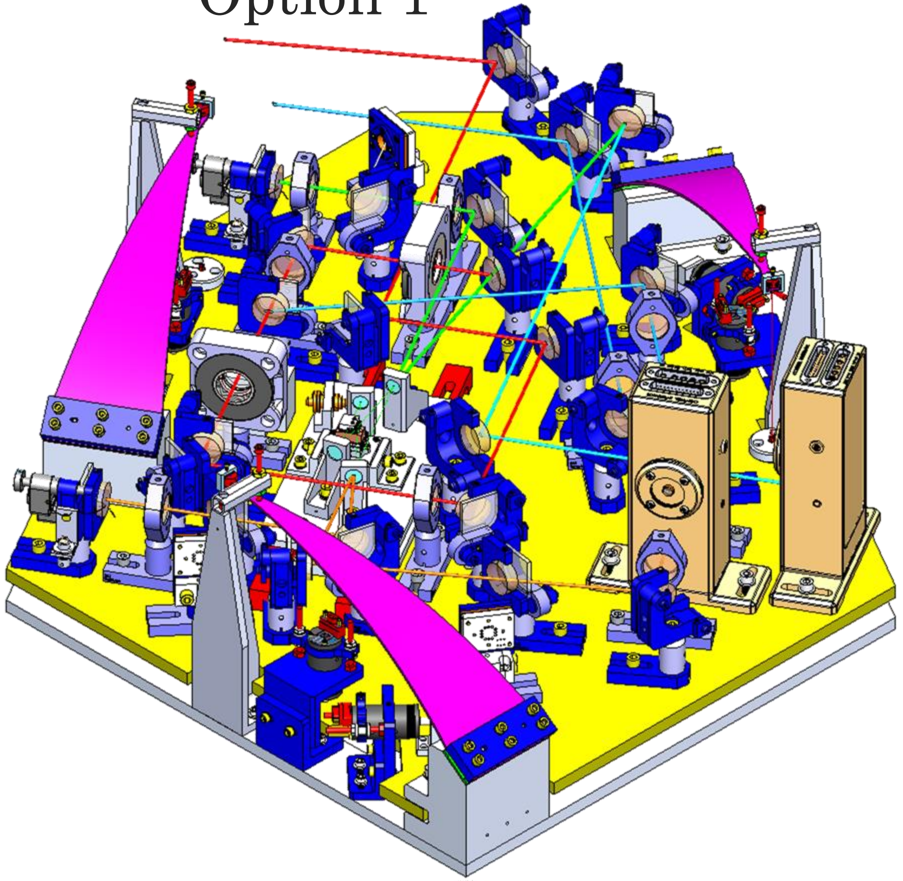
- Solid Works Optical Layout

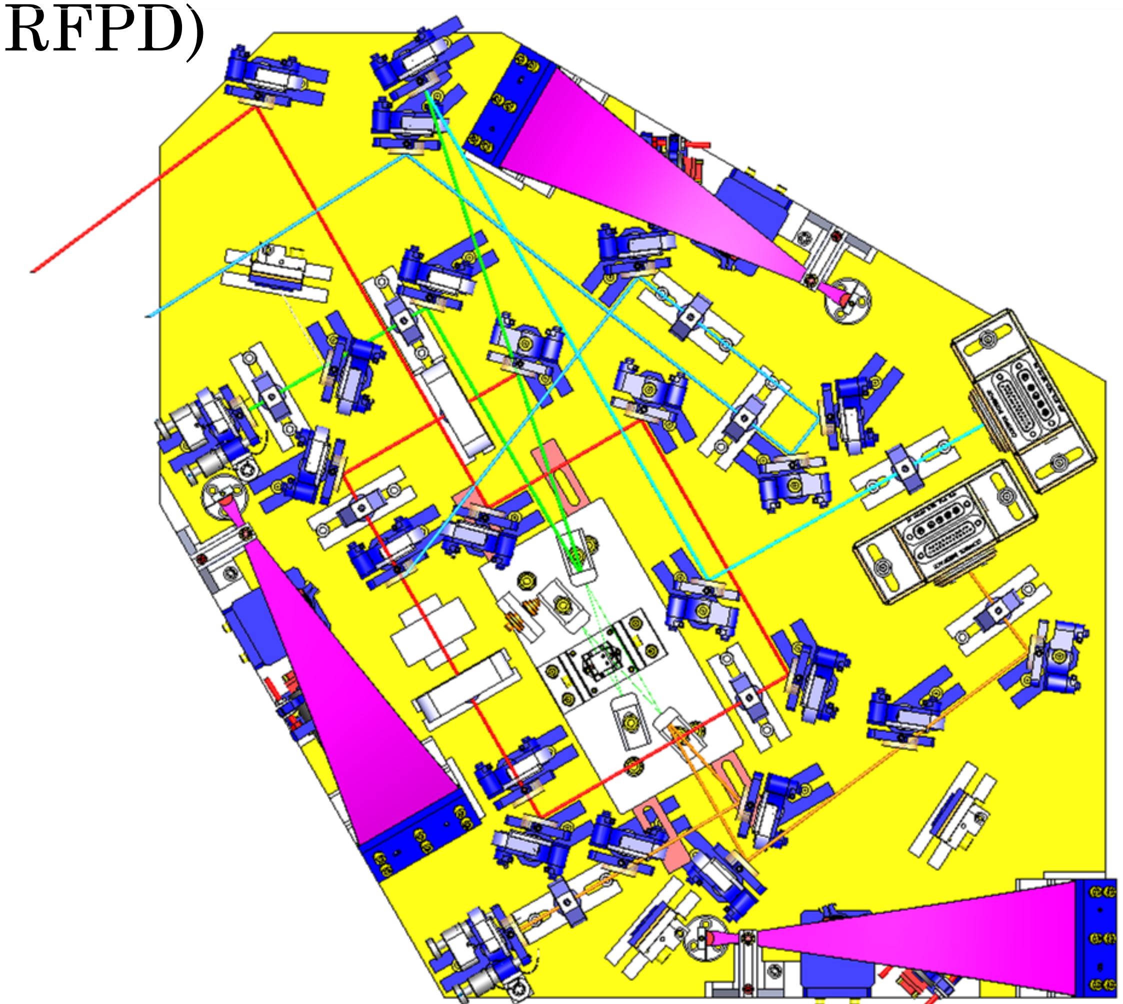


- VOPO Cavity:
  - Mass:: 1463 g
  - Quantity: 1 / 1

Optical Layout

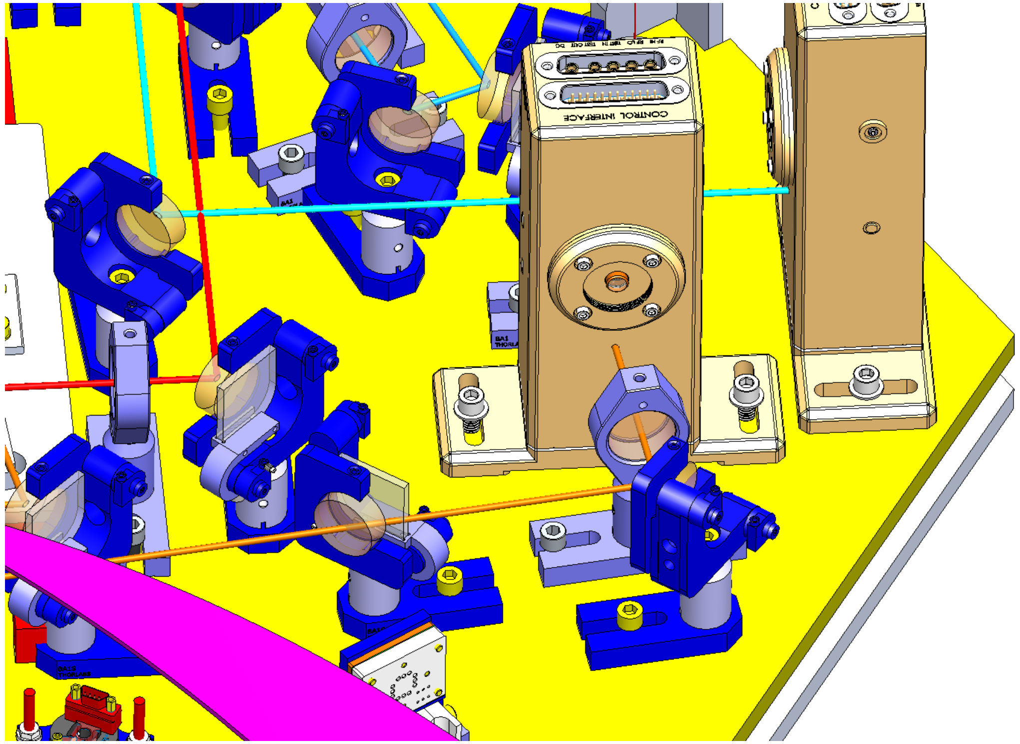
- O3 (Filter Cavity + In Vacuum RFPD)
  - Option 1

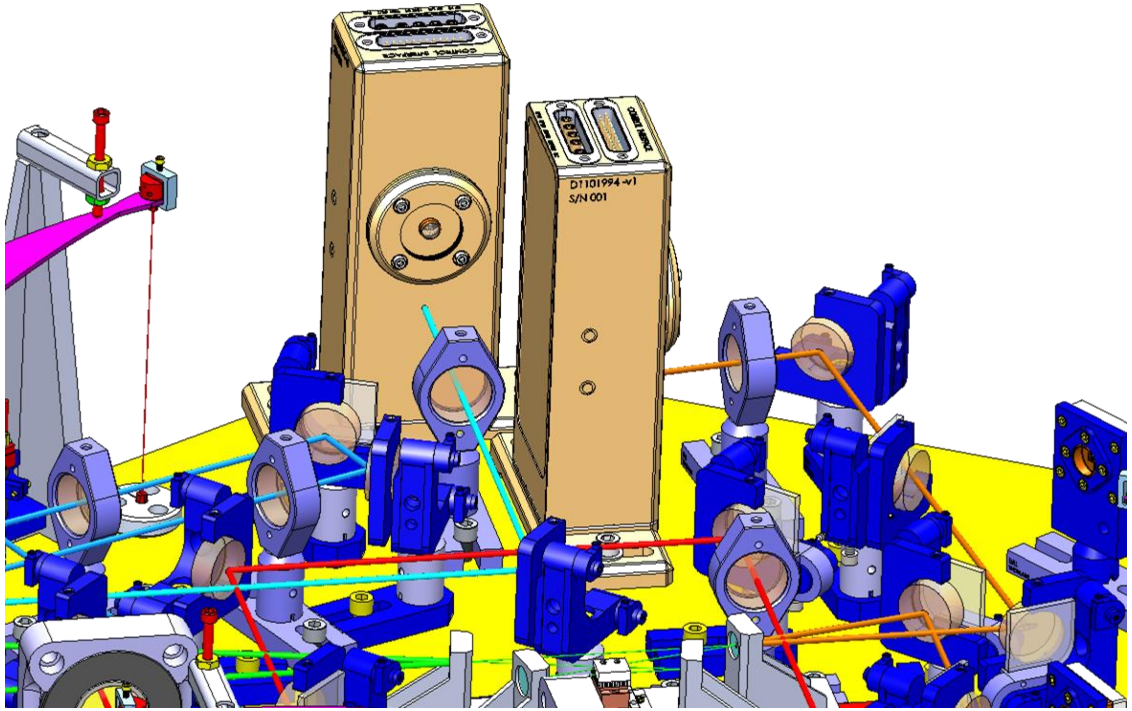




Optical Layout

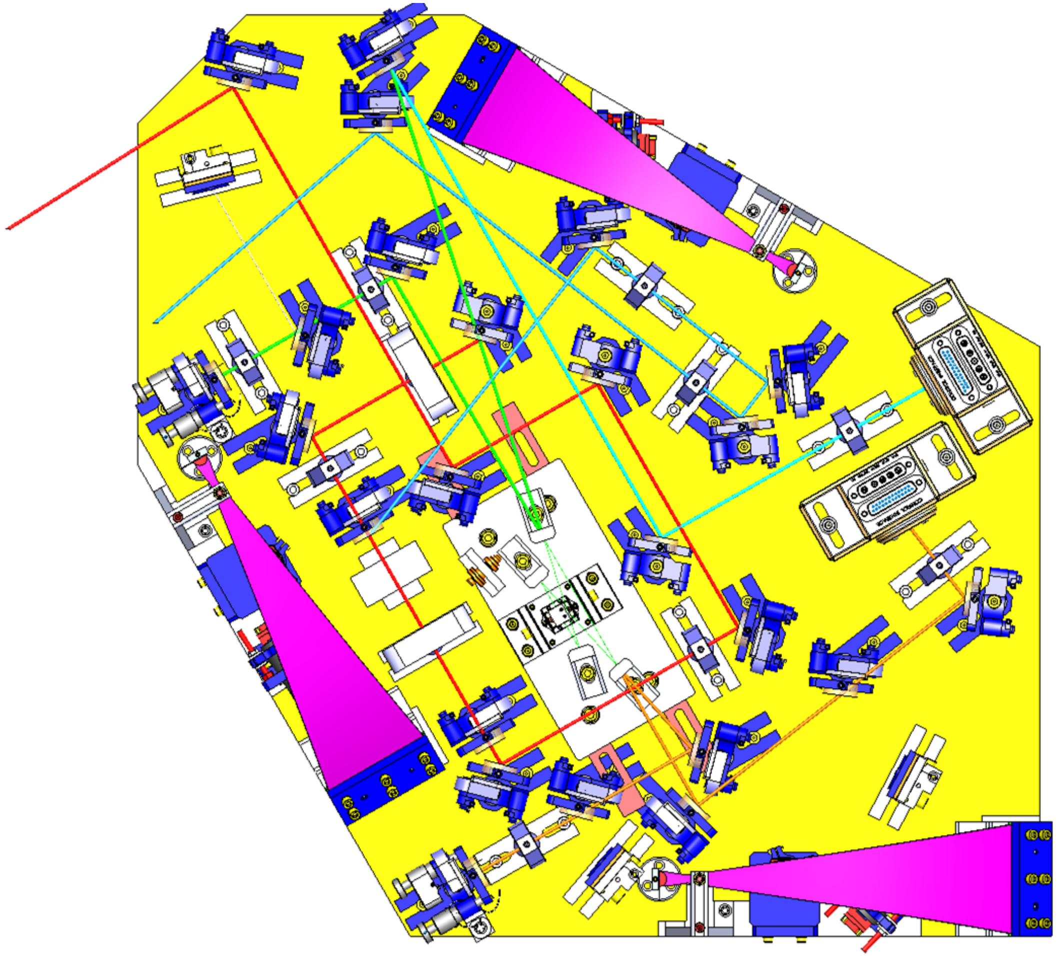
- O3 (Filter Cavity + In Vacuum RFPD)
  - Option 1
    - Problems





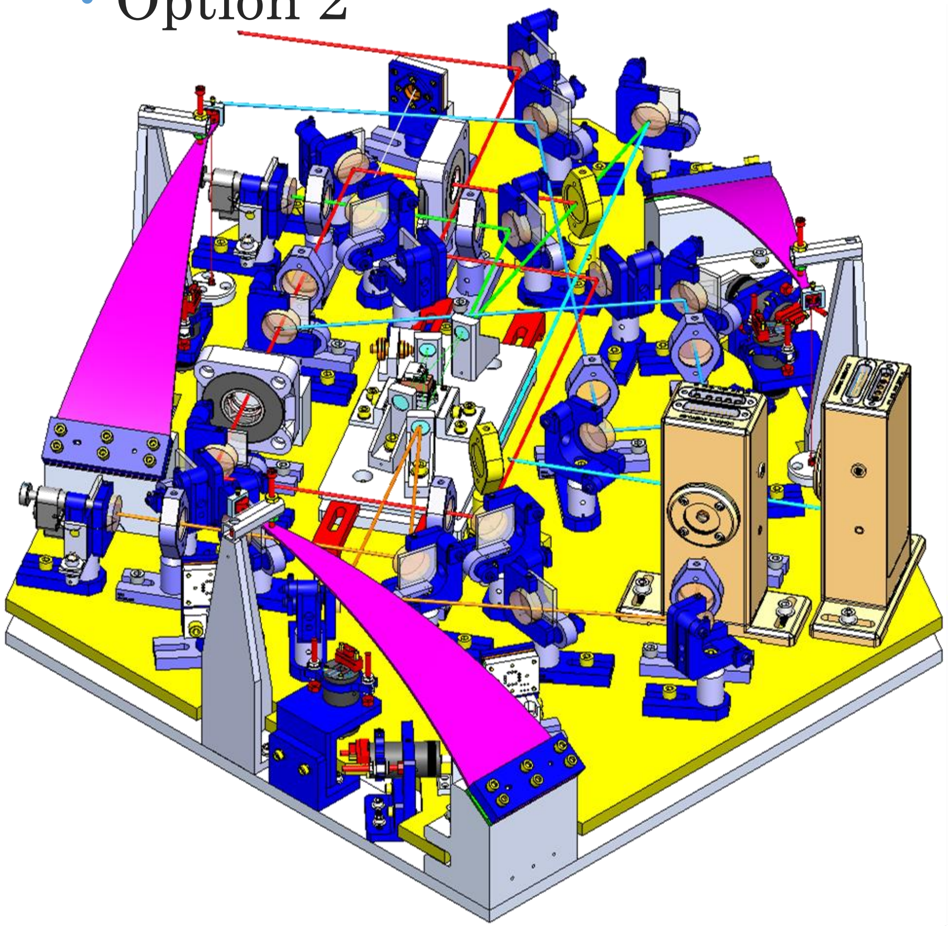
Optical Layout

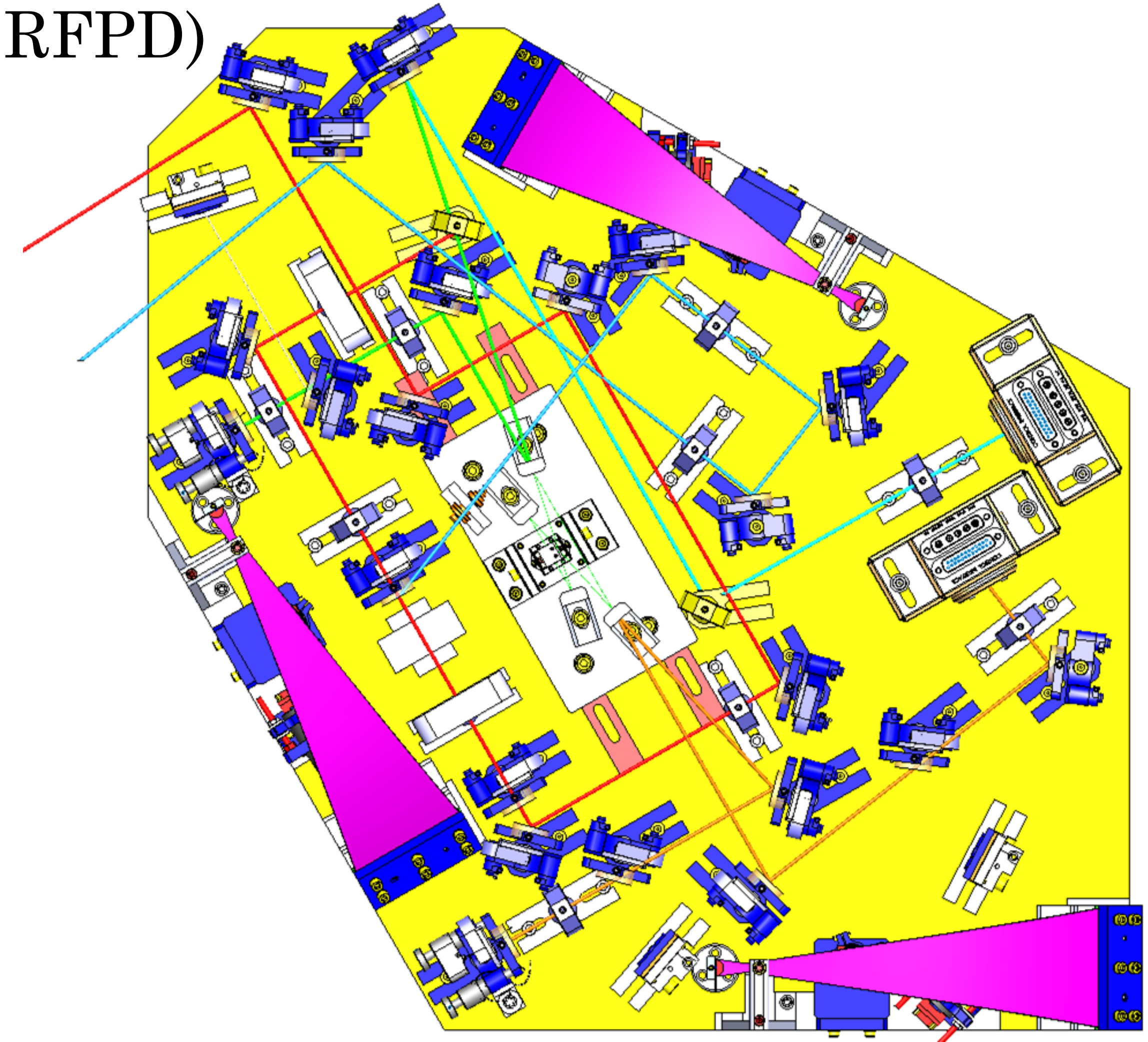
- O3 (Filter Cavity + In Vacuum RFPD)
  - Option 1
    - Problems



Optical Layout

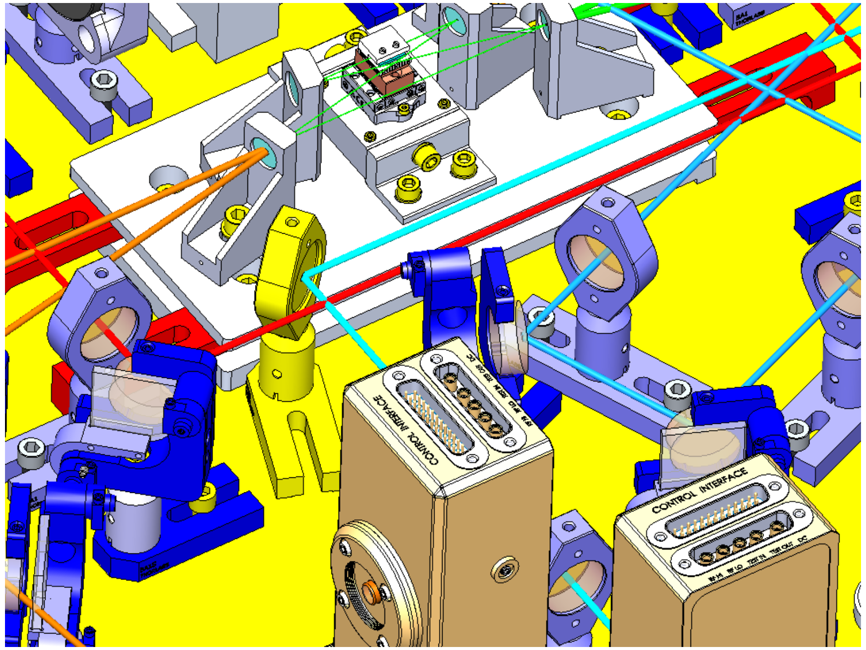
- O3 (Filter Cavity + In Vacuum RFPD)
  - Option 2

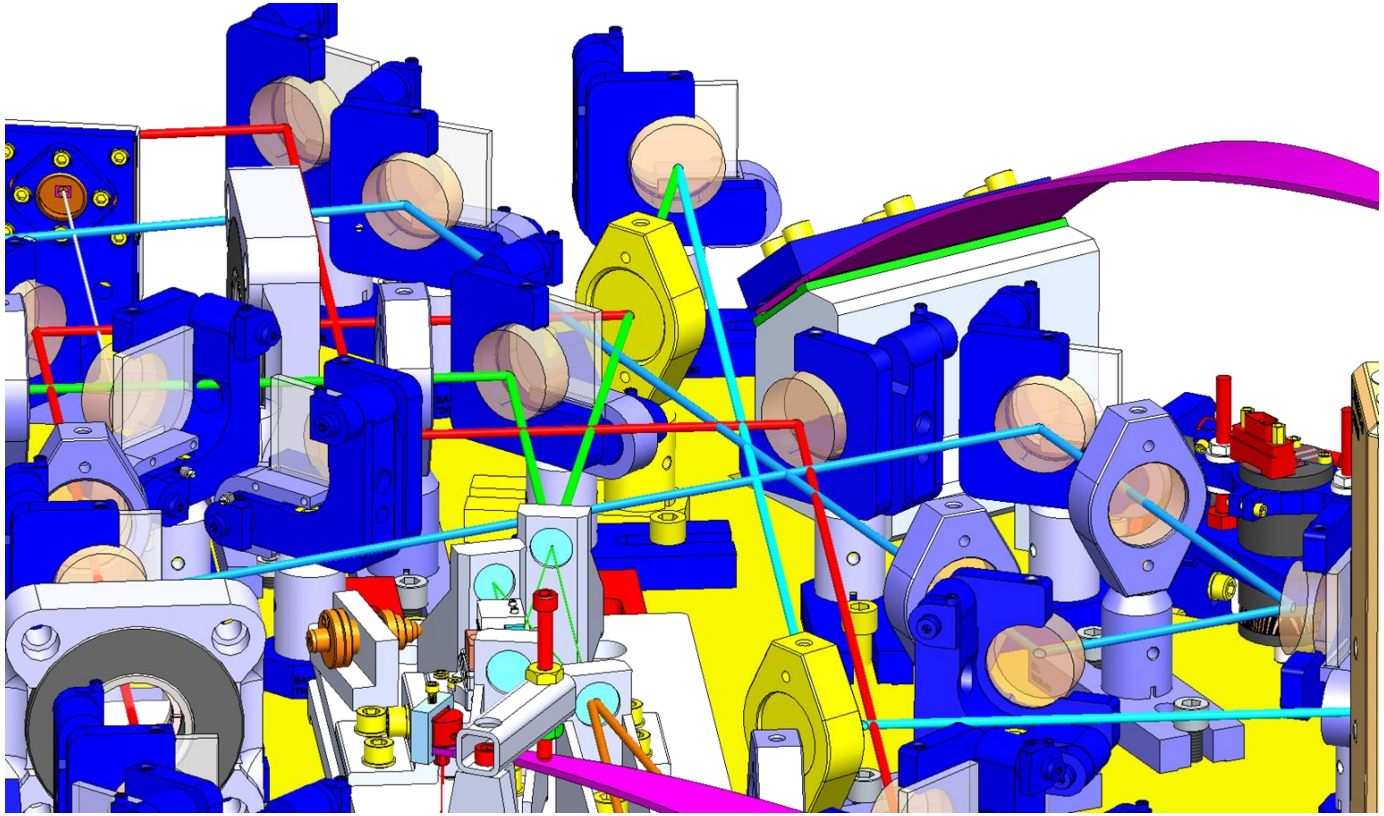




Optical Layout

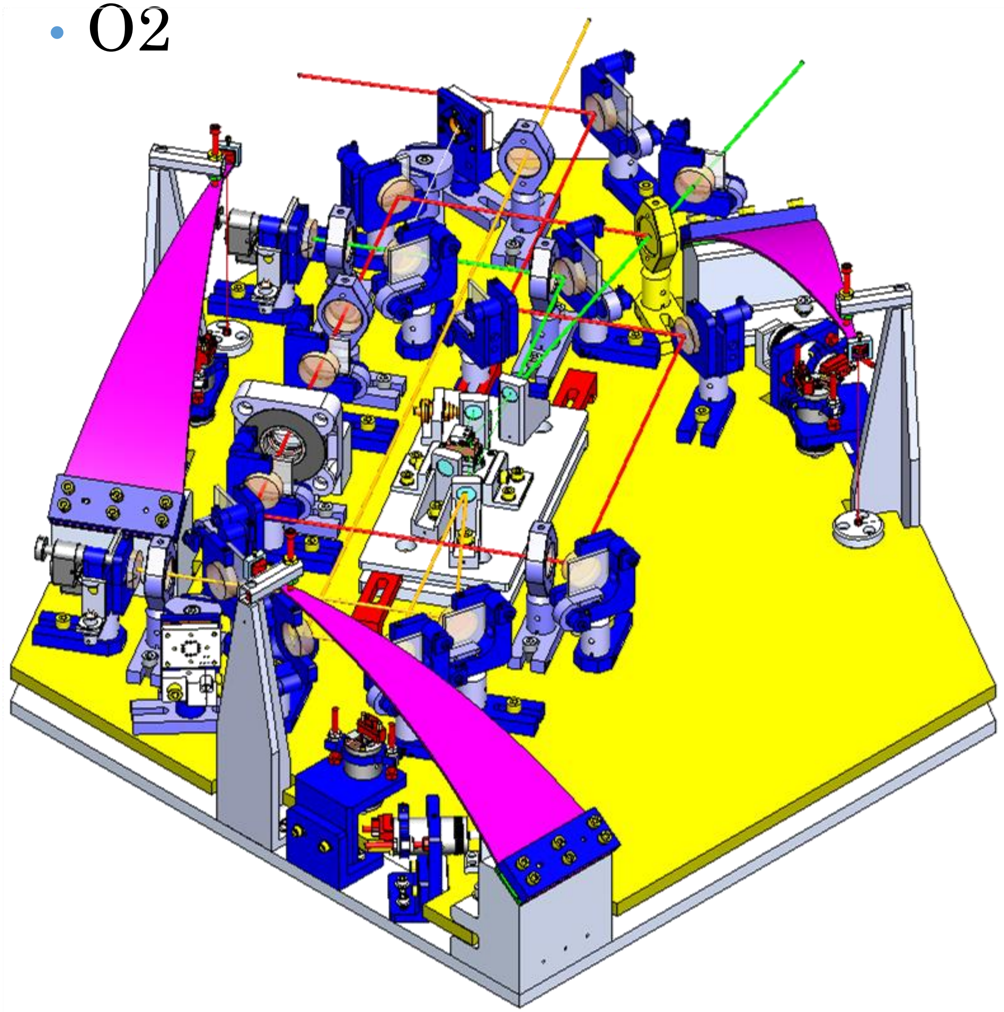
- O3 (Filter Cavity + In Vacuum RFPD)
  - Option 2
    - Problems

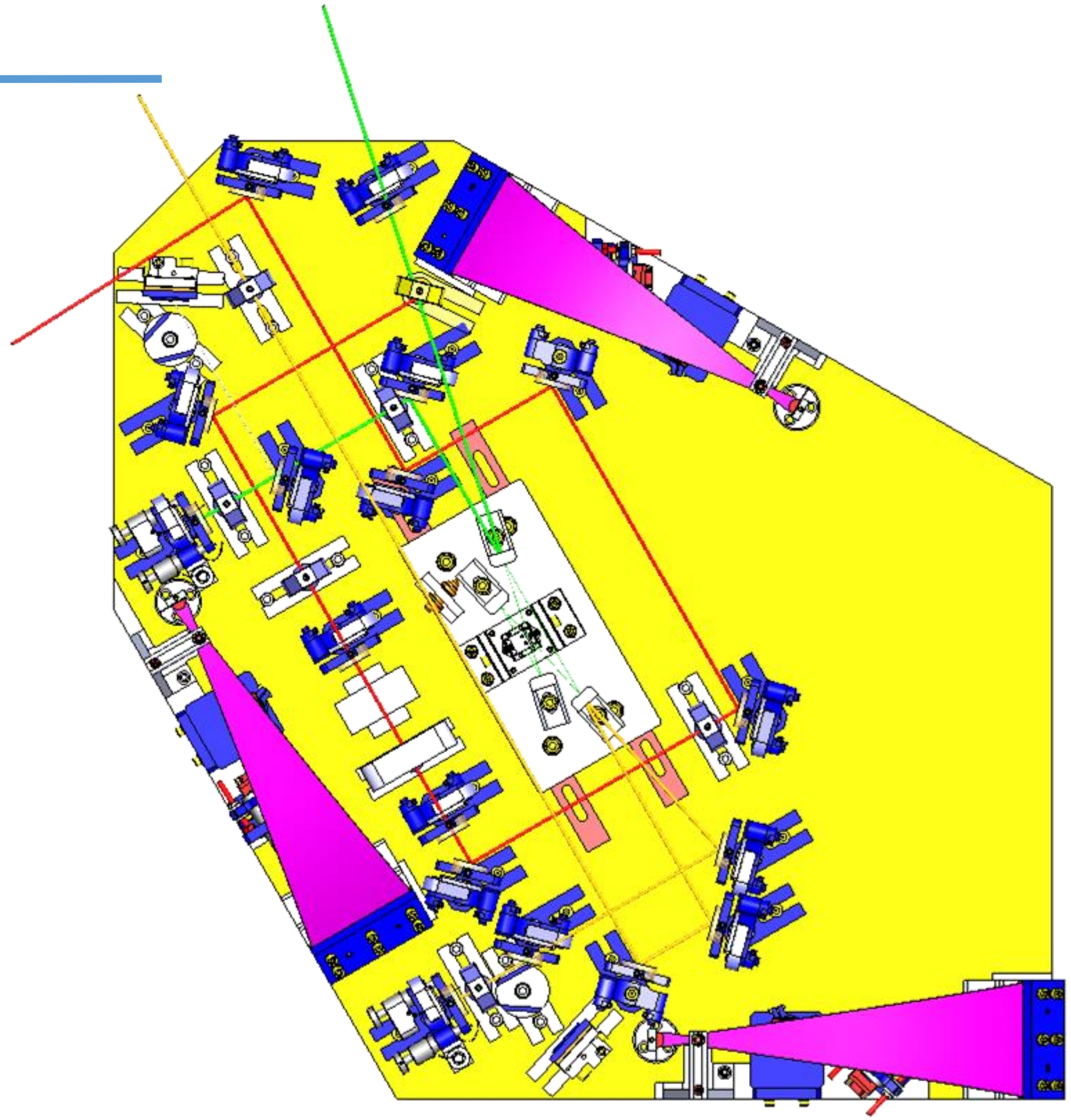




Optical Layout

- O2





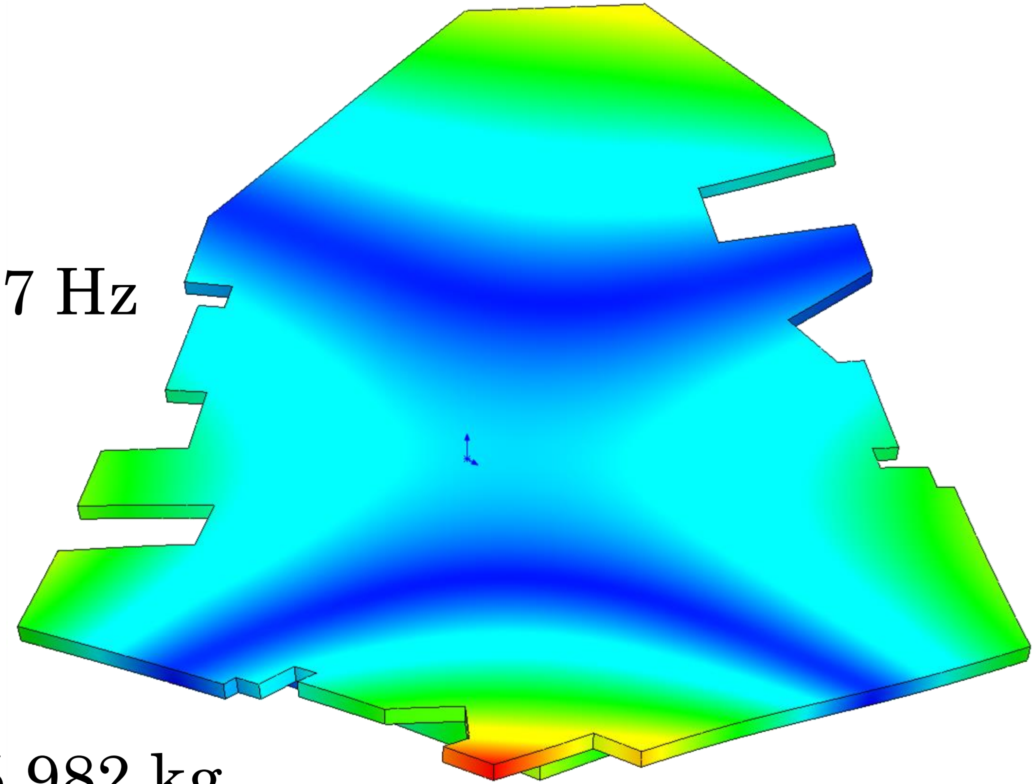
Optical Layout

- CONCLUSIONS
  - Injection Bench is large enough

- QUESTIONS

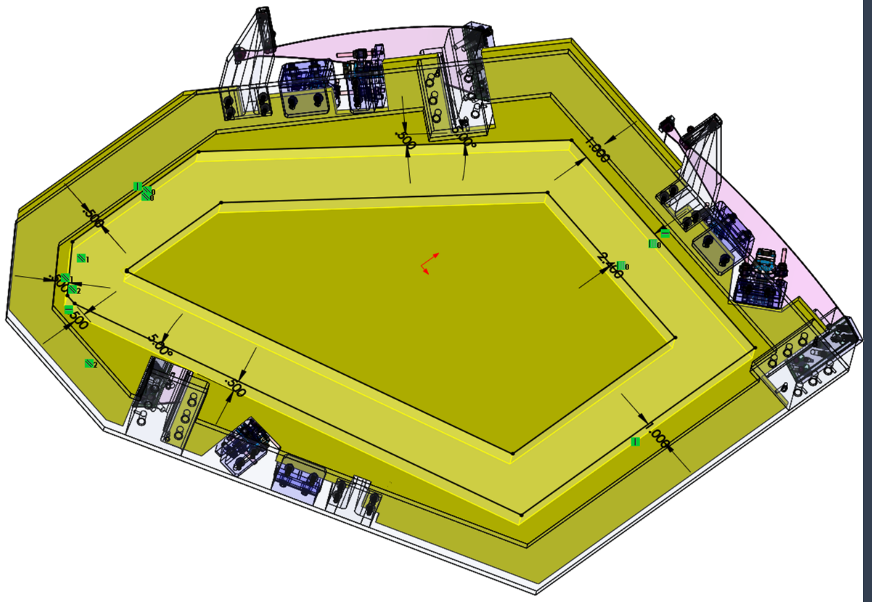
Injection Bench

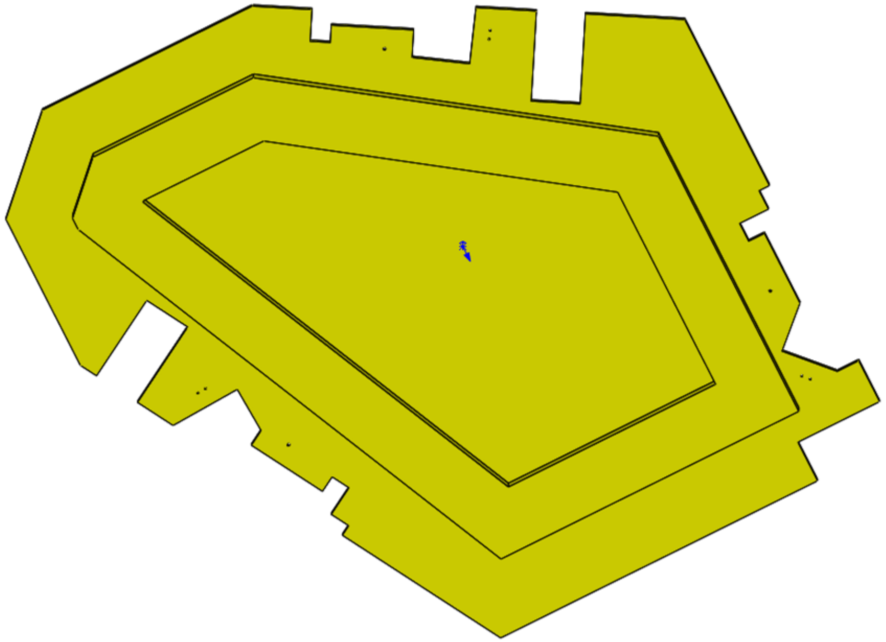
- Stiffener first design (dummy)



- f = 267.77 Hz

- Mass: 15.982 kg

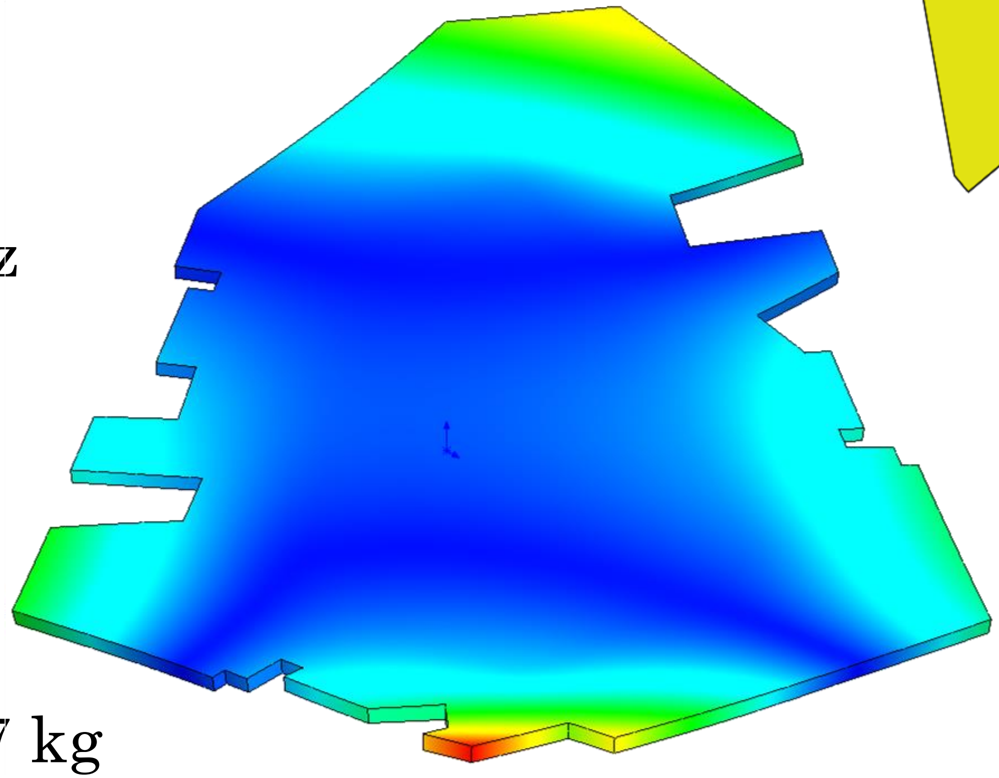


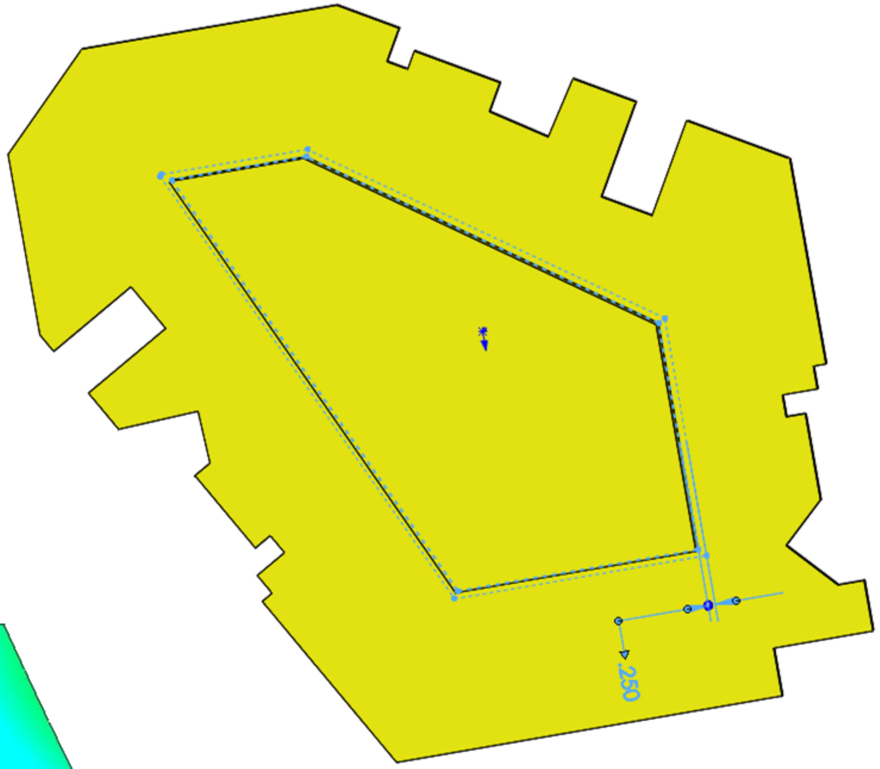


Injection Bench

- Stiffener first design (dummy II)

- f = 276.29 Hz





- Mass: 15.977 kg

Injection Bench: Mass Budget

- O3 (Filter Cavity + RFPD)

- Optics: 12 kg (2.1kg contingency)
- Bench: 18 kg
- Balancing Mass: 6kg

SUSPENDED MASS: 36 kg

NOTE I: The weight of the Injection Bench has been set at 18kg but it may vary after the frequency FEA

NOTE II: In this calculation the Faraday Rotator is not considered, just its base, and the model for polarizers and fiber in is set as the one of a mirror mount

MASS BUDGET

ELEMENT TYPE	Name	Description	Unit Weight (g)	Quantity	Total mass (g)	Final Design?	Mass Checked?
OPTICS	MIRROR	With Beam Dump	205.87	7	1441.09		YES
OPTICS	MIRROR	With Beam Dump 2	207.55	6	1245.30		NO
OPTICS	MIRROR	Without Beam Dump	192.90	3	578.70		NO
OPTICS	MIRROR II	Lens	121.38	1	121.38		NO
OPTICS	MIRROR III	Lens Sigle Base	97.07	1	97.07		NO
OPTICS	LENS	Desc 2	121.38	9	1092.38		NO
OPTICS	BEAM DUMP	Without One Black Glass	164.61	5	823.05		NO
OPTICS	QPD	Desc 5	142.98	3	428.94		NO
OPTICS	POLARIZER	Desc 6	203.05	4	812.19		NO
OPTICS	WAVE PLATE	Desc 7	299.69	2	599.38		NO
OPTICS	RFPD in Vacuum	Desc 8	270.41	2	540.82		NO
OPTICS	FIBER IN	Desc 9	252.01	2	504.02		NO
OPTICS	FARADAY ROTATOR	Desc 10	170.43	1	170.43		NO
OPTICS	VOPO CAVITY	Desc 11	1463.27	1	1463.27		NO
SUSPENSION	INJECTION BENCH	Desc 12	17797.97	1	17797.97		NO
SUSPENSION	LIMITERS & CLAMPS	Desc 13	193.50	1	193.50		NO
MASS	BALANCE MASS 1	Lateral	3857.36	0	0.00		NO
MASS	BALANCE MASS 2	Lateral Removable	1302.18	0	0.00		NO
MASS	BALANCE MASS 3	On Bench	2631.72	0	0.00		NO
MASS	SCREWS	On Bench	174.88	0	0.00		NO

OPTICS	**9.918**	**kg**
SUSPENSION	**17.991**	**kg**
MASS	**0.000**	**kg**
TOTAL WEIGHT	**27.909**	**kg**
Mass to 36 kg	**8.09**	**kg**

Injection Bench: Mass Budget

- O2

- Optics: 8 kg (1.2kg contingency)
- Bench: 18 kg
- Balancing Mass: 10kg

SUSPENDED MASS: 36 kg

NOTE I: The weight of the Injection Bench has been set at 18kg but it may vary after the frequency FEA

NOTE II: In this calculation the Faraday Rotator is not considered, just its base, and the model for polarizers and fiber in is set as the one of a mirror mount

MASS BUDGET

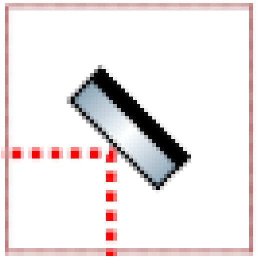
ELEMENT TYPE	Name	Description	Unit Weight (g)	Quantity	Total mass (g)	Final Design?	Mass Checked?
OPTICS	MIRROR	With Beam Dump	205.87	5	1029.35		YES
OPTICS	MIRROR	With Beam Dump 2	207.55	3	622.65		NO
OPTICS	MIRROR	Without Beam Dump	192.90	2	385.80		NO
OPTICS	MIRROR III	Lens Sigle Base	97.07	1	97.07		NO
OPTICS	LENS	Desc 2	121.38	7	849.63		NO
OPTICS	BEAM DUMP	Without One Black Glass	164.61	2	329.22		NO
OPTICS	QPD	Desc 5	142.98	2	285.96		NO
OPTICS	POLARIZER	Desc 6	206.71	4	826.84		NO
OPTICS	WAVE PLATE	Desc 7	299.69	1	299.69		NO
OPTICS	RFPD in Vacuum	Desc 8	270.41	0	0.00		NO
OPTICS	FIBER IN	Desc 9	195.18	2	390.35		NO
OPTICS	FARADAY ROTATOR	Desc 10	170.43	1	170.43		NO
OPTICS	VOPO CAVITY	Desc 11	1463.27	1	1463.27		NO
SUSPENSION	INJECTION BENCH	Desc 12	18000.00	1	18000.00		NO
SUSPENSION	LIMITERS & CLAMPS	Desc 13	100.92	1	100.92		NO
MASS	BALANCE MASS 1	Lateral	0.00	1	0.00		NO
MASS	BALANCE MASS 2	On Bench	0.00	1	0.00		NO

OPTICS	**6.750**	**kg**
SUSPENSION	**18.101**	**kg**
MASS	**0.000**	**kg**
TOTAL WEIGHT	**24.851**	**kg**
Mass to 36 kg	**11.15**	**kg**

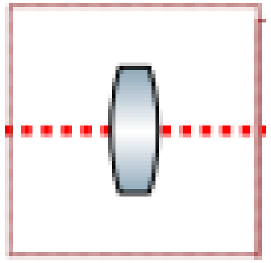
Injection Bench Assembly FEA

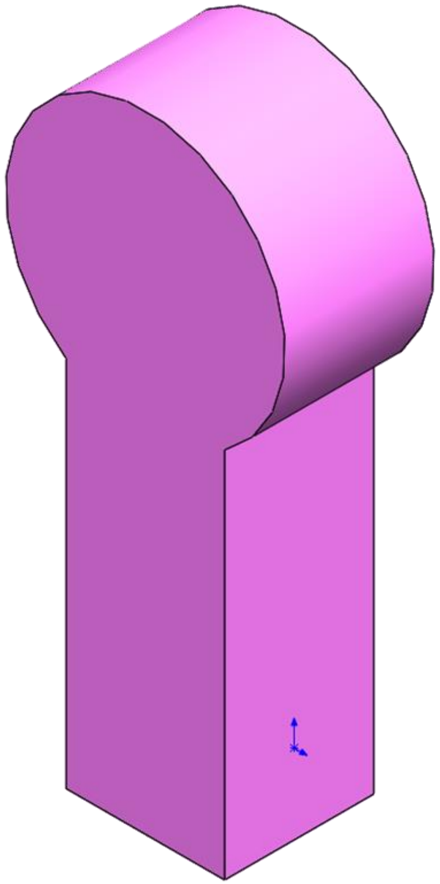
- Optical components for FEA

- Mirror:
  - Mass: 205.87 g
  - Mass FEA: 203 g
  - Quantity: 11 / 18



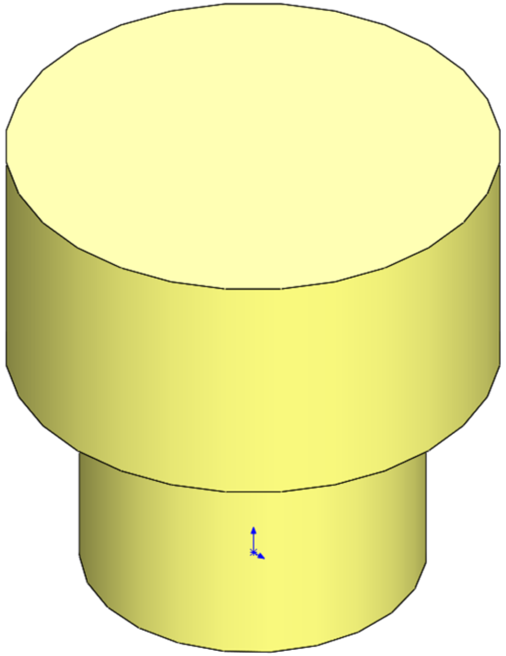
- Lens:
  - Mass: 121.375 g
  - Mass FEA: 120 g
  - Quantity: 7 / 10



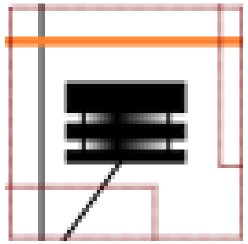


Injection Bench Assembly FEA

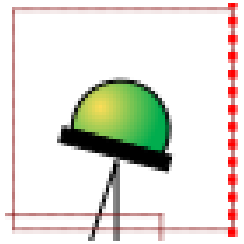
- Optical components for FEA

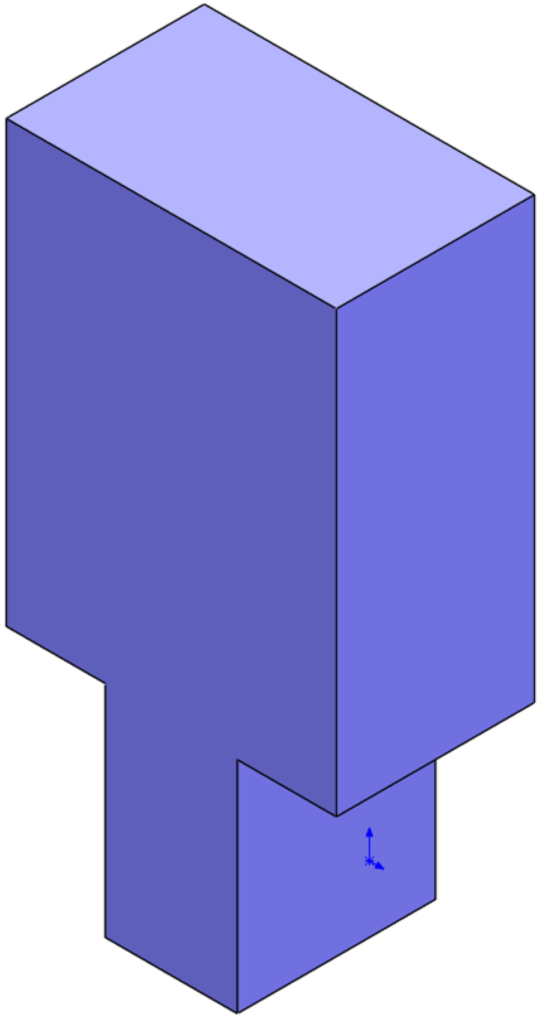


- Beam Dump:
  - Mass: 164.61 g
  - Mass to FEA: 163 g
  - Quantity: 2 / 5



- QPD:
  - Mass: 142.98 g
  - Mass FEA: 143 g
  - Quantity: 2 / 3

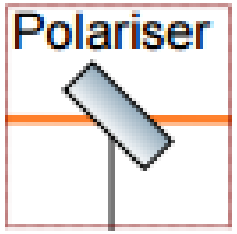




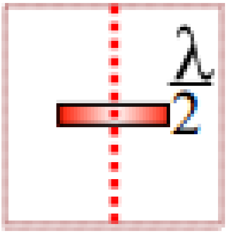
Injection Bench Assembly FEA

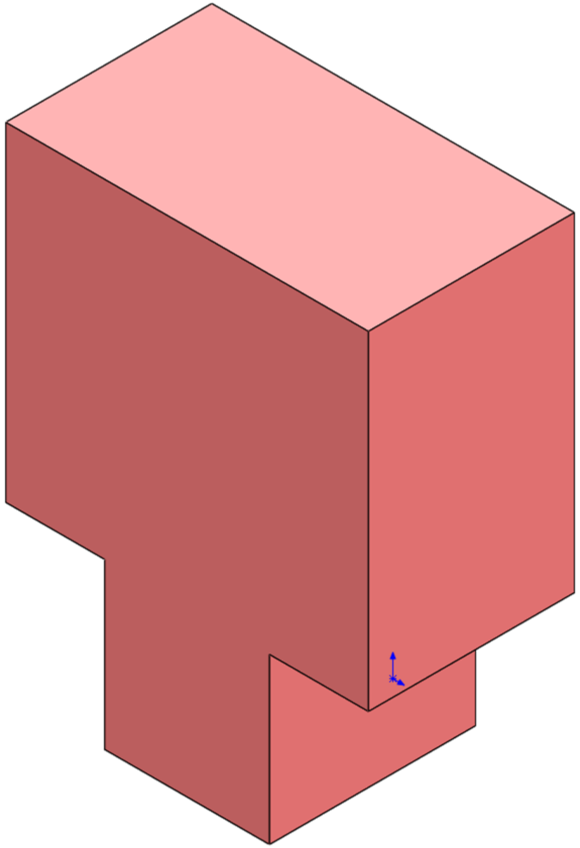
- Optical components for FEA

- Polarizer:
  - Mass: 206.71 g
  - Mass FEA: 203 g
  - Quantity: 2+2 / 2+2



- Wave Plate:
  - Mass: 300 g
  - Mass FEA: 297 g
  - Quantity: 1 / 2

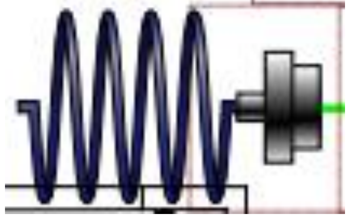


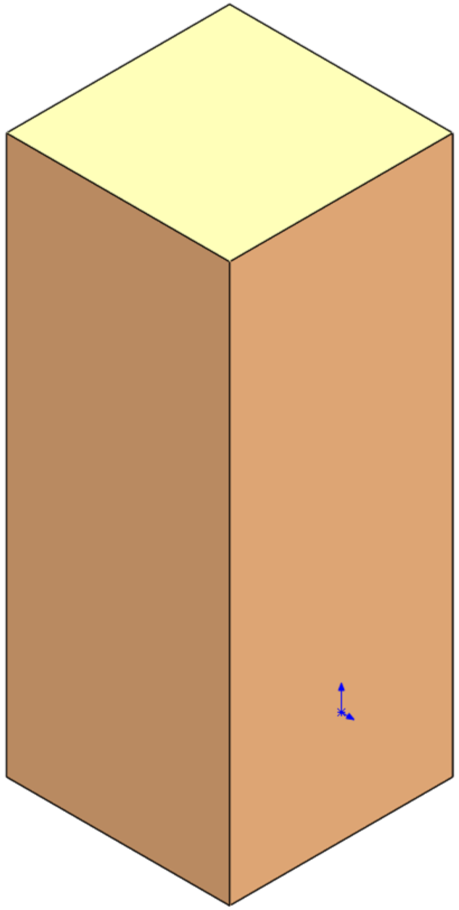


Injection Bench Assembly FEA

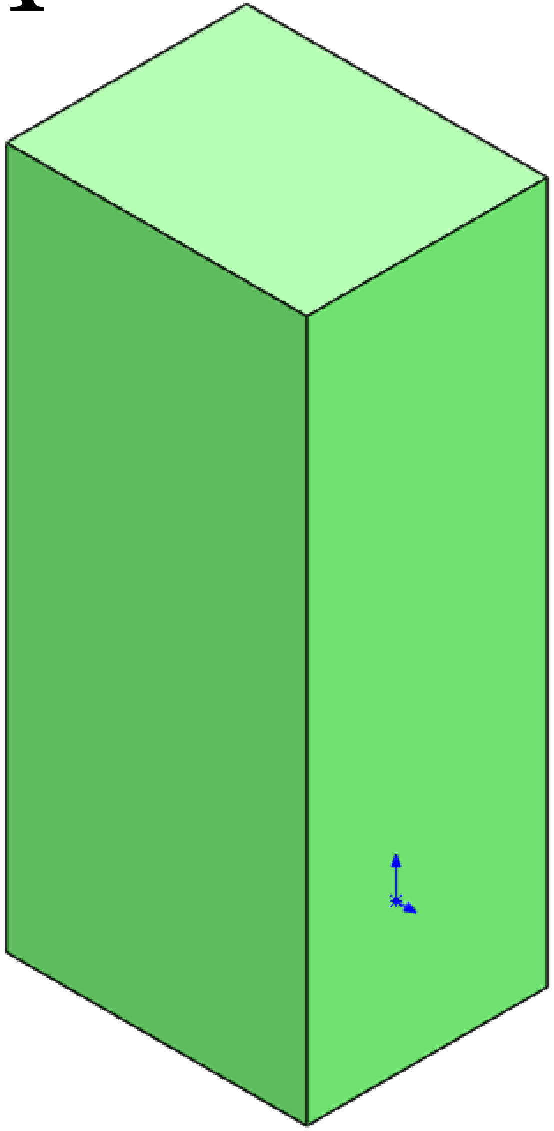
- Optical components for FEA

- Fiber In:
  - Mass: 252.01 g
  - Mass FEA: 191 g
  - Quantity: 2 / 2





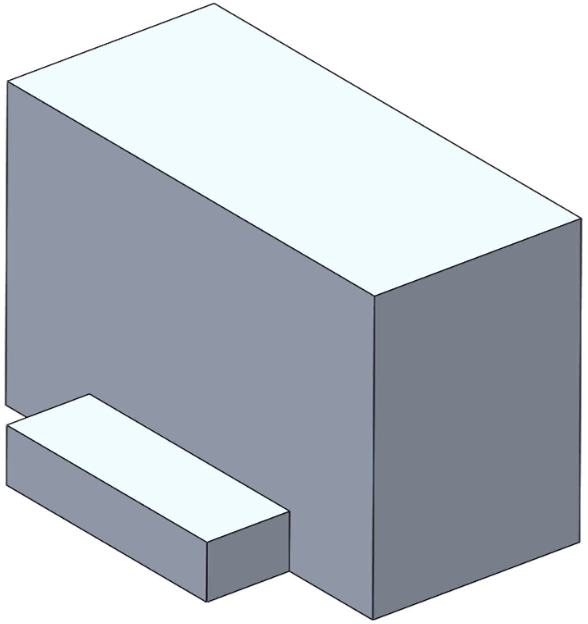
- RFPD in Vacuum
  - Mass: 270.41 g
  - Mass: 279 g
  - Quantity: 0 / 2



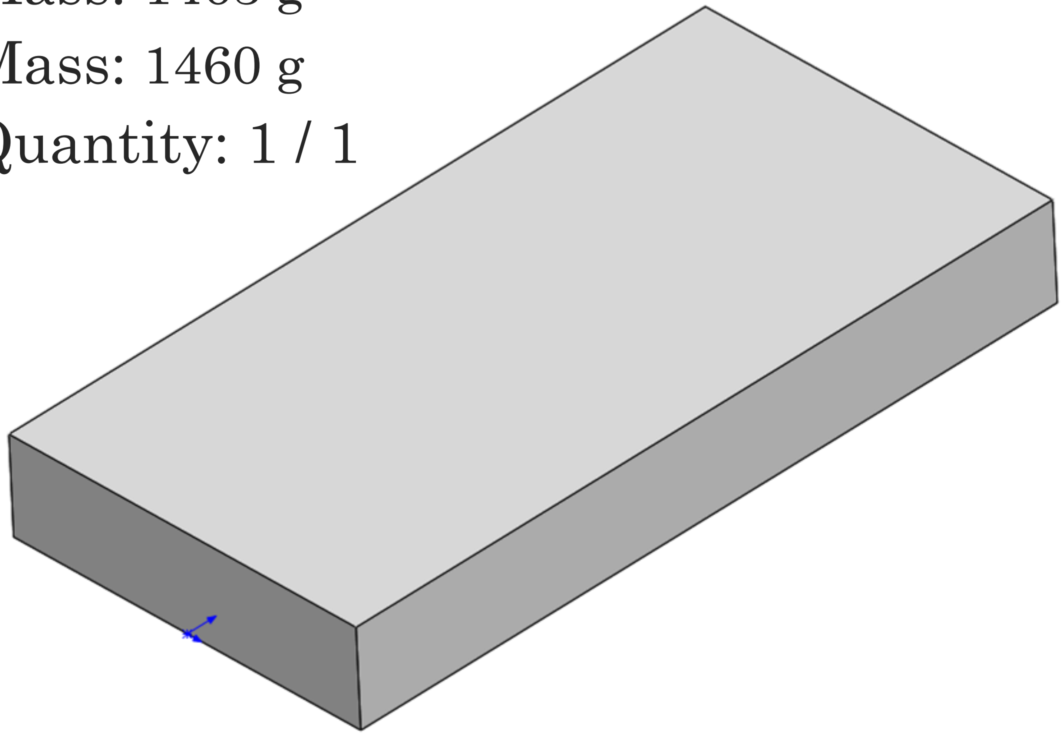
Injection Bench Assembly FEA

- Optical components for FEA

- Faraday Rotator:
  - Mass:
    - Base: 170.43 g
    - Base FEA: 170 g
    - Rotator: X g
  - Quantity: 1 / 1



- VOPO Cavity:
  - Mass: 1463 g
  - Mass: 1460 g
  - Quantity: 1 / 1



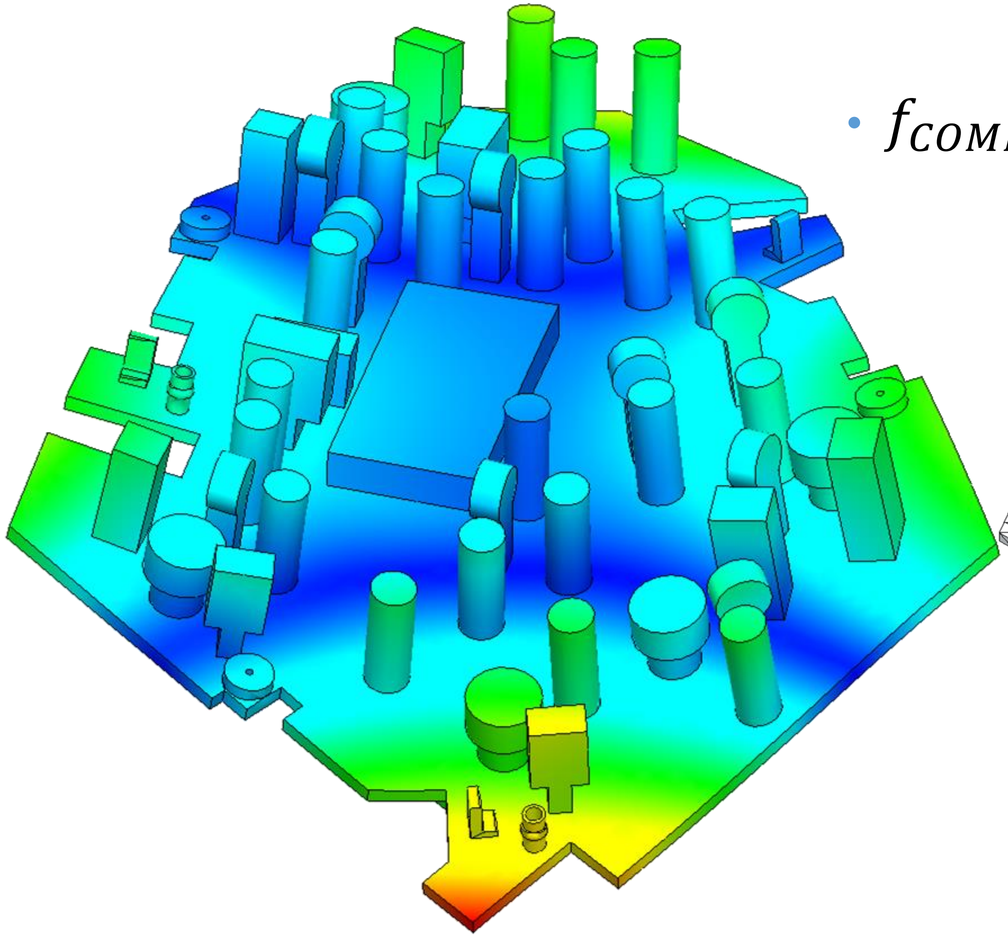
Injection Bench Assembly FEA

- Injection Bench Assembly for FEA

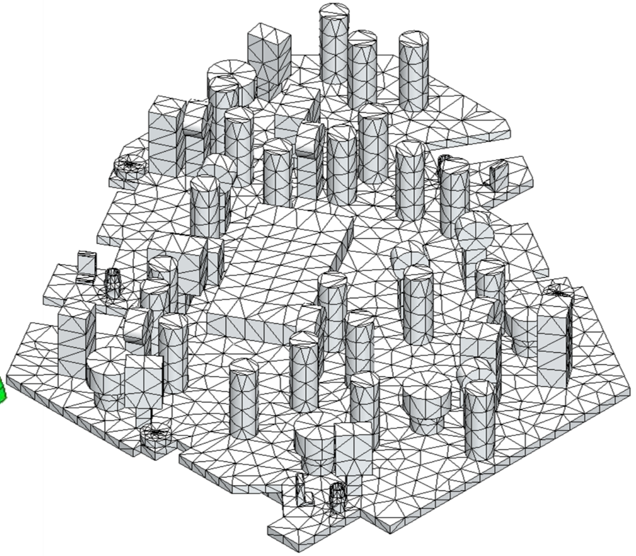
- Global Contact: Bonded

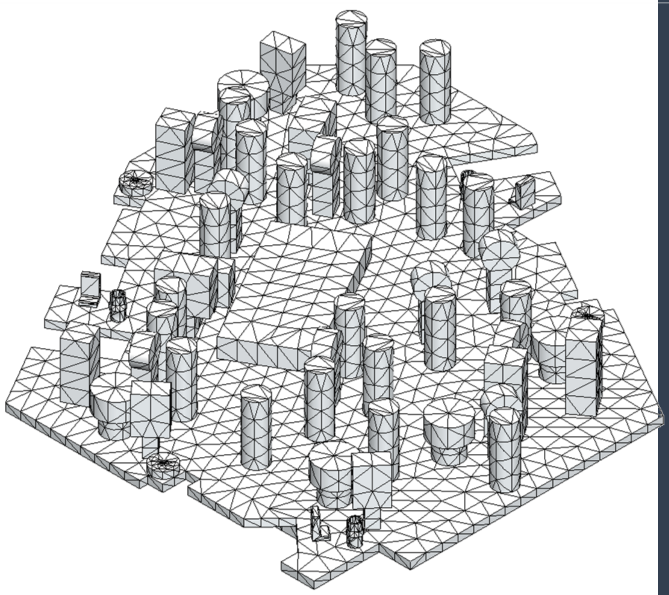
Injection Bench Assembly FEA

- Injection Bench Assembly for FEA (no MASSES)



- $f_{COMPATIBLE} = 238.09\,Hz$
- $f_{INCOMPATIBLE} = 239.76\,Hz$



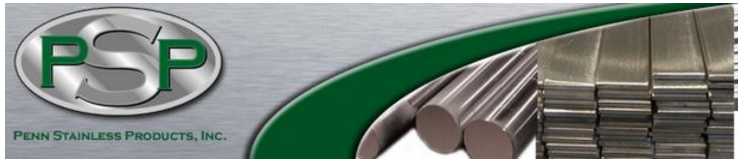


NOTE: No significant difference has been observed between compatible and incompatible meshing

BLADE DESIGN: Material

- Material: 440C SSTL (E = 210 GPa, σ_Y = 1800 MPa, UTS = 1970 MPa, ρ = 7800 kg/m^3, v = 0.285)
- Total Suspended Mass: m = 36 kg
- Charge per blade: P = 117.72N (12 kg)

- Constraints:
- Factor of Safety: ≥ 33.3% (FoS ≥ 3)
- Desired frequency: f ≈ 1.5 Hz



440C STAINLESS STEEL

MECHANICAL PROPERTIES

Tempering Temperature (°C)	Tensile Strength (MPa)	Yield Strength 0.2% Proof (MPa)	Elongation (% in 50mm)	Hardness Rockwell (HR C)	Impact Charpy V (J)
Annealed*	758	448	14	269HB max#	-
204	2030	1900	4	59	9
260	1960	1830	4	57	9
316	1860	1740	4	56	9
371	1790	1660	4	56	9

* Annealed properties are typical for Condition A of ASTM A276# Brinell Hardness is ASTM A276 specified maximum for annealed 440A, B and C.

http://www.pennstainless.com/stainless-grades/400-series-stainless/440c-stainless-steel/
http://www.makeitfrom.com/material-properties/Hardened-440C-Stainless-Steel

BLADE DESIGN: Dimensions

- Design Parameters:
  - Blade Width: a
  - Blade Length: l
  - Blade thickness: h

3 Parameters

- Equations (for triangular blades):
  - $Kzz = \frac{Eah^3}{4l^3}$
  - $f = \frac{1}{2\pi}\sqrt{\frac{K_{zz}}{m}} = 1.5\ Hz$
  - $\sigma_{max} = \frac{6Pl}{ah^2}$

2 Equations

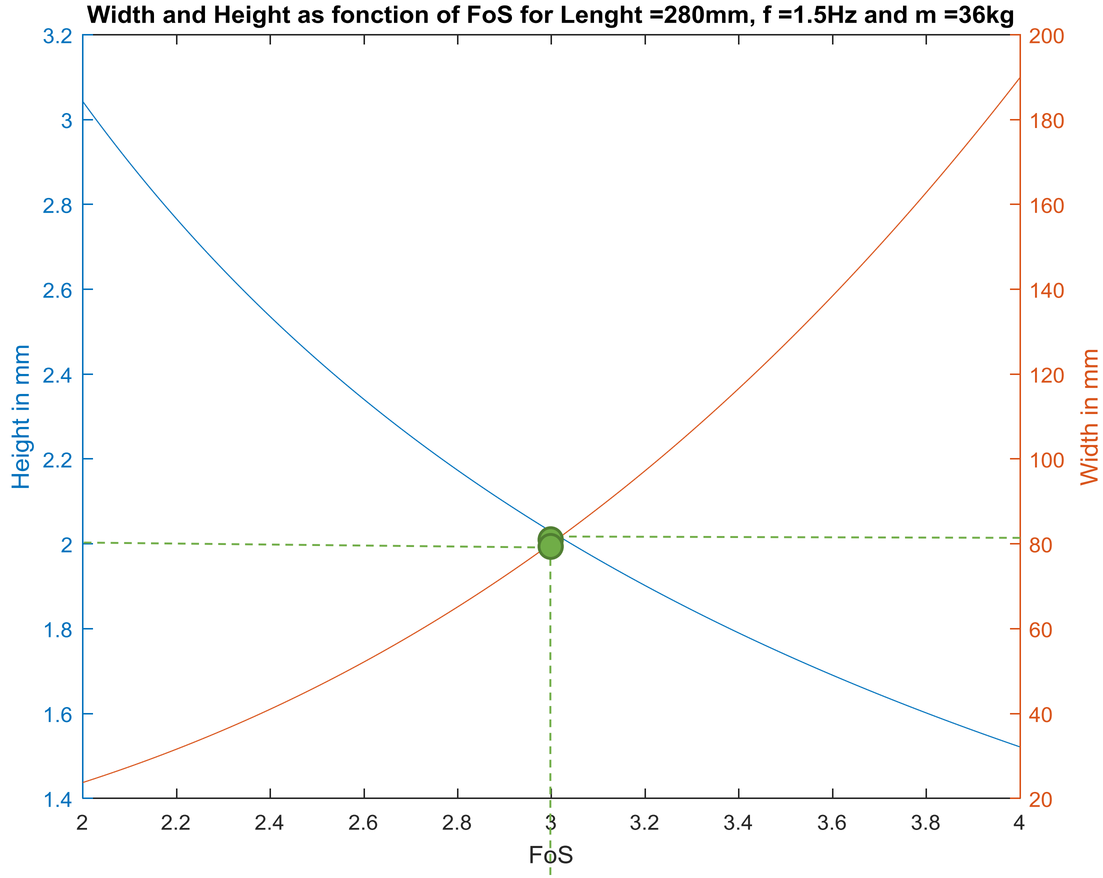
1 DOF

l = 280 mm

NOTE: The choice of this length has been made after checking the optical layout

BLADE DESIGN: Dimensions

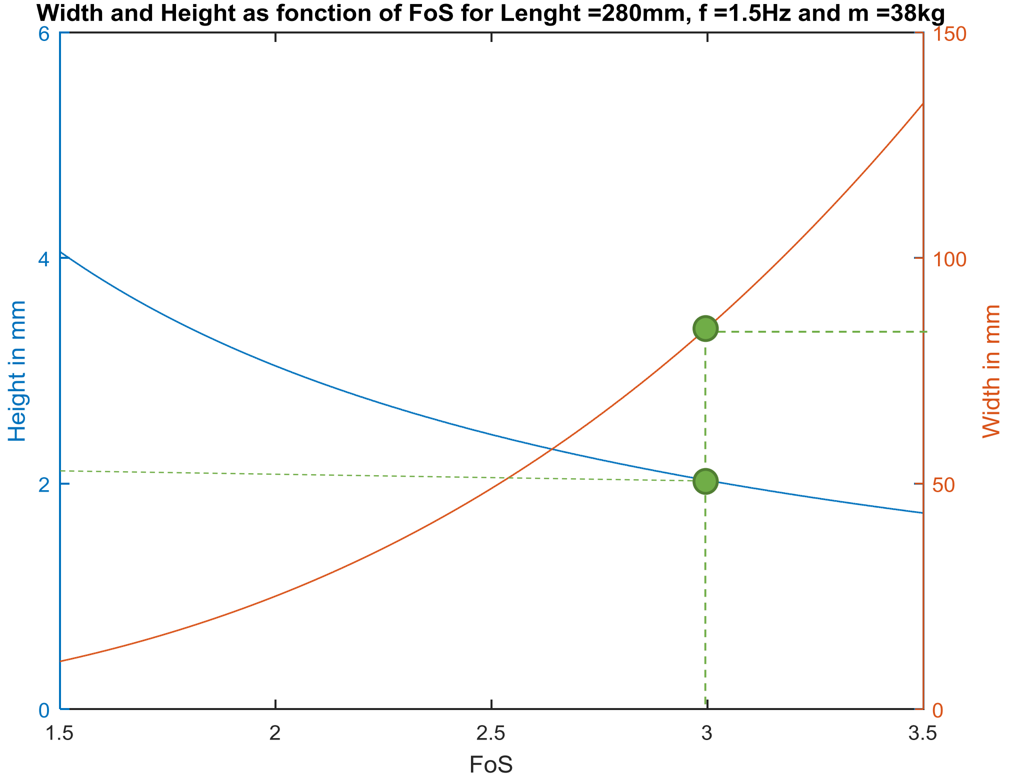
- Theoretical Results (BladeDesign.m) for m = 36kg, f = 1.5Hz and FoS = 3:
- l = 280 mm
- b = 80.12 mm
- h = 2.0282 mm
- Kzz = 1065.9 N/m
- Tip deflection = 110.4 mm



NOTE: 80mm is less than what was previously used for the blade design (85 mm) so it fits widely in the designed bench.

BLADE DESIGN: Dimensions

- Theoretical Results (BladeDesign.m) for m = 36kg, f = 1.6 Hz
- l = 280 mm
- b = 85 mm
- h = 2.0761 mm
- FoS = 3.3346 (30%)
- Kzz = 1212.8 N/m



NOTE: In order to increase the FoS and knowing that 280 mm length and 85 mm wide blade fits in the design, the desired frequency has been raised to 1.6 Hz.

BLADE DESIGN: Dimensions

- FINAL DIMENSIONS:

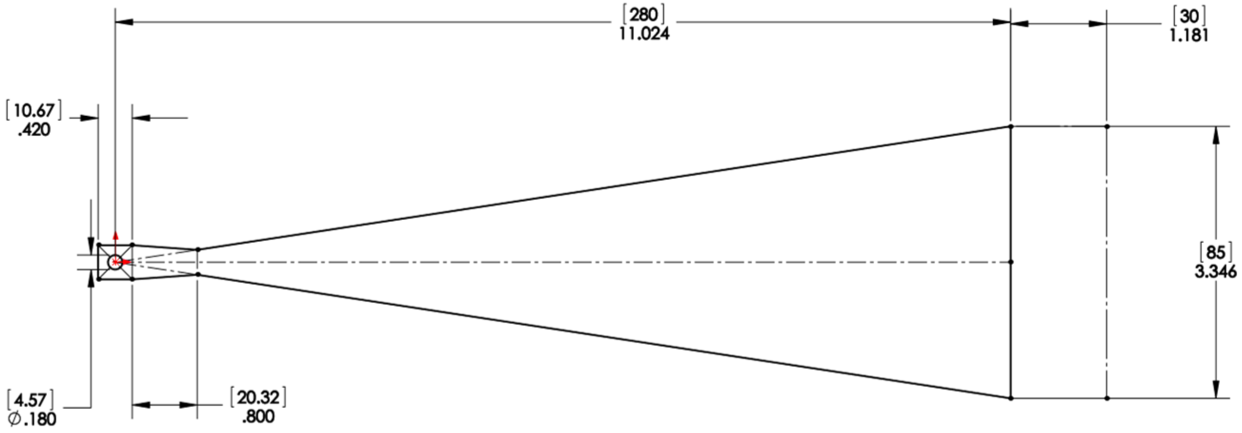
- l = 280 mm
- b = 85 mm
- h = 2.1 mm

- m = 41kg

- f = 1.5252 Hz
- Kzz = 1255.1 N/m
- FoS = 3

- m = 36kg

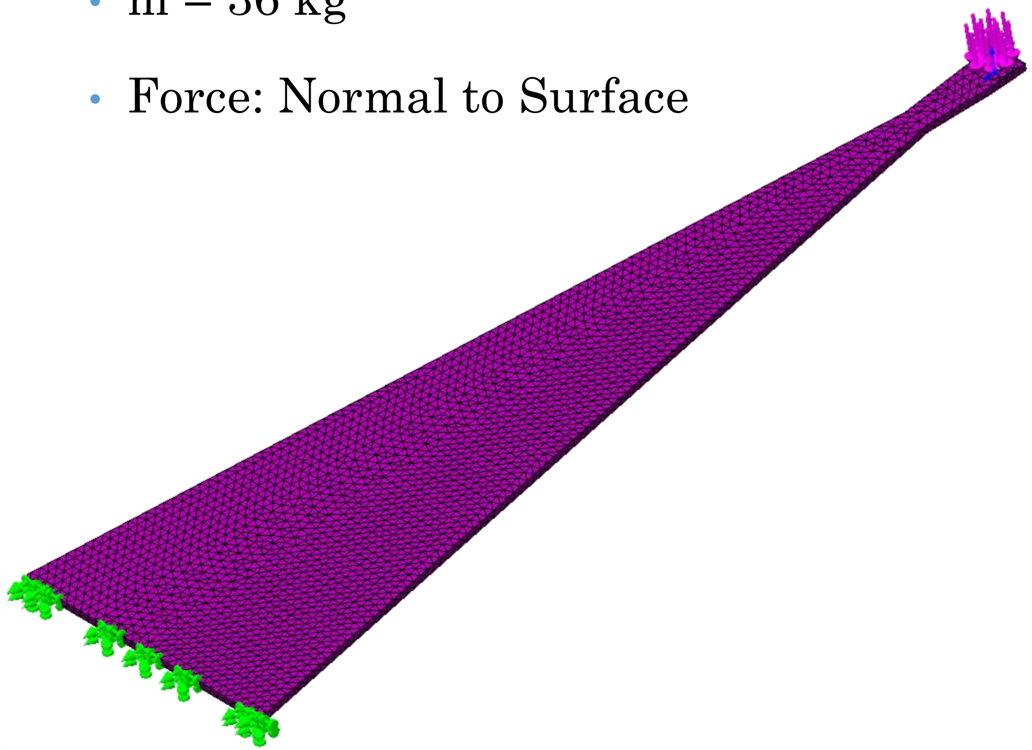
- f = 1.6277 Hz
- Kzz = 1255.1 N/m
- FoS = 3.5473

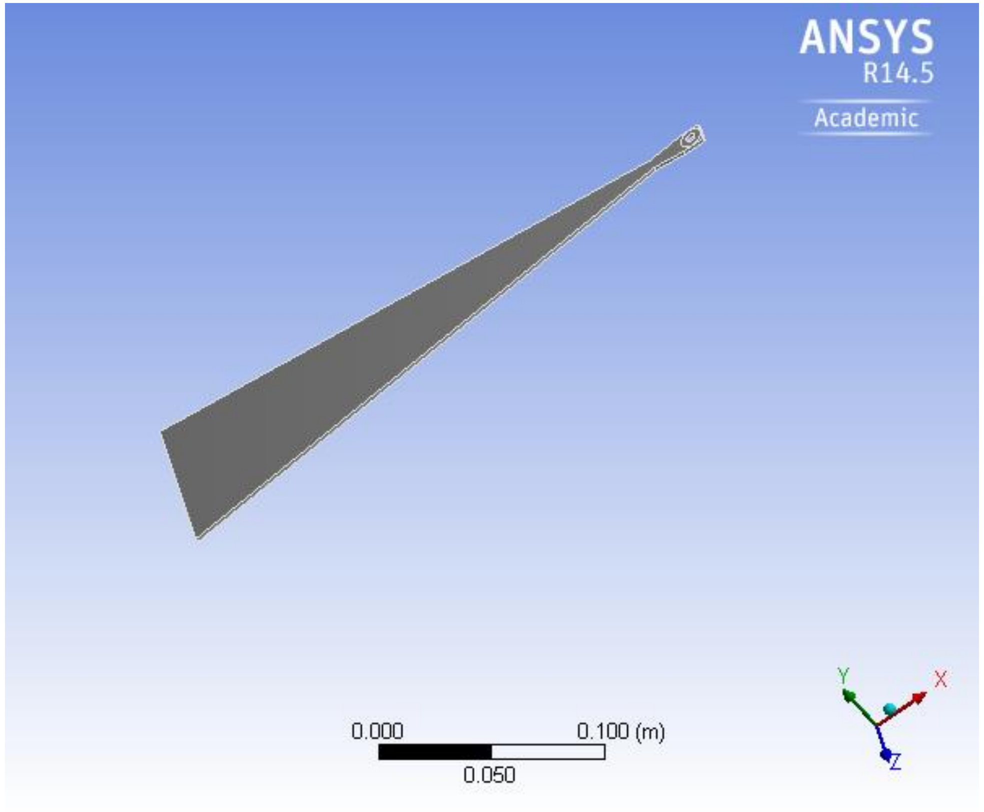


NOTE: The expected performances are those shown for 36 kg (that already include some contingency). However, the suspended mass could be raised up to 41 kg keeping FoS ≥ 3

BLADE DESIGN: FEA

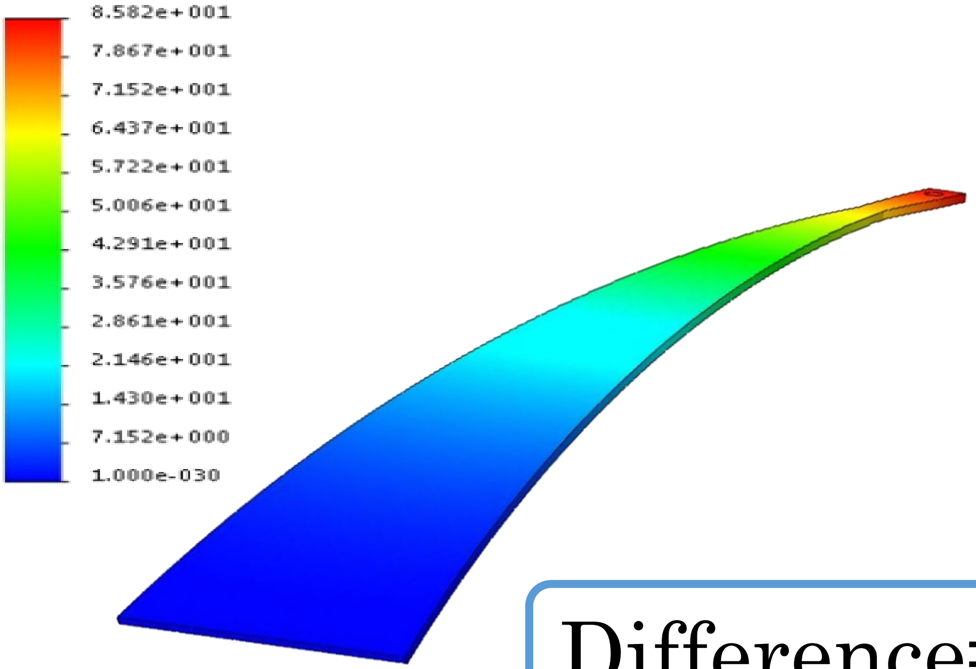
- First Analysis using SW Simulation
- Second Analysis using ANSYS
- m = 36 kg
- Force: Normal to Surface

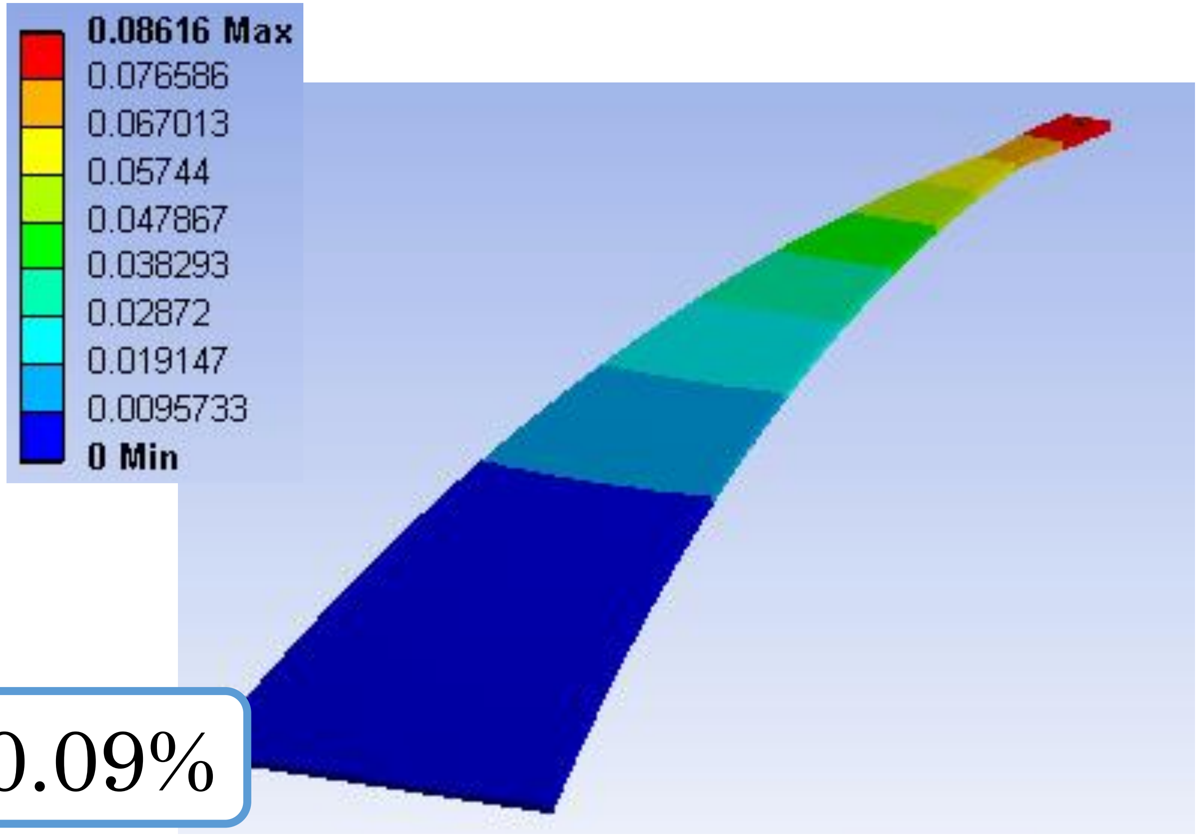




BLADE DESIGN: FEA

- Deformation





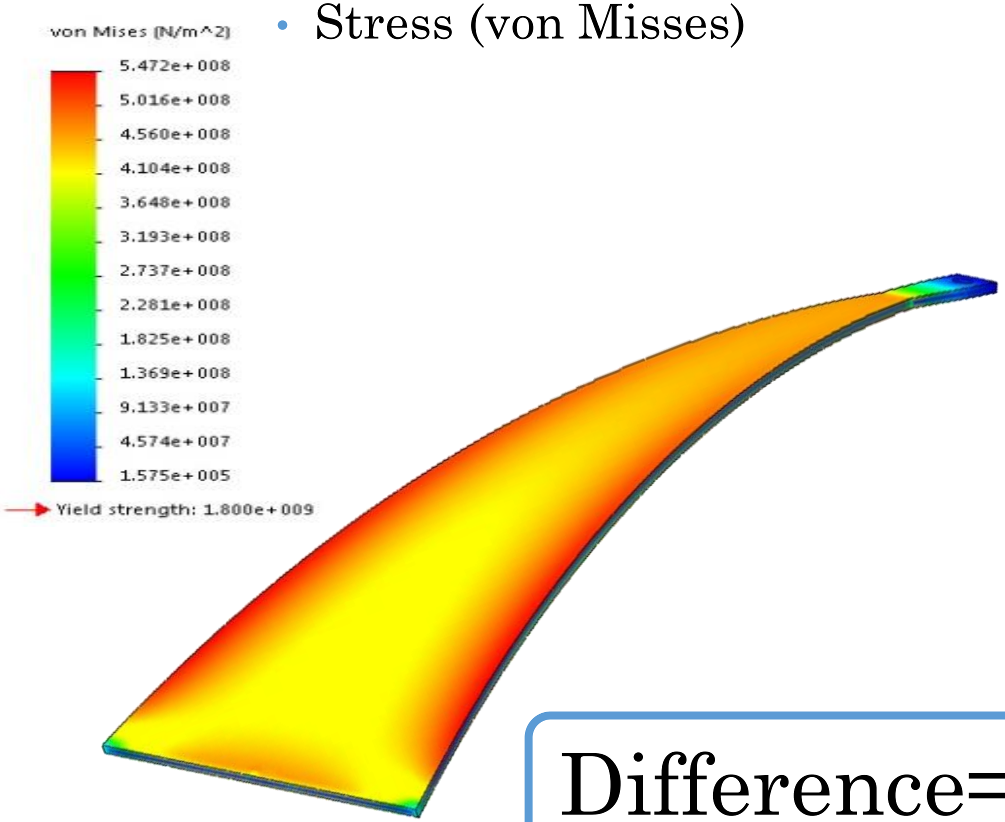
Difference= 0.09%

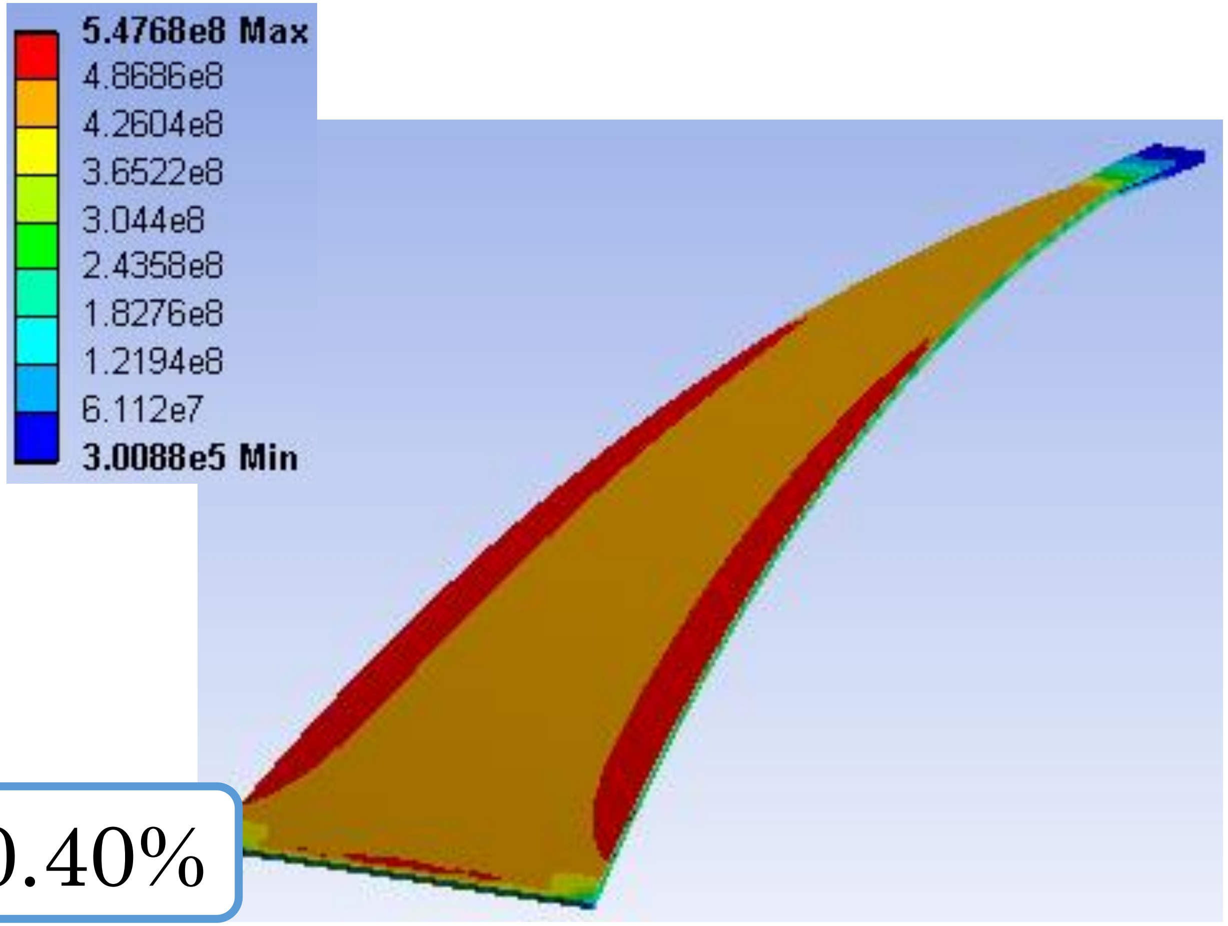
SW SIMULATION

ANSYS

BLADE DESIGN: FEA

- Stress (von Misses)





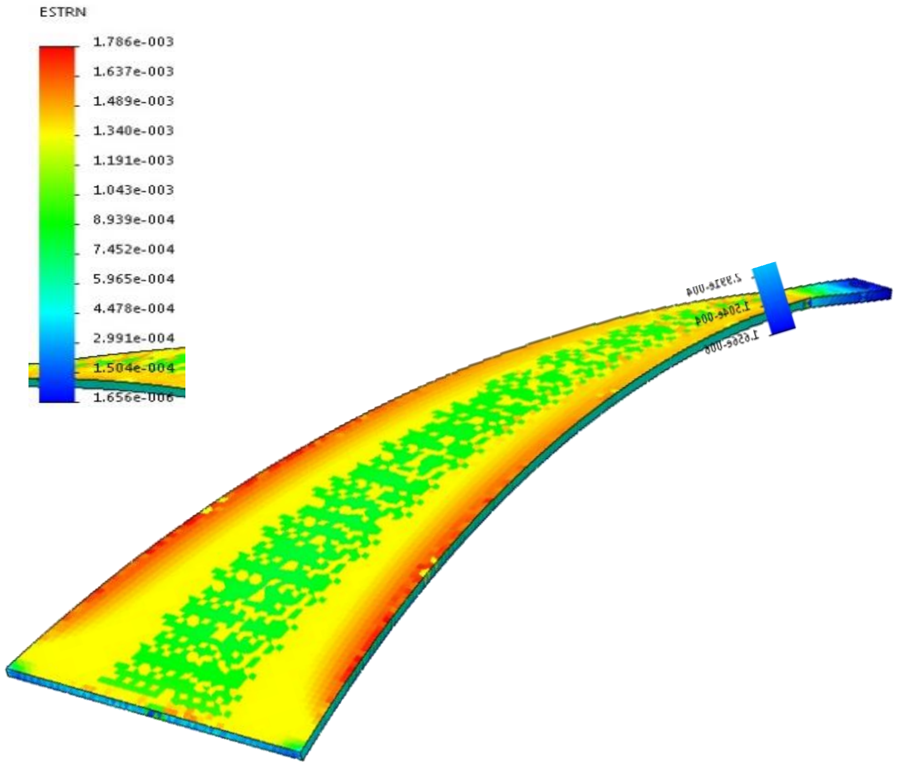
Difference= 0.40%

SW SIMULATION

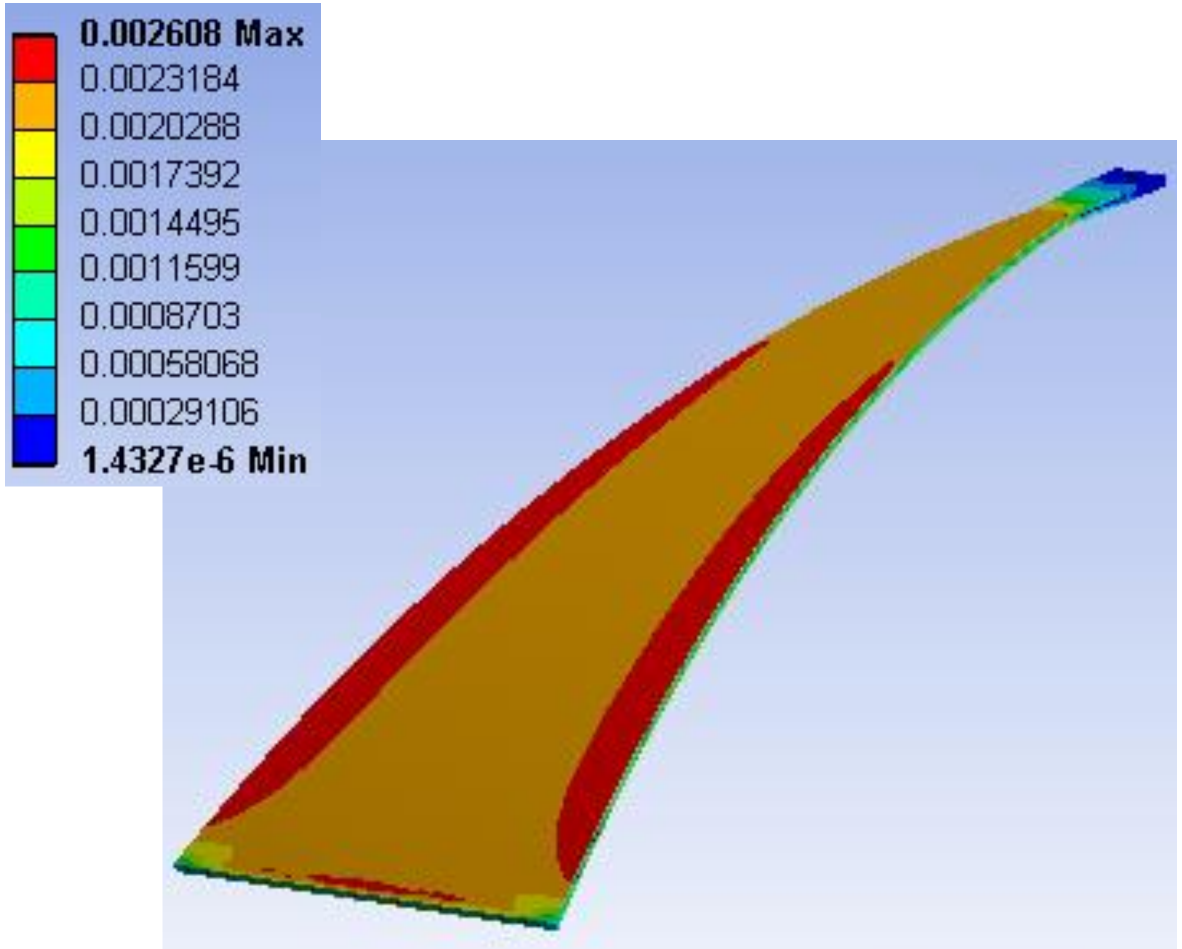
ANSYS

BLADE DESIGN: FEA

- Strain (Equivalent)



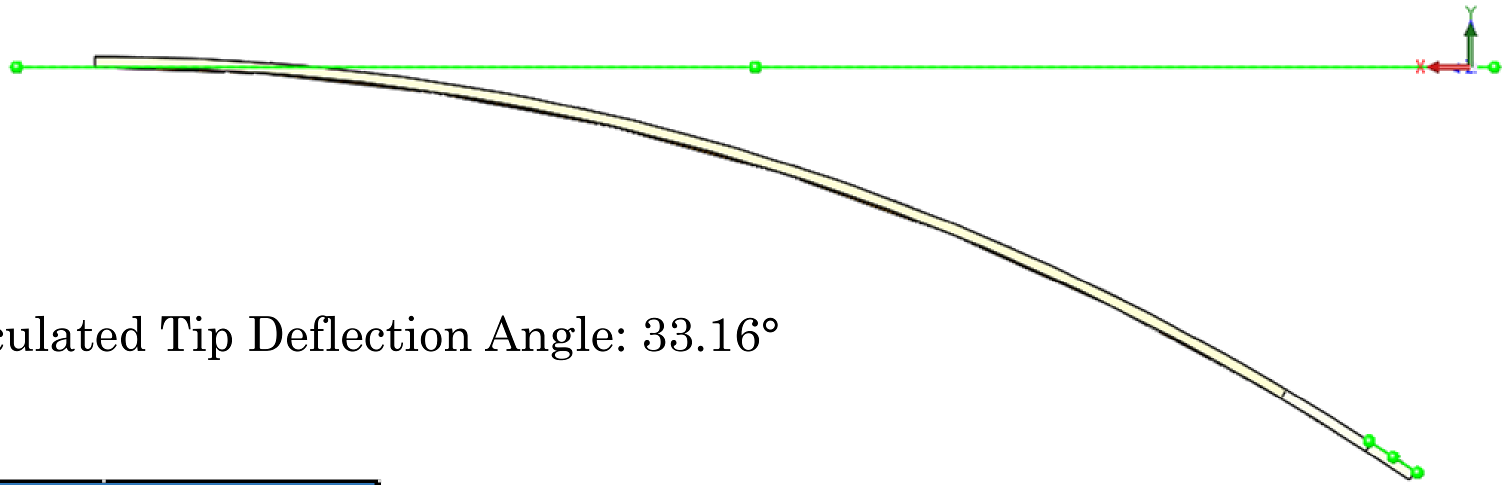
SW SIMULATION



ANSYS

BLADE DESIGN: FEA

- Conclusions:



Calculated Tip Deflection Angle: 33.16°

FEA			
	SW	**ANSYS**	**Difference %**
Stress (MPa)	547.2	547.68	0.088
Displacement (mm)	85.82	86.16	0.395
Strain	1.79E-03	2.61E-03	31.52
FoS	3.29	3.29	

SW and ANSYS show similar results

Possible different Strain Definition

FoS significantly lower than calculated (FoS = 3.55) [-7.32%]

FLEXURE DESIGN: Properties

- Material: Music Wire Steel (E = 154-201 GPa, σ_Y = 1600-2000 Mpa)
- Total Suspended Mass: m = 36 kg
- Charge per wire: P = 117.12 N

Instron 5500R: Tensile Strength Testing, Coiled Wires					
untreated wires			cryotreated wires		
diameter (mm)	max stress (Pa)	Young's Modulus (Pa)	diameter (mm)	max stress (Pa)	Young's Modulus (Pa)
0.635	2.16E+09	1.54E+11	0.635	2.16E+09	-
0.457	2.52E+09	2.01E+11	0.457	2.51E+09	2.11E+11
0.203	2.23E+09	1.99E+11	0.2	2.24E+09	4.32E+11

T1500539

D (in)	Min Tensile (ksi)	D (mm)	Min Tensile (MPa)
0.0047	360	0.1194	2482.11
0.0060	350	0.1524	2413.17
0.0079	340	0.2007	2344.22
0.0098	330	0.2489	2275.27
0.0106	330	0.2692	2275.27
0.0134	320	0.3404	2206.32
0.0140	320	0.3556	2206.32
0.0160	310	0.4064	2137.38
0.0180	310	0.4572	2137.38
0.0240	290	0.6096	1999.48
0.0250	290	0.6350	1999.48
0.0280	290	0.7112	1999.48
0.0433	290	1.0998	1999.48

Minimum Tensile Strengths (E1100187)

NOTE: T1500539 shows a 84.6% average relation between σ_Y and UTS. Therefore, in further calculations σ_Y is calculated as 80% of the Minimum Tensile Strength

D (mm)	0.1194	0.1524	0.2007	0.2489	0.2692	0.3404	0.3556	0.4064	0.4572	0.6096	0.6350	0.7112	1.0998
Considered Yield Strenght (Mpa)	1986	1931	1875	1820	1820	1765	1765	1710	1710	1600	1600	1600	1600
Average Porportional Yield Strenght (Mpa)				1930	1840	1780	1770		1930	2190		1620	2170

FLEXURE DESIGN: Music Wire

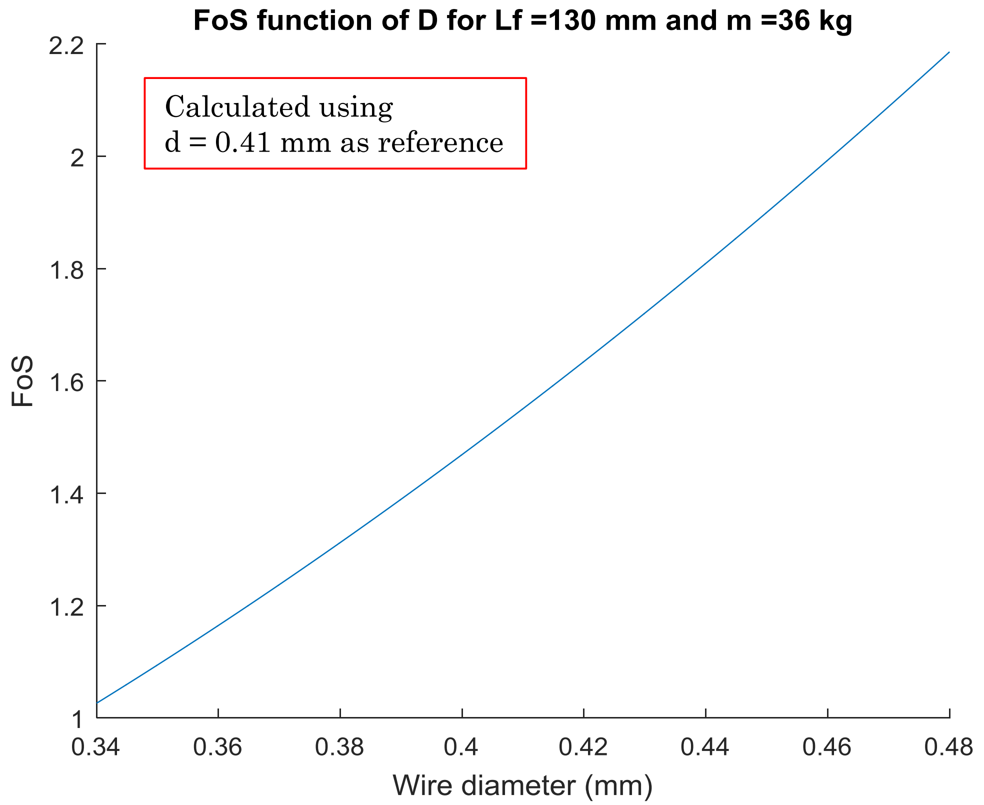
- Material: Music Wire Steel ($E = 201$ GPa, $\sigma_Y = 1710$ Mpa)
- Total Suspended Mass: $m = 36$ kg
- Charge per wire: $P = 117.72$ N

- Desired frequency: $f < 1.5$ Hz
- FoS ≥ 33.3% (FoS ≥ 3)

- Lf = 130mm
- d = 0.41 mm

FlexureDesign.m

- f = 1.3992 Hz
- Kxx = 927.5 N/m
- FoS = 1.5508



NOTE: Diameter of 0.41mm enables to re-use the Faraday Isolator clamps but FoS = 1.55 is too low for our purposes

FLEXURE DESIGN: Music Wire

- Material: Music Wire Steel (E = 201 GPa, σ_Y = 1600 Mpa)
- Total Suspended Mass: m = 36 kg
- Charge per wire: P = 117.72 N

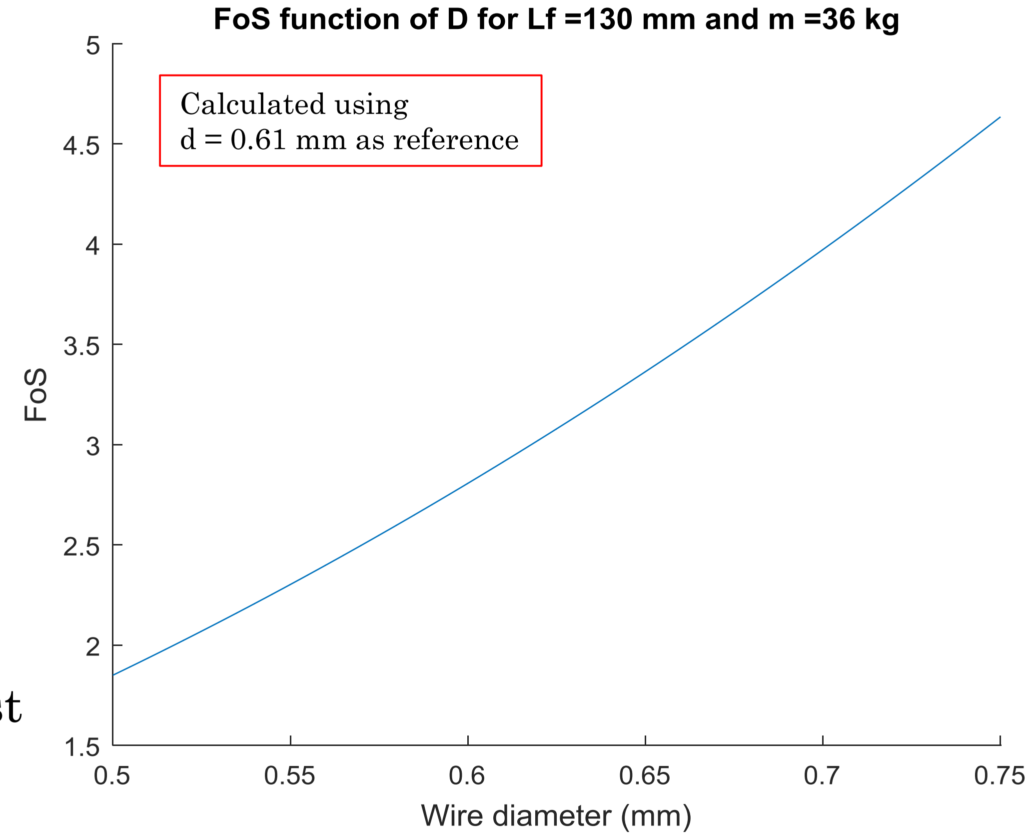
- Desired frequency: f < 1.5 Hz
- FoS ≥ 33.3% (FoS ≥ 3)

- Lf = 130mm
- d = 0.61 mm

FlexureDesign.m

- f = 1.4203 Hz
- Kxx = 955.62 N/m
- FoS = 2.9148

NOTE: Wire clamps will have to be redefined



NOTE: Diameter of 0.61mm raise FoS up to almost 3, which is considered enough as the minimal guaranteed tensile strength has been considered

FLEXURE DESIGN: Theory

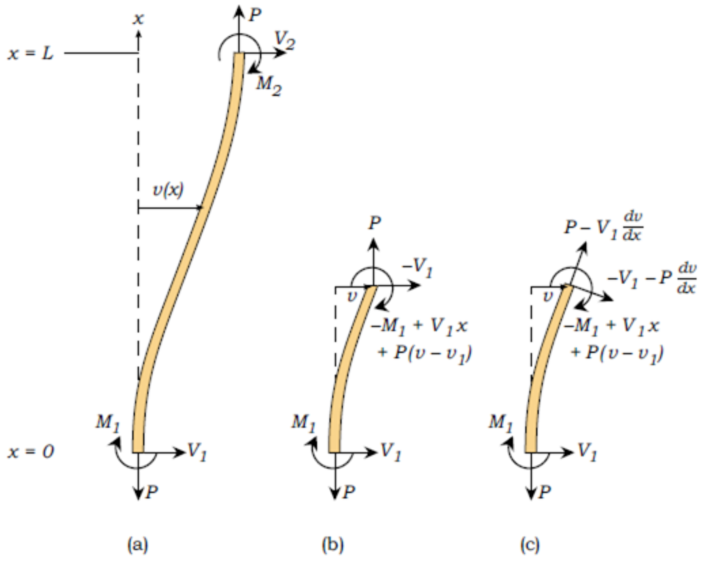
- Frequency calculation using pendulum theory

$$\ddot{\alpha} + \frac{g}{lz} sin\alpha = 0$$

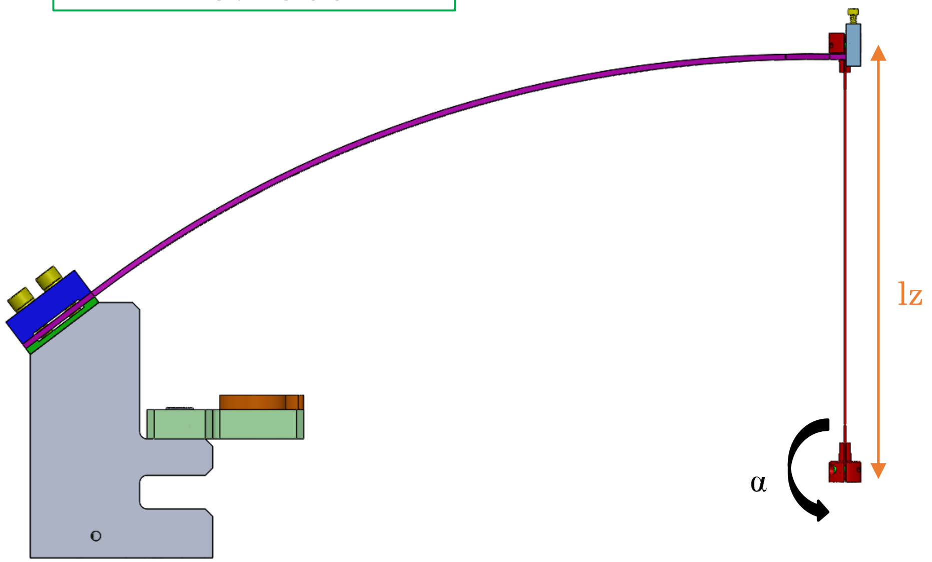
$$\omega^2 = \frac{g}{lz}$$

$$f = \frac{1}{2\pi}\sqrt{\frac{g}{lz}}$$

$$f_{PEND} = 1.4203\ Hz$$



$lz = 123.1869$ mm



CLAMP DESIGN: Material & Preload

- SCREW MATERIAL
  - 316 SSTL + HELICOILS

Bolt	Hole	Measured Coefficient	Expected coefficient
Silver plated	Steel	0.30-0.31	---
Silver plated	Helicoil	0.26-0.35	---
Steel	Helicoil	0.44-0.52	---
Steel	Aluminum	0.44-0.61	0.61*

Table 3 MECHANICAL REQUIREMENTS FOR STAINLESS STEEL BOLTS, SCREWS, STUDS AND NUTS (ASTM F593-91)

		MECHANICAL REQUIREMENTS							
		BOLTS, SCREWS AND STUDS						NUTS	
		FULL SIZE BOLTS, SCREWS, STUDS		MACHINED TEST SPECIMENS OF BOLTS, SCREWS, STUDS					
GRADE[1]	GENERAL DESCRIPTION	YIELD[2] STRENGTH min ksi	TENSILE STRENGTH min ksi	YIELD[2] STRENGTH min ksi	TENSILE STRENGTH min ksi	ELONGATION[3] % Min	HARDNESS ROCKWELL Min	PROOF LOAD STRESS ksi	HARDNESS ROCKWELL Min
303-A 304-A	Austenitic Stainless Steel-Sol. Annealed	30	75	30	75	20	B75	75	B75
304 305 316 384 XM7*	Austenitic Stainless Steel-Cold Worked	50	90	45	85	20	B85	90	B85
305-A 316-A 384-A XM7-A*	Austenitic Stainless Steel-Sol. Annealed	30	75	30	75	20	B70	75	B70
304-SH 305-SH 316-SH	Austenitic Stainless Steel-Strain Hardened	See Note 6	See Note 6	See Note 6	See Note 6	15	C25	See Note 6	C20
410-H 416-H	Martensitic Stainless Steel-Hardened and Tempered	95	125	95	125	20	C22	125	C22
410-HT 416-HT	Martensitic Stainless Steel-Hardened and Tempered	135	180	135	180	12	C36	180	C36
430	Ferritic Stainless Steel-	40	70	40	70	20	B75	70	B75

- http://www.ssina.com/download_a_file/fasteners.pdf

- σ_Y = 344.74 Mpa (50 ksi)
- μ = 0.5

clampDesign.m FoS = 3

- Tension = 2290.7 N
- T = 8.8702 Nm (78.51 in-lb)

Note: No Socket Head Screw for this material neither Silver Plated option (McMaster & Holo-Krome)

Note II: Torque similar to the recommended for Generic Screws in T1100066 (75 in-lb)

CLAMP DESIGN: Material & Preload

- SCREW MATERIAL
  - 18-8 SSTL + HELICOILS

US Bolts					
Head Marking	Grade and Material	Nominal Size Range (inches)	Mechanical Properties		
			Proof Load (psi)	Min. Yield Strength (psi)	Min. Tensile Strength (psi)
No Markings	Grade 2 Low or medium carbon steel	1/4 thru 3/4	55,000	57,000	74,000
		Over 3/4 thru 1-1/2	33,000	36,000	60,000
3 Radial Lines	Grade 5 Medium Carbon Steel, Quenched and Tempered	1/4 thru 1	85,000	92,000	120,000
		Over 1 thru 1-1/2	74,000	81,000	105,000
6 Radial Lines	Grade 8 Medium Carbon Alloy Steel, Quenched and Tempered	1/4 thru 1-1/2	120,000	130,000	150,000
Stainless markings vary. Most stainless is non-magnetic	18-8 Stainless Steel alloy with 17-19% Chromium and 8-13% Nickel	All Sizes thru 1		20,000 Min. 65,000 Typical	65,000 Min. 100,000 – 150,000 Typical

- http://www.nuttybolts.com/nutty-bolts/?page_id=146
- http://www.mcmaster.com/#socket-head-cap-screws/=z2xdjy
- https://www.boltdepot.com/fastener-information/materials-and-grades/bolt-grade-chart.aspx

Bolt	Hole	Measured Coefficient	Expected coefficient
Silver plated	Steel	0.30-0.31	---
Silver plated	Helicoil	0.26-0.35	---
Steel	Helicoil	0.44-0.52	---
Steel	Aluminum	0.44-0.61	0.61*

- σ_Y = 448.16 Mpa (65 ksi)
- $\mu = 0.5$

clampDesign.m FoS = 3

- Tension = 3066.9 N
- T = 11.8757 Nm (105.11 in-lb)

Note I: Torque similar to the recommended for 18-8 Holo-Krome in T1100066 (100 in-lb)

CLAMP DESIGN: Material & Preload

- SCREW MATERIAL
  - 17-4 PH SSTL + HELICOILS

Bolt	Hole	Measured Coefficient	Expected coefficient
Silver plated	Steel	0.30-0.31	---
Silver plated	Helicoil	0.26-0.35	---
Steel	Helicoil	0.44-0.52	---
Steel	Aluminum	0.44-0.61	0.61*

Nominal Composition by Percent

	C	Mn	Si	P	S	Cr	Ni	Cu	Columbium plus Tantalum	
Min	-	-	-	-	-	15.00	3.00	3.00	0.15	%
Max	.07	1	1.0	.04	.03	17.50	5.00	5.00	0.45	%

Condition	Ultimate Tensile Strength (PSI)	0.2% Yield Strength (PSI)	Elongation (% In 2in.)	Reduction Of Area (%)	Hardness Brinell	Hardness Rockwell
H900	190,000	170,000	10	40	388	C40
H1025	155,000	145,000	12	45	331	C35
H1075	145,000	125,000	13	45	311	C32
H1150	135,000	105,000	16	50	277	C28
H1150-M	115,000	75,000	18	55	255	C24
H1150-D	125,000	105,000	16	50	255 min - 311 max	C24 - 33

- http://www.deltafastener.com/17-4%20ph.html
- http://www.mcmaster.com/#=z2x9xd

- σ_Y = 861.84 Mpa (125 ksi)
- μ = 0.5 (conservative)

clampDesign.m FoS = 3

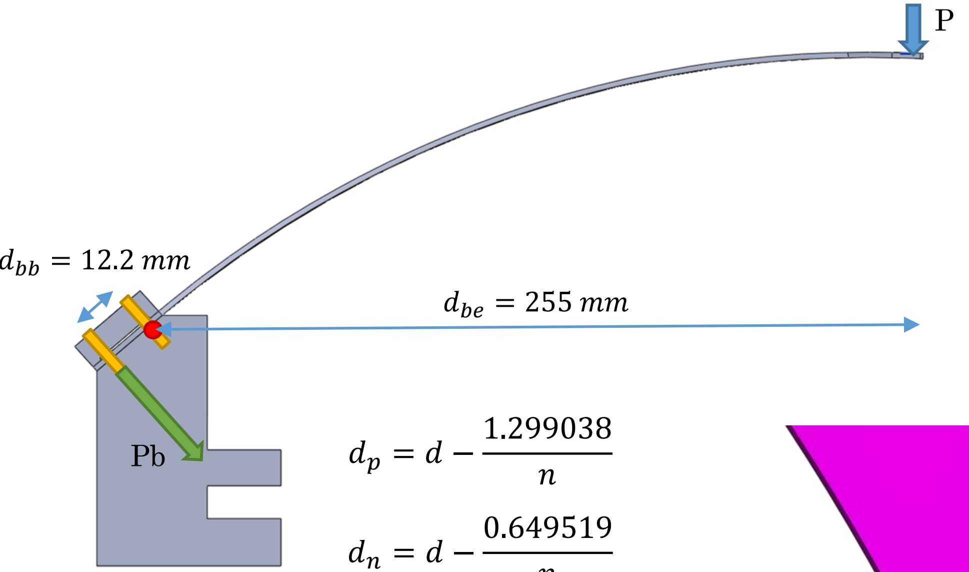
- Tension = 5897.8 N
- T = 22.8376 Nm (202.13 in-lb)

Note: No Socket Head Screw for this material neither Silver Plated option (McMaster & Holo-Krome)

Note II: Torque similar to the recommended for Carbon Steel 1960 Series in T1100066 (200 in-lb)

CLAMP DESIGN: Number of Screws

- Preliminary calculation using ClampDesign.m



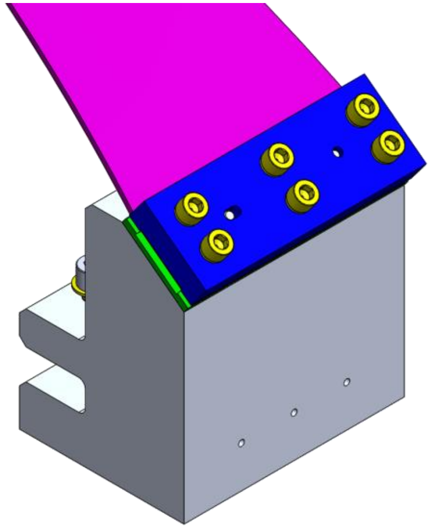
$$d_p = d - \frac{1.299038}{n}$$

$$d_n = d - \frac{0.649519}{n}$$

$$A_s = \frac{\pi}{4}\left(\frac{d_m + d_p}{2}\right)^2$$

$$P_{B_{MAX}} = \frac{\sigma_{YIELD}}{FoS} A_s$$

- $P_B = 2460.5N$



- 316 SSTL + HELICOILS
  - Bolts needed: min 2 screw per row for FoS > 3
  - FoS = 5.5859 (with 2 screw per row)
- 18-8 SSTL + HELICOILS
  - Bolts needed: min 1 screw per row for FoS > 3
  - FoS = 3.7393 (with 1 screw per row)
- 17-4 PH SSTL + HELICOILS
  - Bolts needed: min 1 screw per row for FoS > 3
  - FoS = 7.1909 (with 1 screw per row)

<u>Note:</u> The final number of screws per row and the material election will be driven by the contact calculation between the blade and the platform

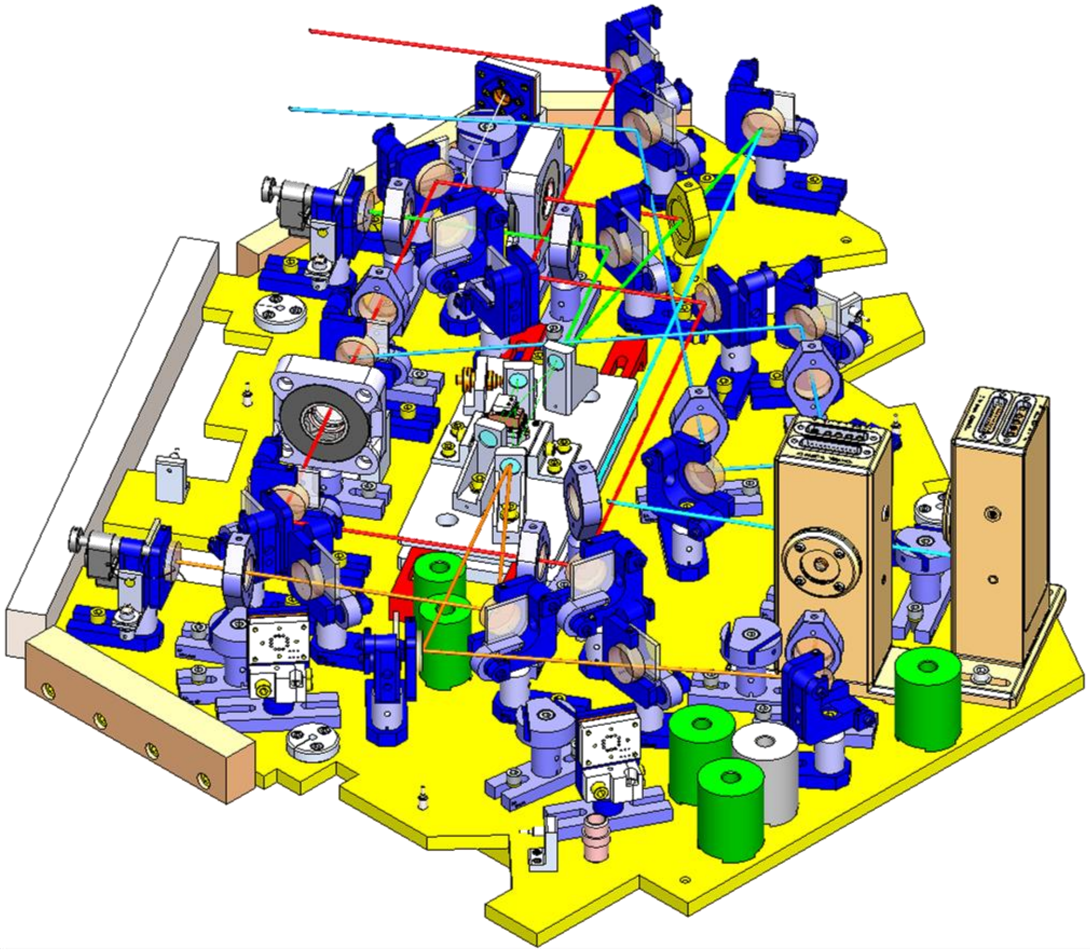
Balancing Mass

- Preliminary Mass Balancing
  - First Bench Design (≈17kg)

Center of mass: (millimeters)
X = 0.0
Y = 0.0
Z = 6.0

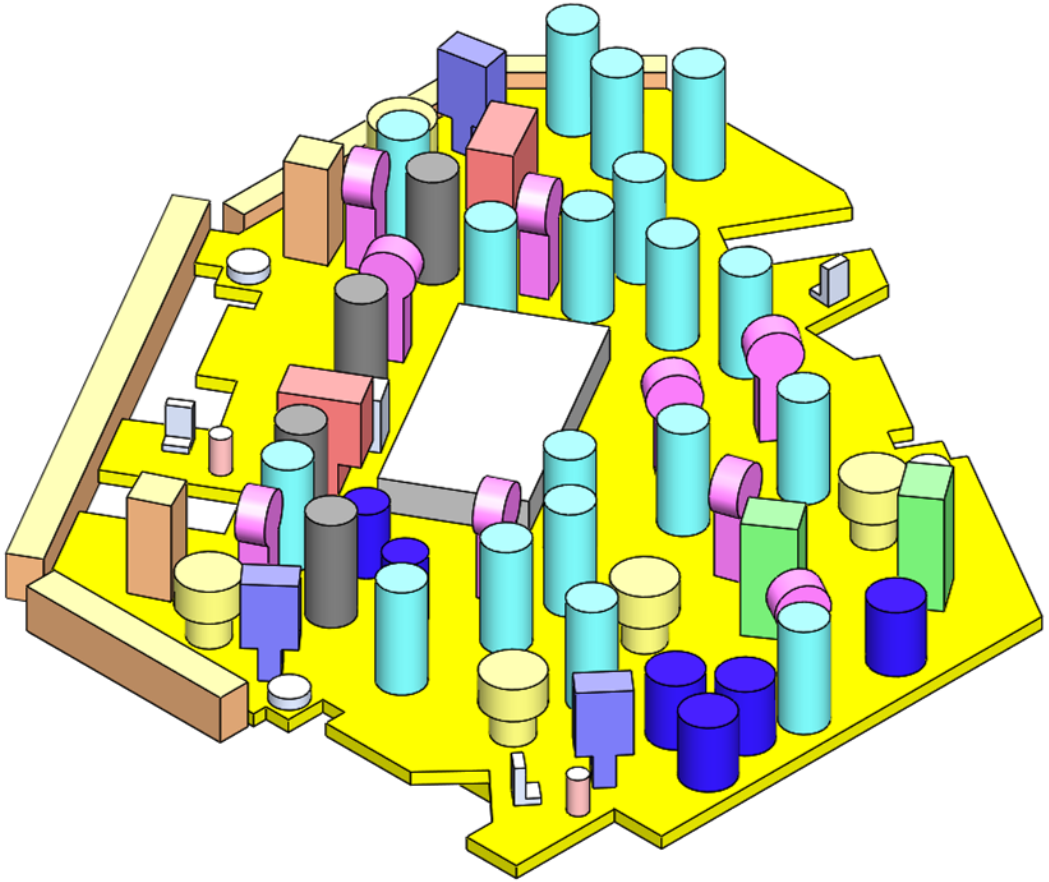
<u>Note:</u> The remaining 1kg has been reserved for the Bench Optimization and final CoG adjustment

<u>Note II:</u> This model is the one that has been used for the injection bench optimization and will be tunned according to the results of this optimization.



Injection Bench Assembly FEA

- Injection Bench Assembly for FEA with Masses



- Global Contact: Bonded
- Mesh: Compatible

Mass = 35301.6 grams

Volume = 675.6 cubic inches

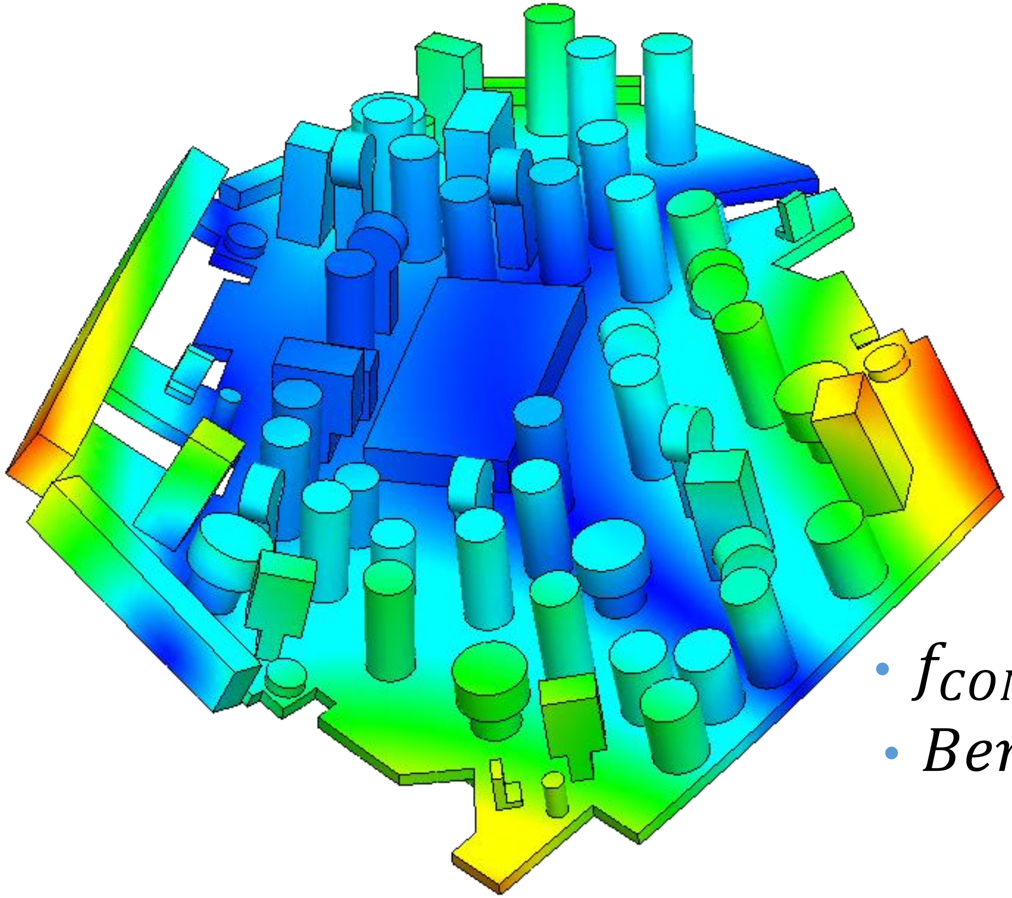
Surface area = 1493992.4 square millimeters

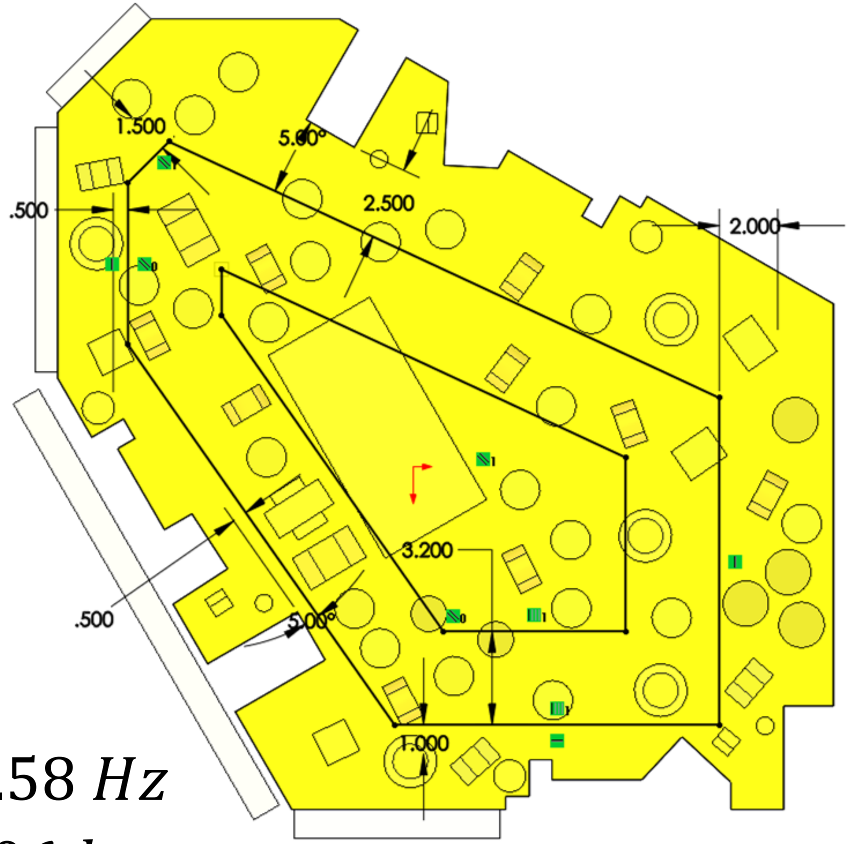
Center of mass: (millimeters)
X = 0.3
Y = 1.3
Z = 6.5

OPTICS	**9.933**	**kg**	**9.94927**
SUSPENSION	**17.131**	**kg**	**17.1857**
MASS	**8.131**	**kg**	**8.167**
TOTAL WEIGHT	**35.195**	**kg**	**35.301**
Mass to 36 kg	**0.80**	**kg**	0.70

Injection Bench Assembly FEA

- Injection Bench Assembly for FEA

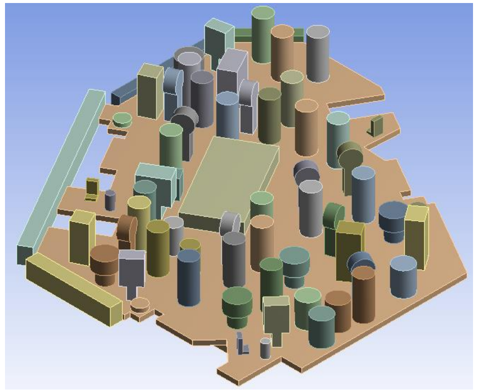




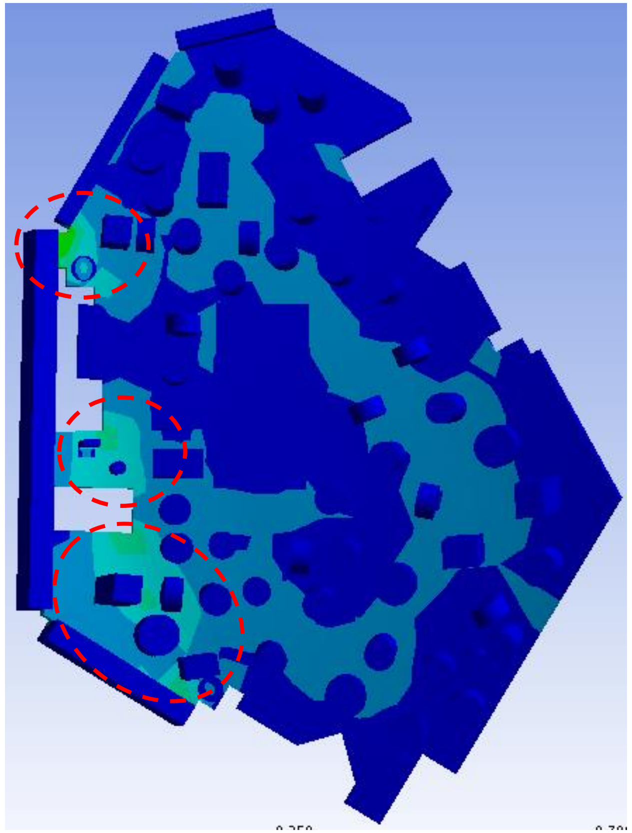
- $f_{COMPATIBLE} = 200.58\ Hz$
- $Bench\ Mass = 17.06\ kg$

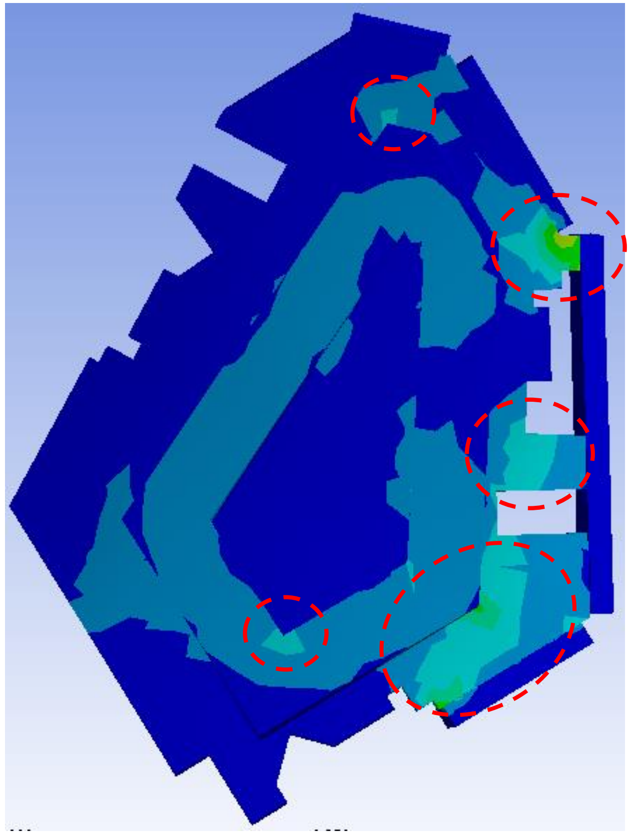
NOTE: The remaining 940g will be used to position the CoG

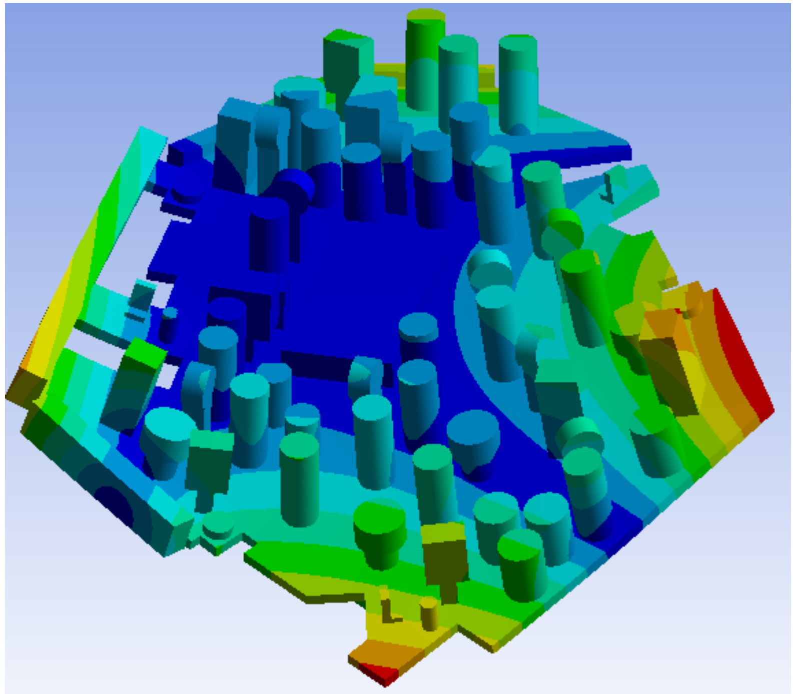
Injection Bench Assembly FEA



- Injection Bench Assembly for FEA (ANSYS)







- $f_{ANSYS} = 200.58\ Hz$

- *Equivalent Strain*

NOTE: The areas with high Strain should be reinforced using the 940g

Injection Bench Assembly FEA

- Injection Bench Assembly for FEA (no MASSES)

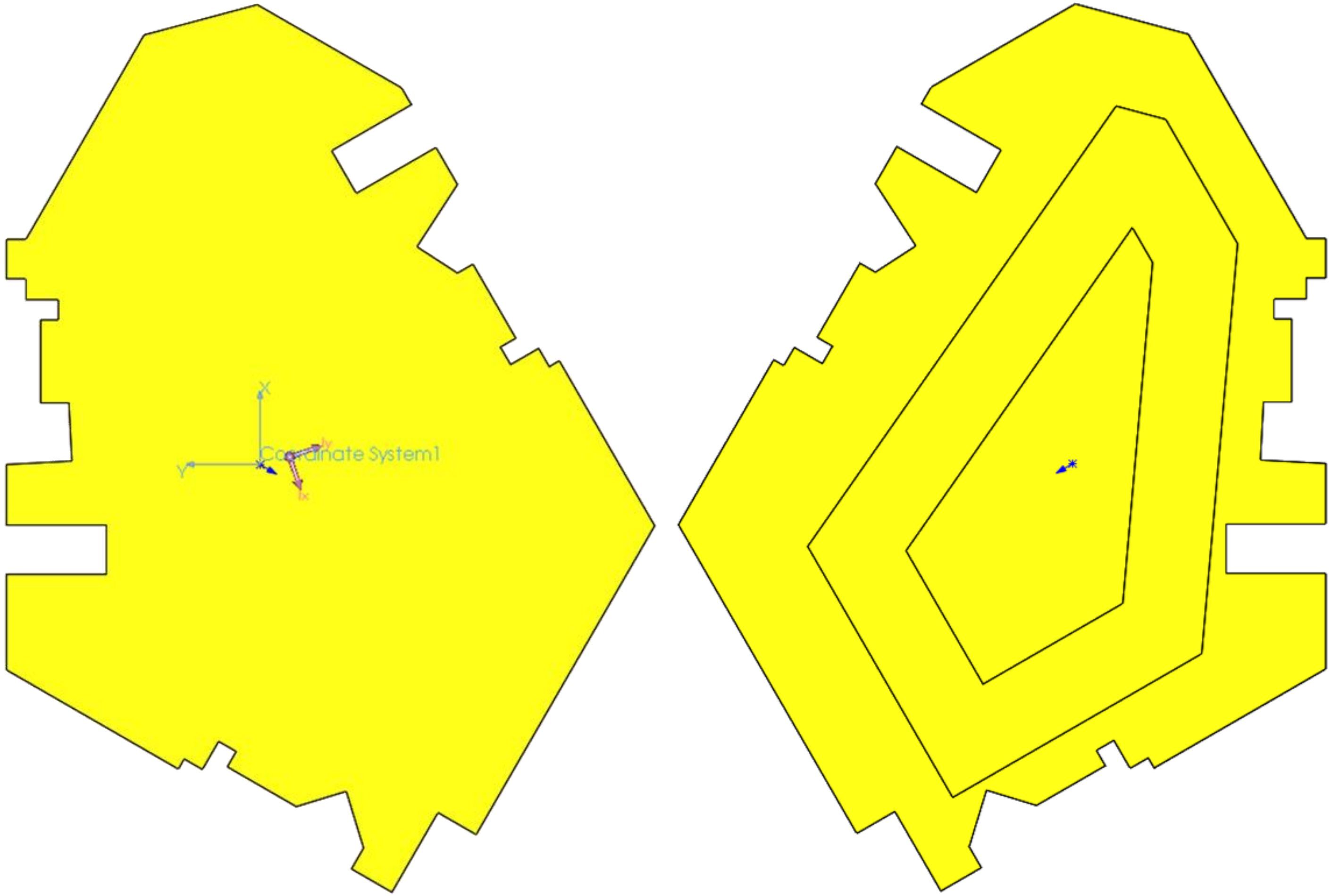
Density = 0.044 kilograms per cubic inch

Mass = 17.060 kilograms

Volume = 385.579 cubic inches

Surface area = 781537.629 square millimeters

Center of mass: (millimeters)
X = 21.518
Y = -13.145
Z = -20.716



NOTE: The remaining 940g will be used to position the CoG and to improve the high strain areas

Center of Mass

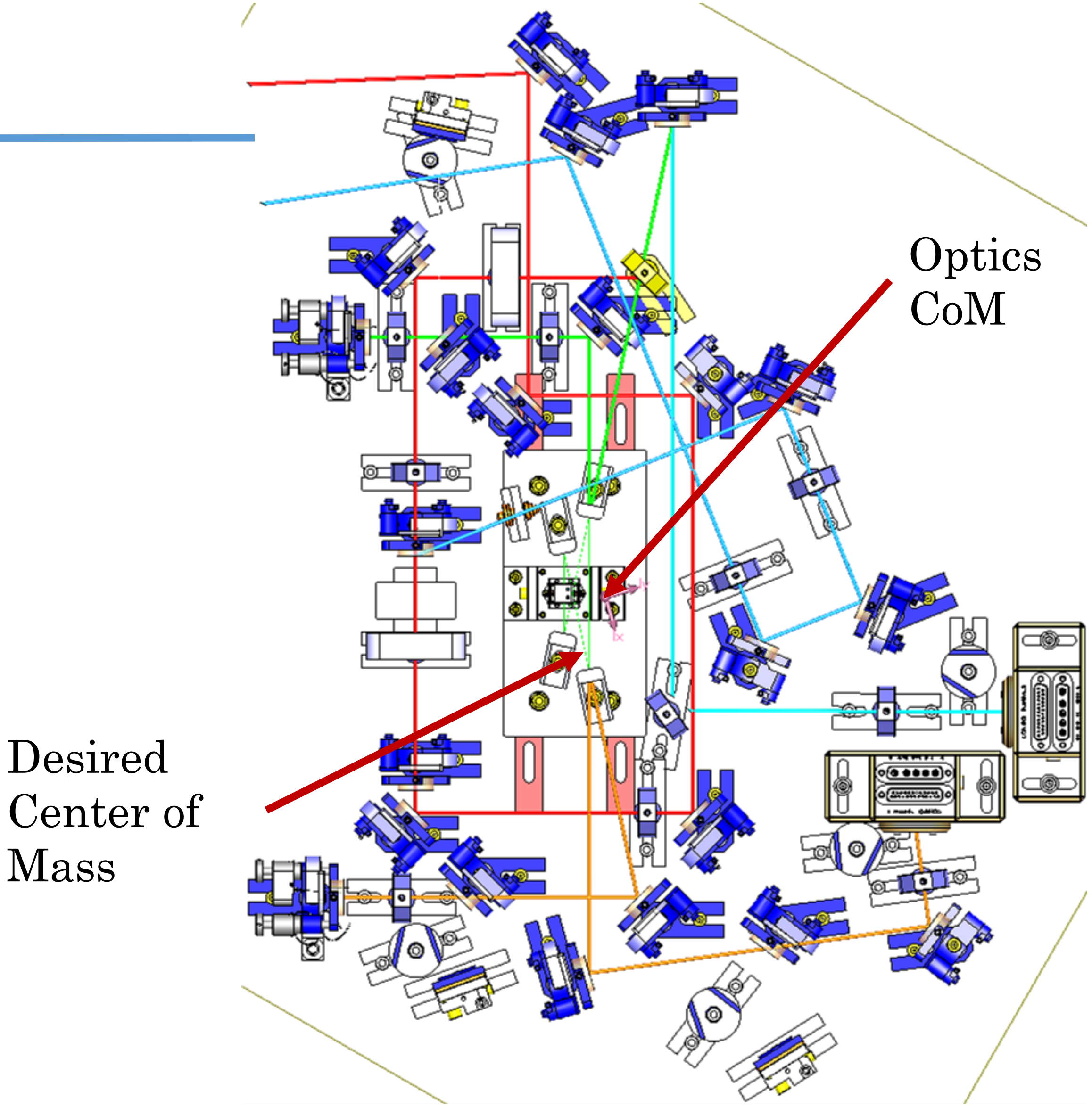
- Optics O3

Mass = 9932.652 grams

Volume = 0.003 cubic meters

Surface area = 1575061.645 square millimeters

Center of mass: (millimeters)
X = 35.471
Y = -16.171
Z = 37.586



Note: The Center of Mass of the optics is already close to the desired CoM (the barycenter of the clamps attachment points)

Balancing Mass

- Preliminary Mass Balancing
  - First Bench Design (≈17kg)
  - Lateral Masses

Mass = 32637.107 grams

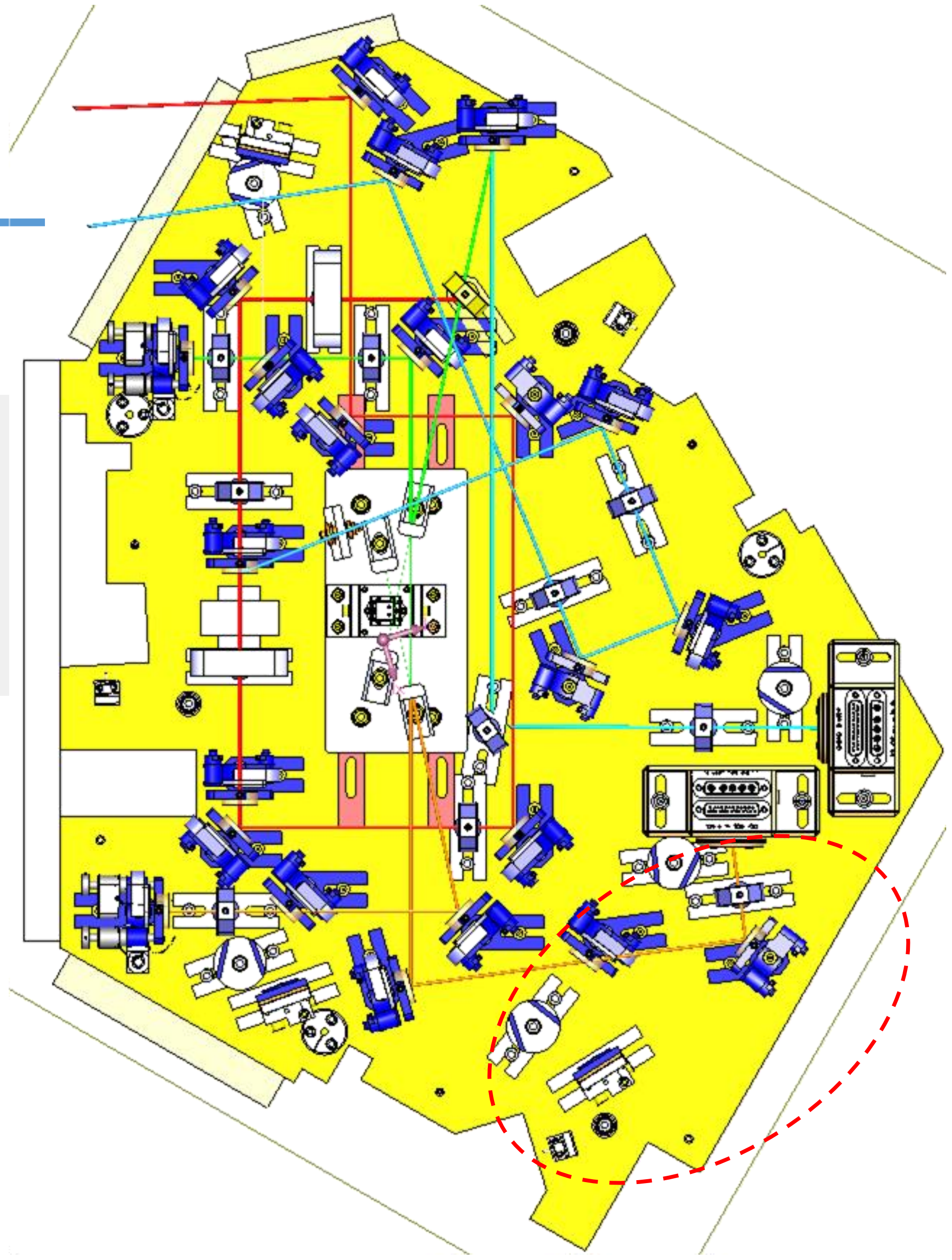
Volume = 0.010 cubic meters

Surface area = 2530447.011 square millimeters

Center of mass: (millimeters)
X = 19.147
Y = 15.506
Z = 5.293

OPTICS	**9.933**	**kg**
SUSPENSION	**17.131**	**kg**
MASS	**5.500**	**kg**
TOTAL WEIGHT	**32.564**	**kg**
Mass to 36 kg	**3.44**	**kg**

Note: The remaining 3.44kg (940g in the injection bench and the rest as balancing masses on the bench) should be placed near the dashed area in order to balance the assembly



Balancing Mass

- Optics + Balancing Mass

Mass = 33974.44 grams

Volume = 0.01 cubic meters

Surface area = 4024.50 square inches

Center of mass: (inches)
X = 0.00
Y = 0.00
Z = 0.37

Real CoM

Desired Center of Mass

<u>Note:</u> The balancing masses are more distributed in the left part of the assembly. That could be solved by "naturally" placing the CoG of the Injection Bench opposed to the Optics one.

Center of Mass

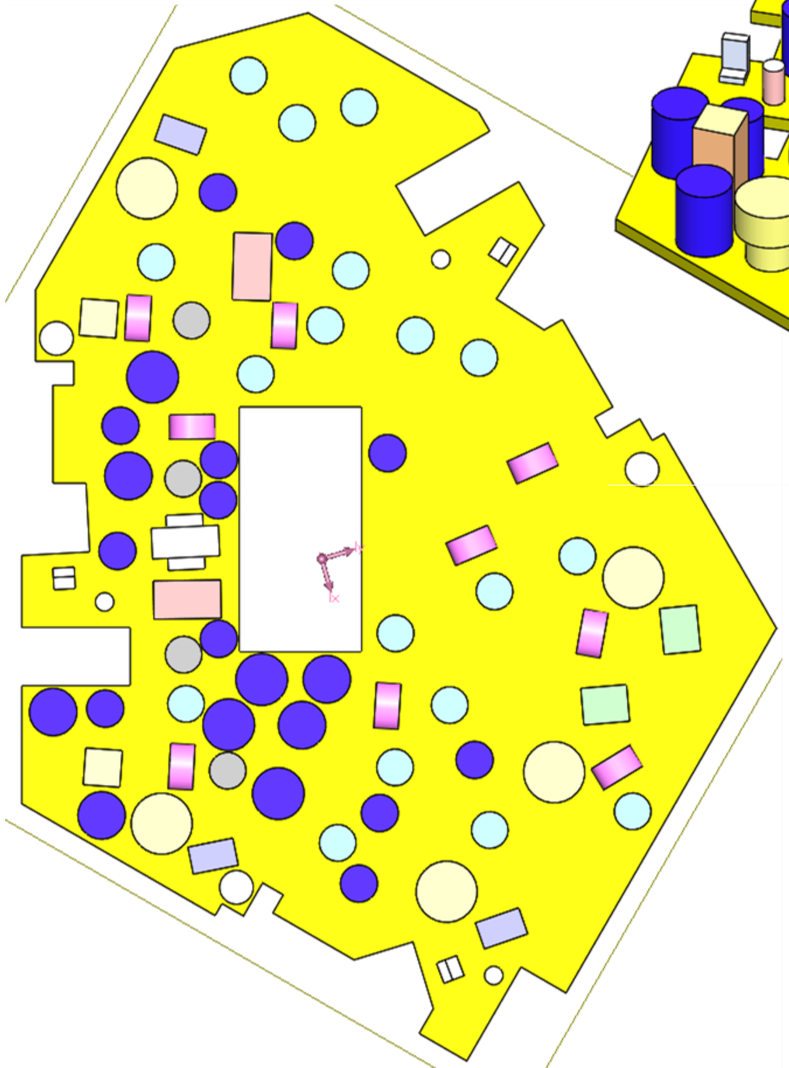
- FEA

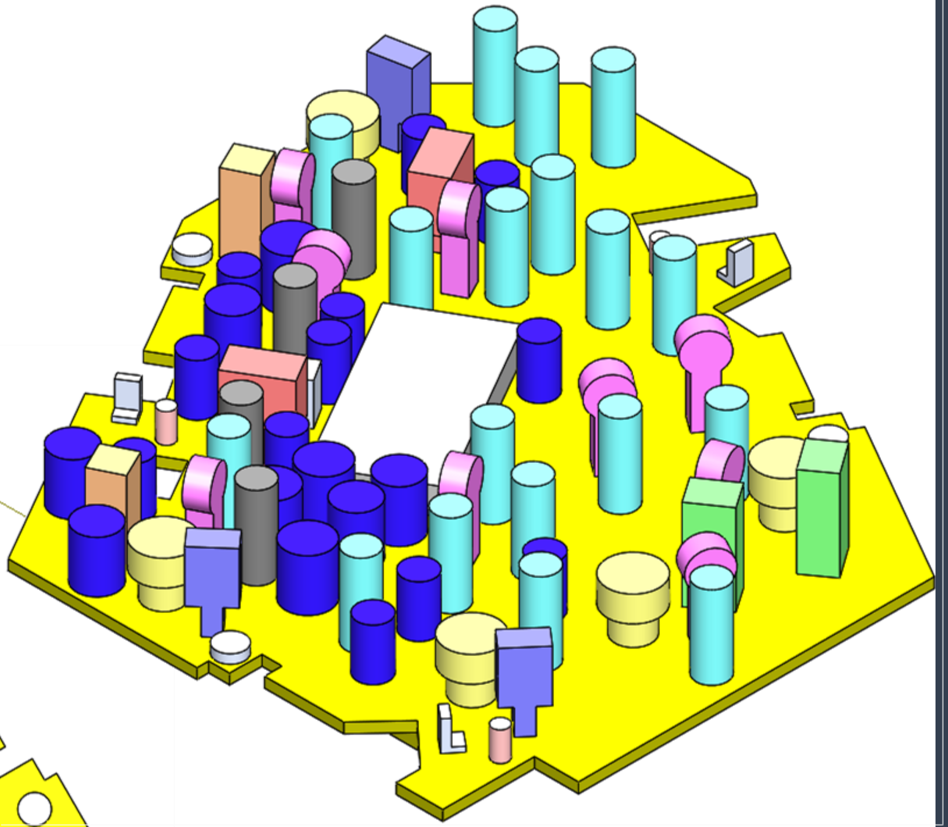
Mass = 33909.985 grams

Volume = 638.177 cubic inches

Surface area = 2301.473 square inches

Center of mass: (inches)
X = 0.346
Y = 0.405
Z = -0.079





Center of Mass

- With balancing masses

Mass properties of D1500292 aLIGO VOPO Injection Bench Assembly TO FEA
Configuration: Default
Coordinate system: Coordinate System1

Mass = 37.37 kilograms

Volume = 727.18 cubic inches

Surface area = 2533.66 square inches

Center of mass: (inches)
X = 0.08
Y = 1.21
Z = 0.09

Principal axes of inertia and principal moments of inertia: (kilograms * square inches)
Taken at the center of mass.

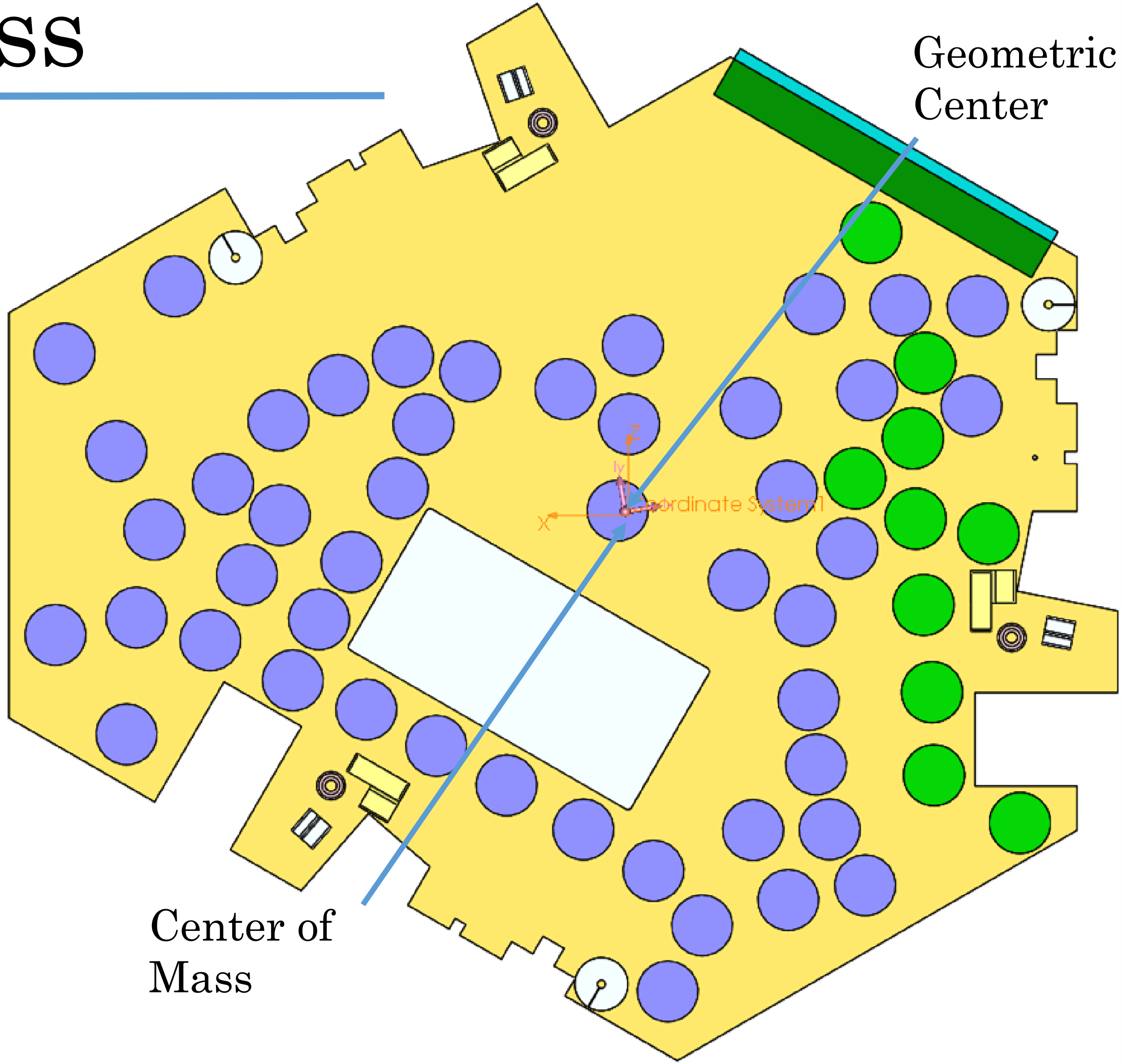
Ix = (-0.99, -0.01, 0.17)	Px = 1150.51
Iy = (0.17, -0.03, 0.99)	Py = 1818.71
Iz = (-0.01, 1.00, 0.04)	Pz = 2833.14

Moments of inertia: (kilograms * square inches)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 1169.36	Lxy = 18.00	Lxz = -109.72
Lyx = 18.00	Lyy = 2831.62	Lyz = -38.10
Lzx = -109.72	Lzy = -38.10	Lzz = 1801.38

Moments of inertia: (kilograms * square inches)
Taken at the output coordinate system.

Ixx = 1224.02	Ixy = 21.63	Ixz = -109.46
Iyx = 21.63	Iyy = 2832.14	Iyz = -34.21
Izx = -109.46	Izy = -34.21	Izz = 1856.00



Center of Mass

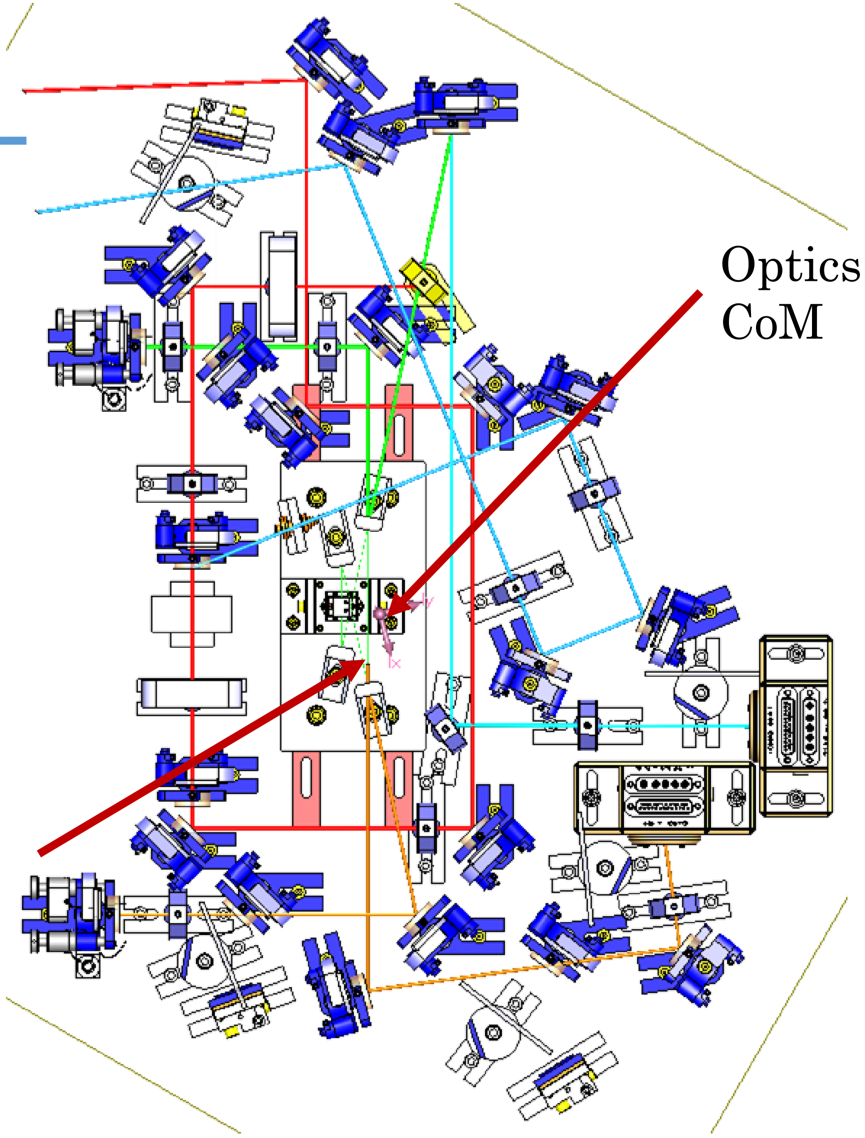
- Optics

Mass = 9893.8 grams

Volume = 0.0 cubic meters

Surface area = 1564570.5 square millimeters

Center of mass: (millimeters)
X = 35.2
Y = -12.3
Z = 37.5

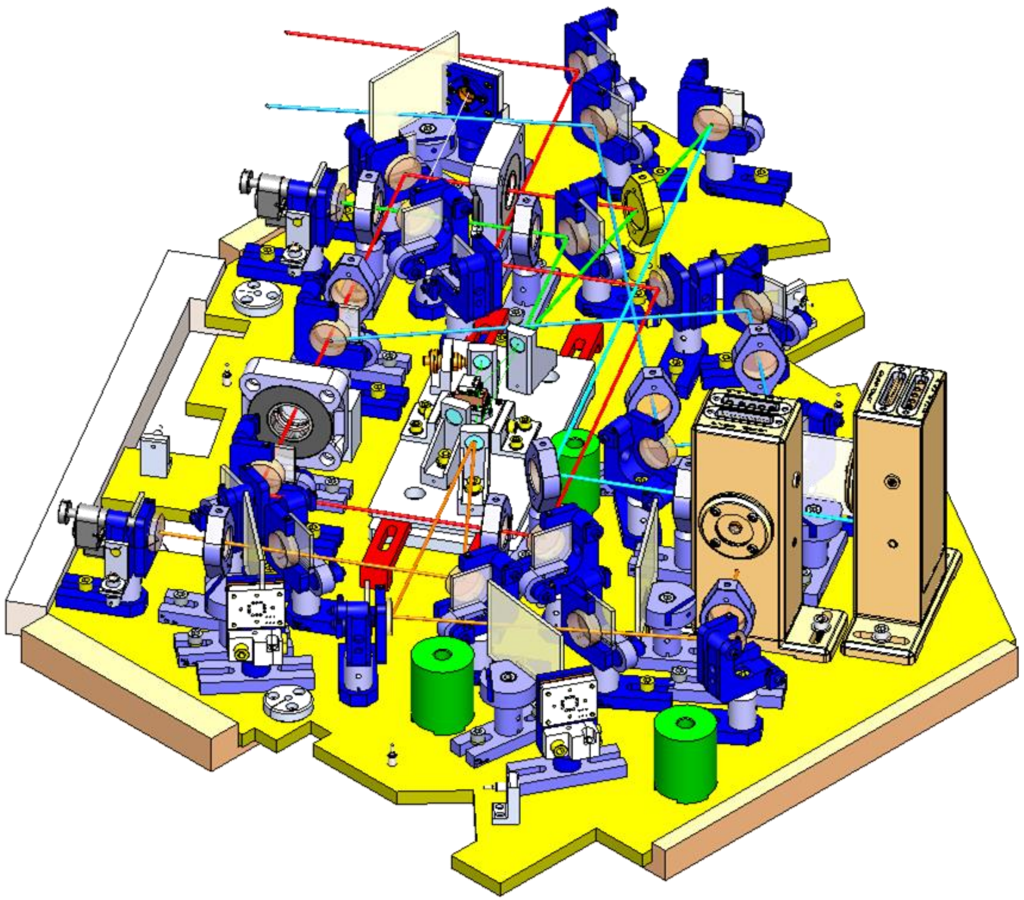


Note: The Center of Mass of the optics is already close to the desired CoM (the barycenter of the clamps attachment points)

Balancing Mass

- Preliminary Mass Balancing
  - First Bench Design (≈16kg)

OPTICS	9.819	kg
SUSPENSION	18.134	kg
MASS	8.050	kg
TOTAL WEIGHT	36.003	kg
Mass to 36 kg	0.00	kg



Note: The weight of the suspension (basically the Injection Bench) is approximate and will be defined after the optimization to increase the frequency

Balancing Mass

- Optics + Balancing Mass

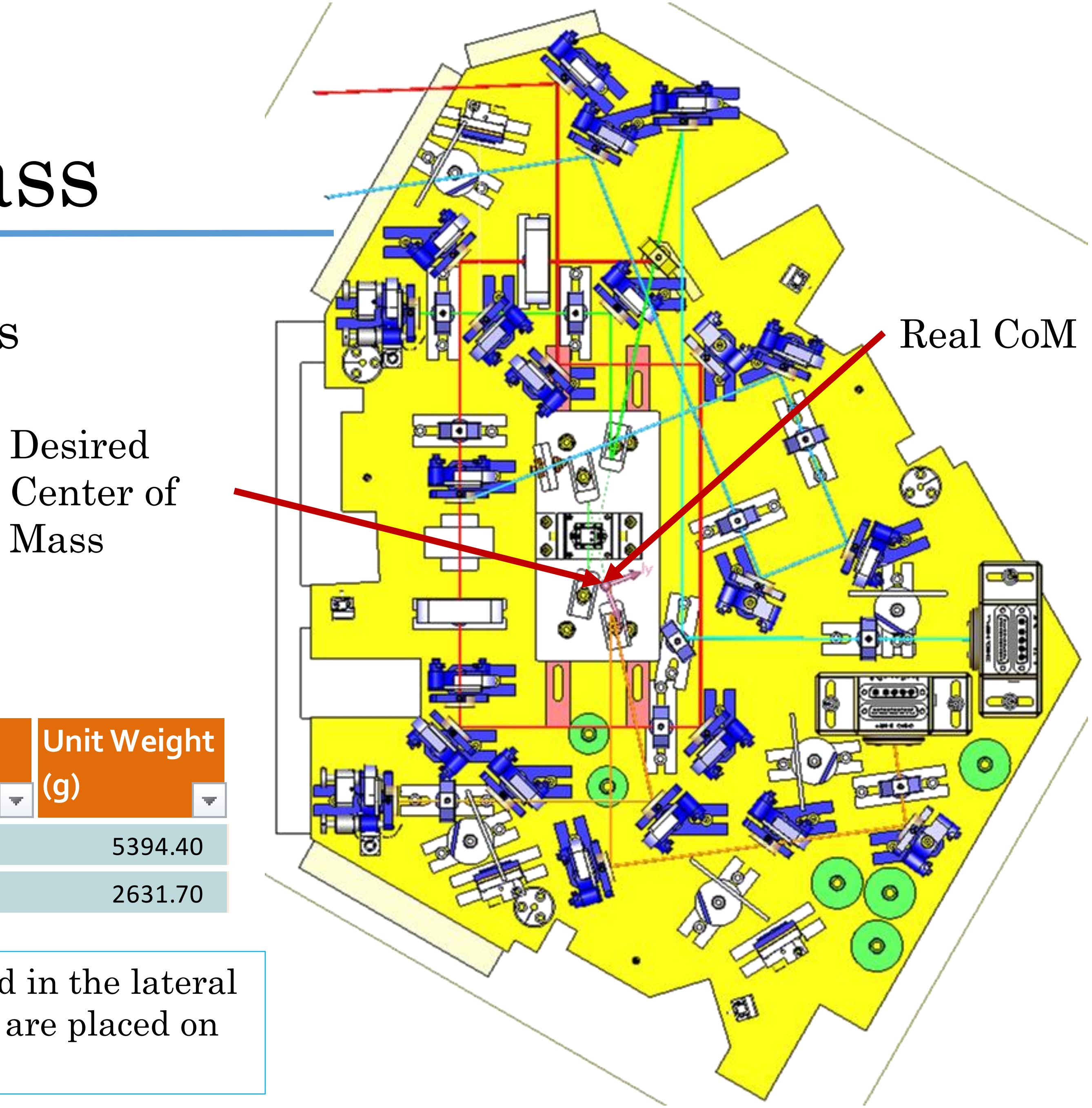
Mass = 36054.2 grams

Volume = 0.0 cubic meters

Surface area = 2528676.9 square millimeters

Center of mass: (millimeters)
X = 0.0
Y = 0.0
Z = 6.0

ELEMENT TYPE	Name	Description	Unit Weight (g)
MASS	BALANCE MASS 1	Lateral	5394.40
MASS	BALANCE MASS 2	On Bench	2631.70



Note: The balancing masses are basically placed in the lateral of the Injection Bench (5.4 kg). However, 2.6 kg are placed on the Bench as contingency for the optics weight

Center of Mass

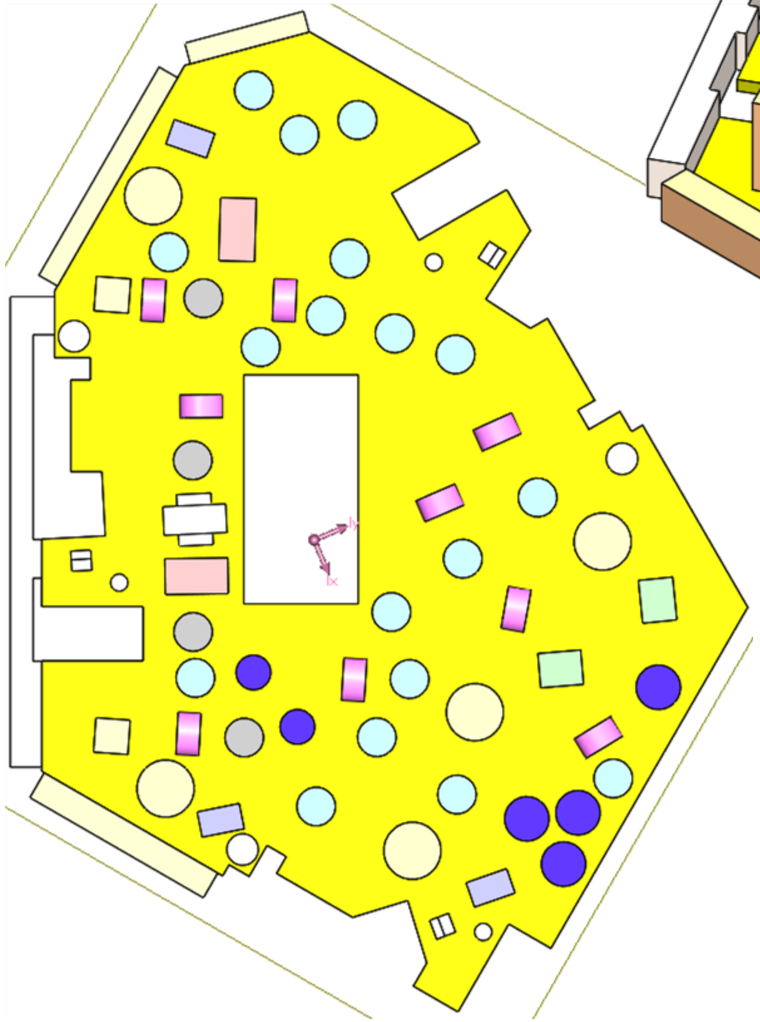
- FEA

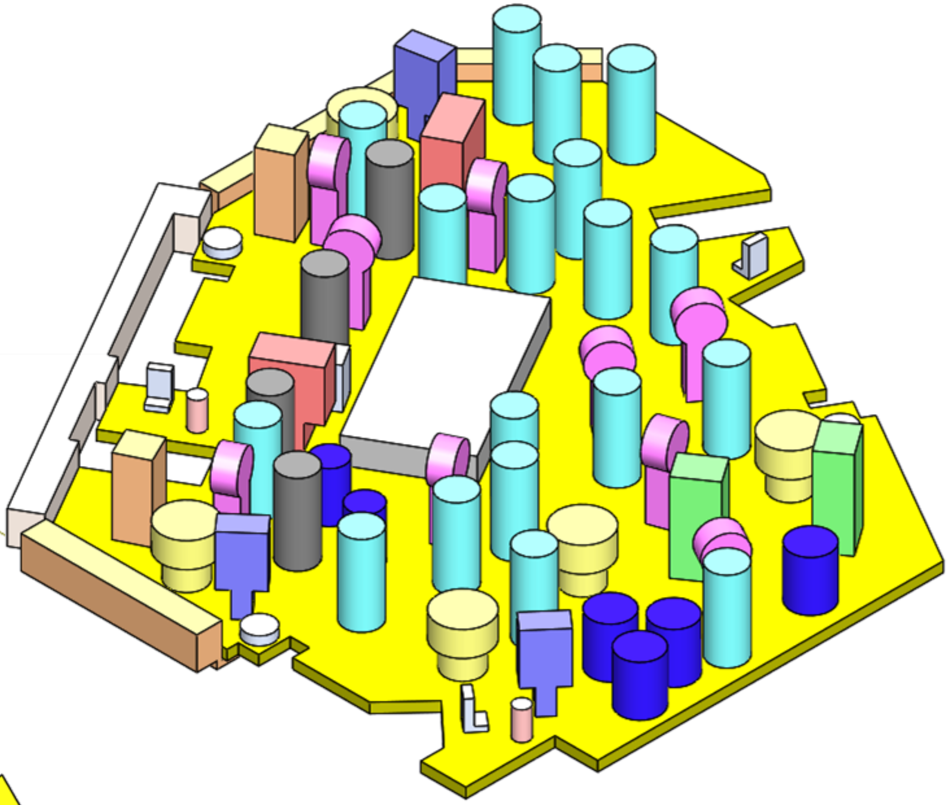
Mass = 35805.3 grams

Volume = 689.3 cubic inches

Surface area = 1496522.6 square millimeters

Center of mass: (millimeters)
X = -0.4
Y = -1.5
Z = 6.3

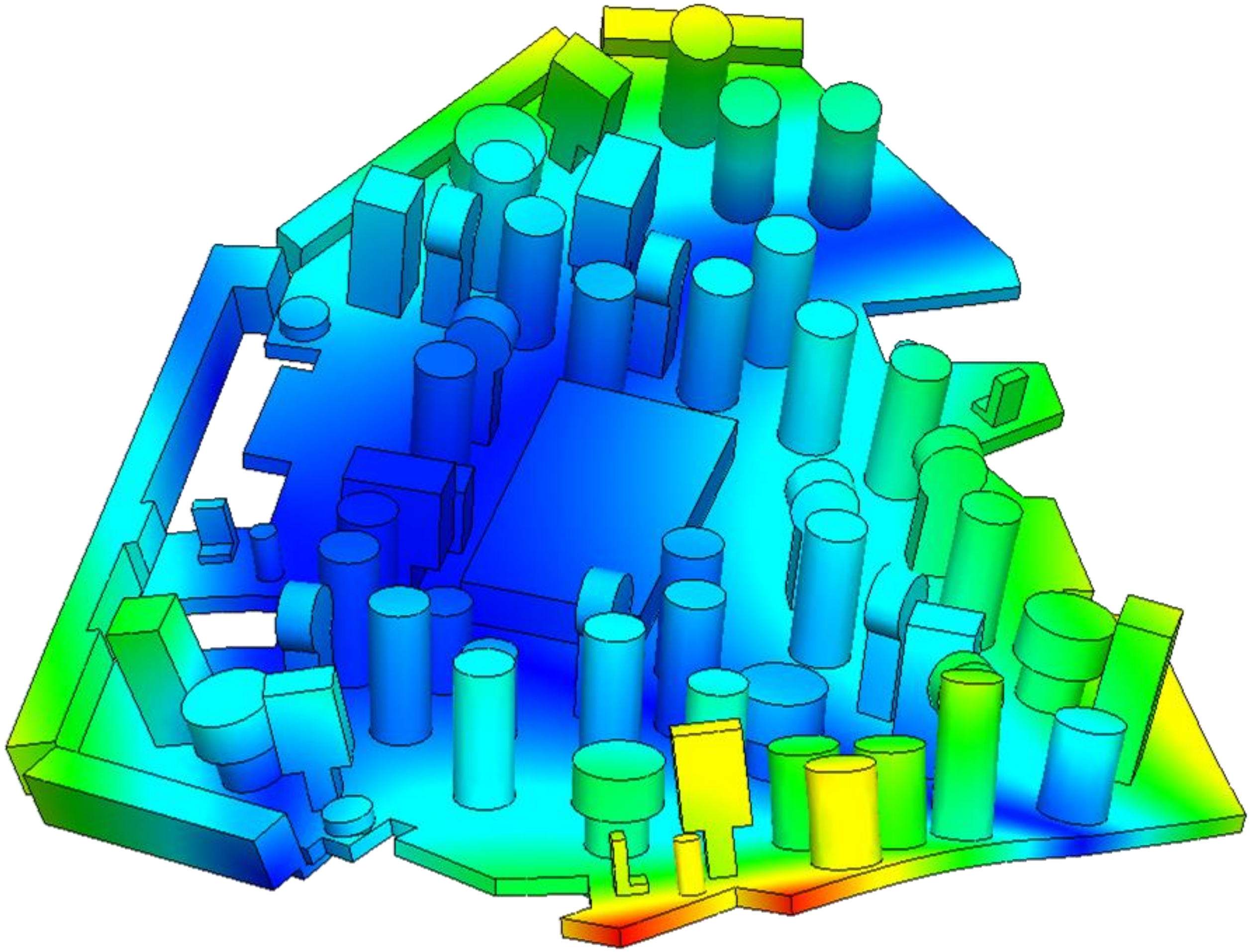




Center of Mass

- FEA
  - First Frequency Study

- $f_{COMPATIBLE} = 205.19\,Hz$



Center of Mass

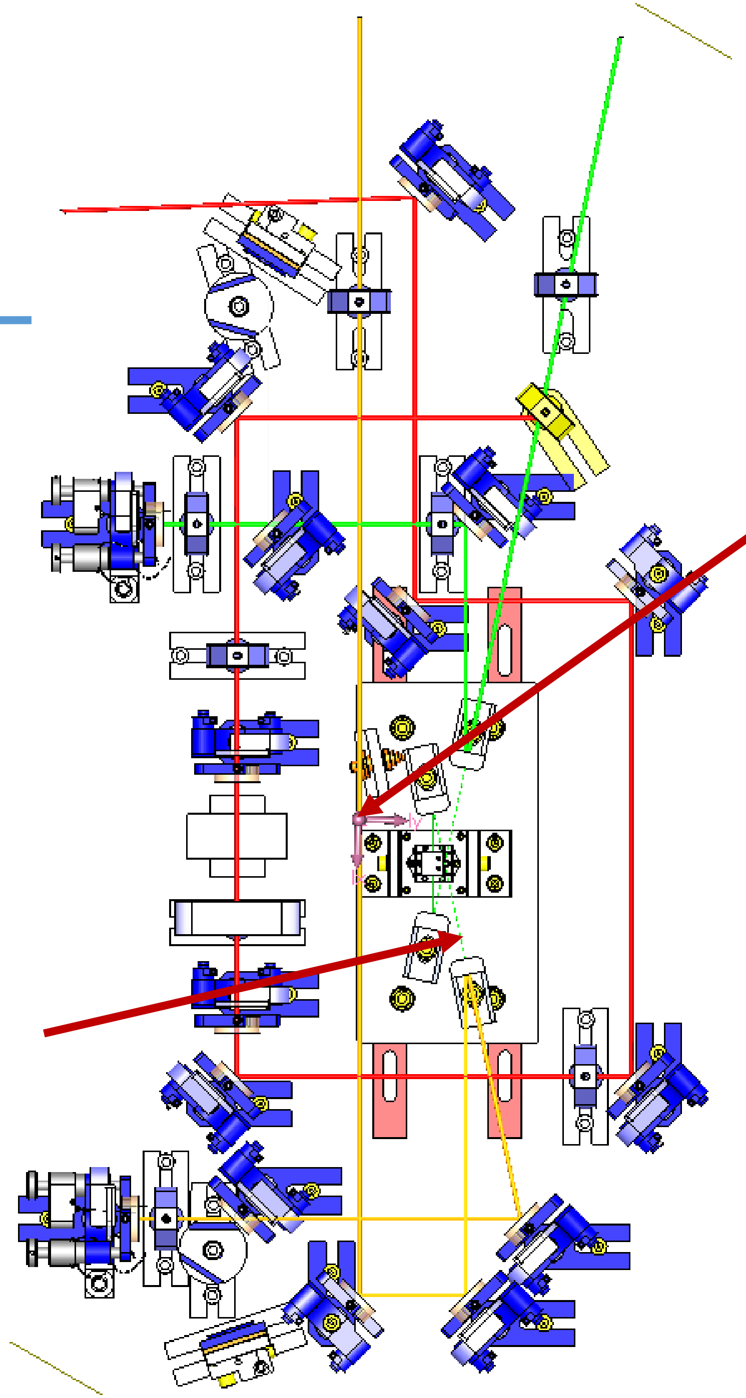
- Optics

Mass = 6773.1 grams

Volume = 0.0 cubic meters

Surface area = 929838.5 square millimeters

Center of mass: (millimeters)
X = 58.7
Y = 41.6
Z = 34.0



Optics CoM

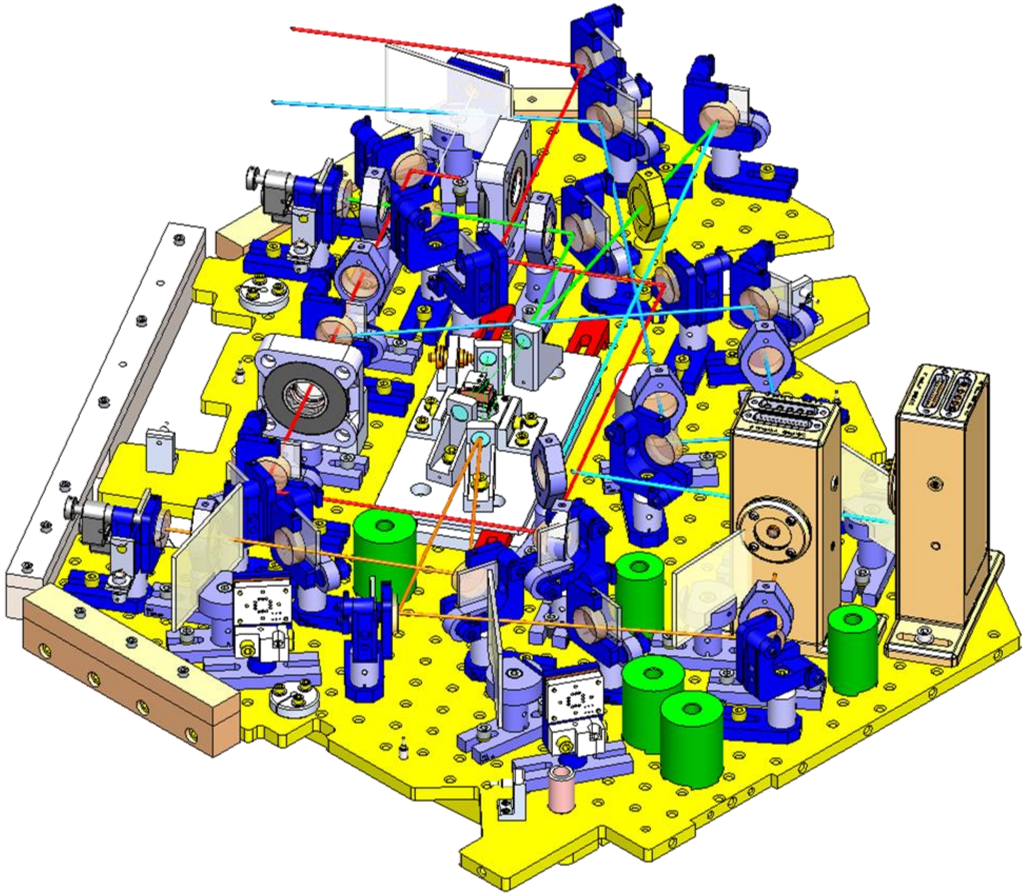
Desired Center of Mass

Note: The Center of Mass of the optics far from the desired but there is a lot of available space to locate the balancing masses

Balancing Mass

- Preliminary Mass Balancing
  - First Bench Design (≈18kg)

OPTICS	6.750	kg
SUSPENSION	18.134	kg
MASS	11.068	kg
TOTAL WEIGHT	35.952	kg
Mass to 36 kg	0.05	kg



Note: The weight of the suspension (basically the Injection Bench) is approximate and will be defined after the optimization to increase the frequency

Balancing Mass

- Optics + Balancing Mass

Mass = 35975.1 grams

Volume = 0.0 cubic meters

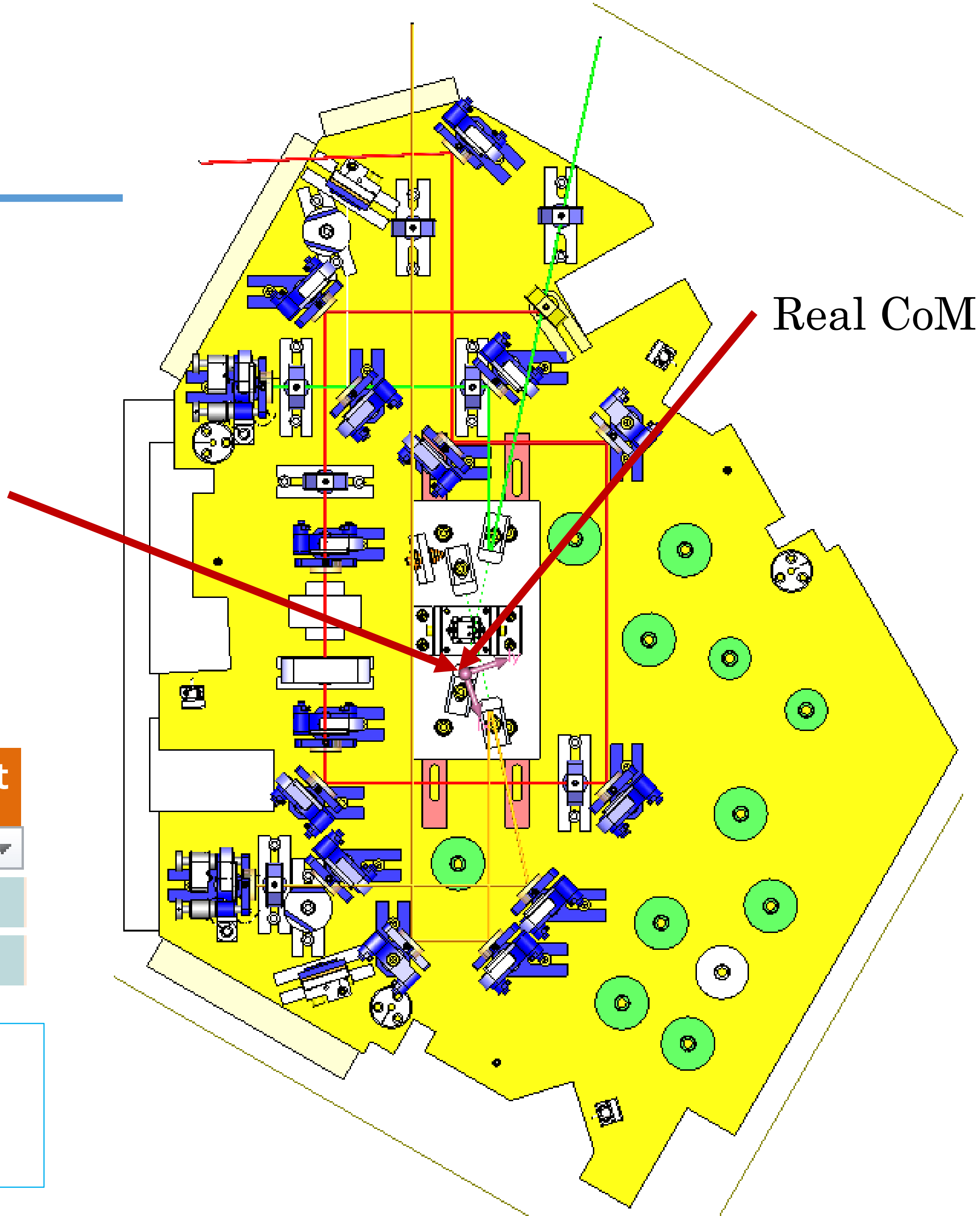
Surface area = 1959822.6 square millimeters

Center of mass: (millimeters)
X = 0.0
Y = 0.0
Z = 4.3

ELEMENT TYPE	Name	Description	Unit Weight (g)
MASS	BALANCE MASS 1	Lateral	5394.40
MASS	BALANCE MASS 2	On Bench	5673.30

Note: In this case there is more balancing mass placed on the bench than in the laterals as it has to compensate the lack of optics

Desired Center of Mass



Real CoM

Center of Mass

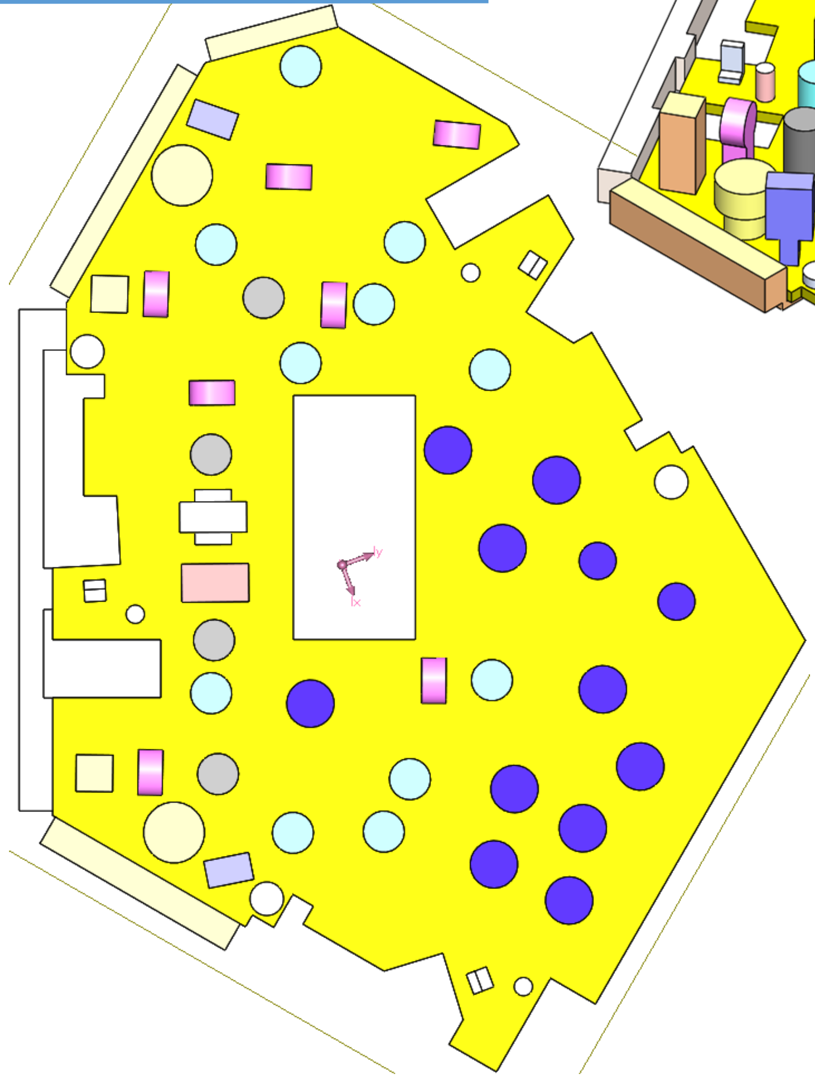
- FEA

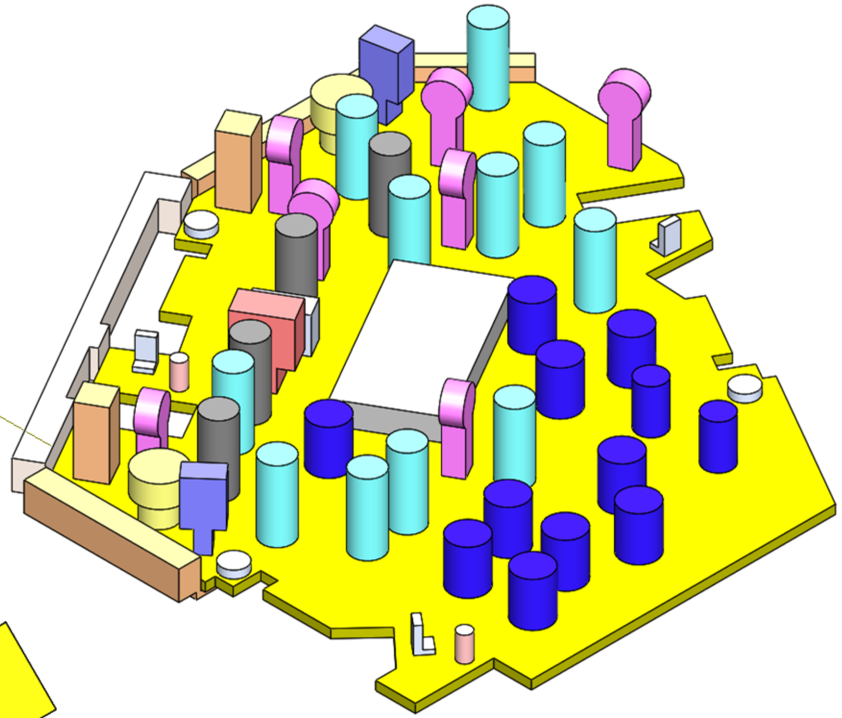
Mass = 35532.6 grams

Volume = 638.1 cubic inches

Surface area = 1370261.1 square millimeters

Center of mass: (millimeters)
X = 2.7
Y = -0.8
Z = 4.8

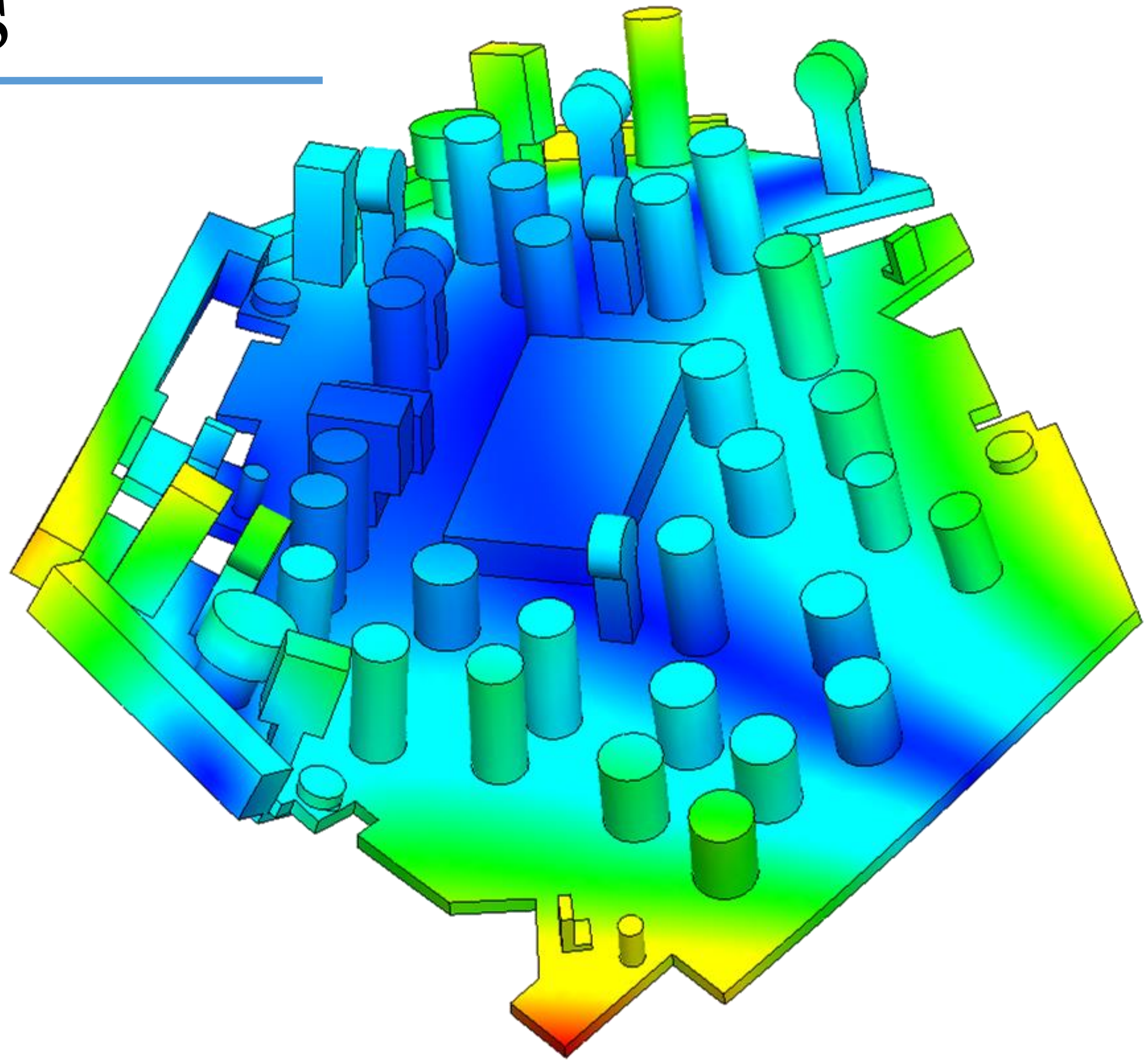




Center of Mass

- FEA
  - First Frequency Study

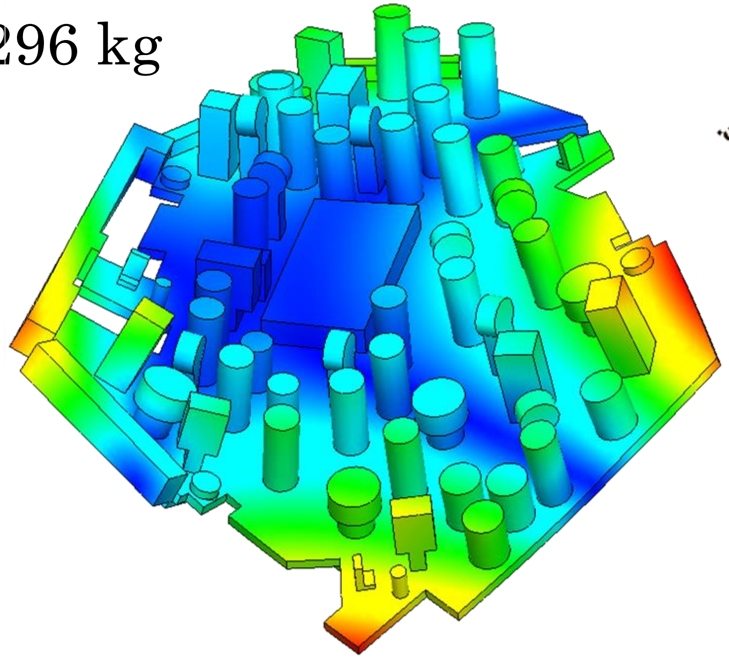
- $f_{COMPATIBLE} = 211.84\ Hz$



Optimization

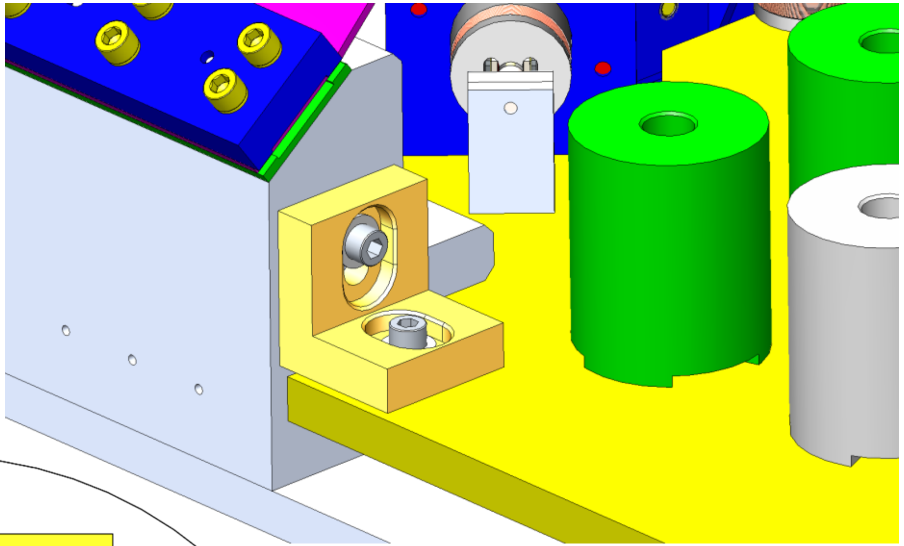
- FEA
  - Bench Optimization for O3

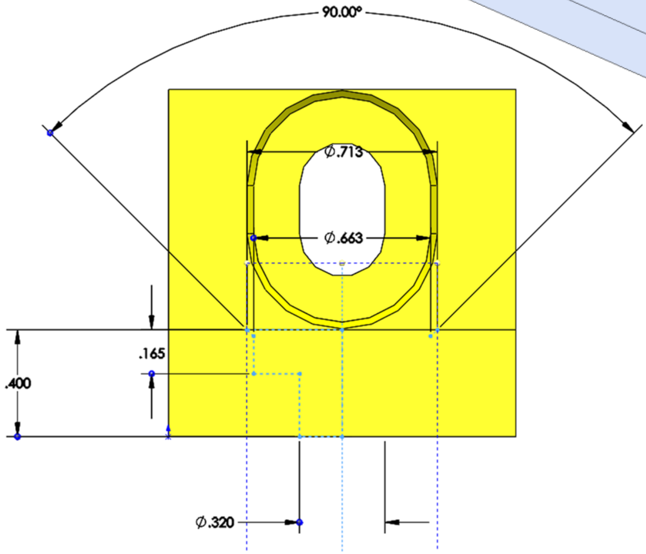
- $f_{COMPATIBLE} = 209.28\,Hz$
- Bench Mass = 17.296 kg



Fixer

- Screw #10-24 Static Calculation
  - Load = P = 117.72N
  - FoS = 32.1622





- Maximum Play
  - Vertical: $0.5 - 2\frac{0.19}{2} = 0.31\ in\ (7.874\ mm)$
  - Horizontal: $0.5 - 2\frac{0.19}{2} = 0.31\ in\ (7.874\ mm)$
  - Lateral: $0.32 - 2\frac{0.19}{2} = 0.13\ in\ (3.302\ mm)$