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HIGH PRECISION
DEVICES, INC.

Advanced LIGO
Single Stage HAM
Vibration Isolation Table

Final Design Review
Part 1

Document Number: G-0701156-00-R

2 April 2007

Characters

LIGO

- Dennis Coyne
- Brian Lantz
- Myron Macinnis
- Ken Mason
- Rich Mittleman
- Brian O'Reilly
- Pradeep Sarin
- Mike Zucker

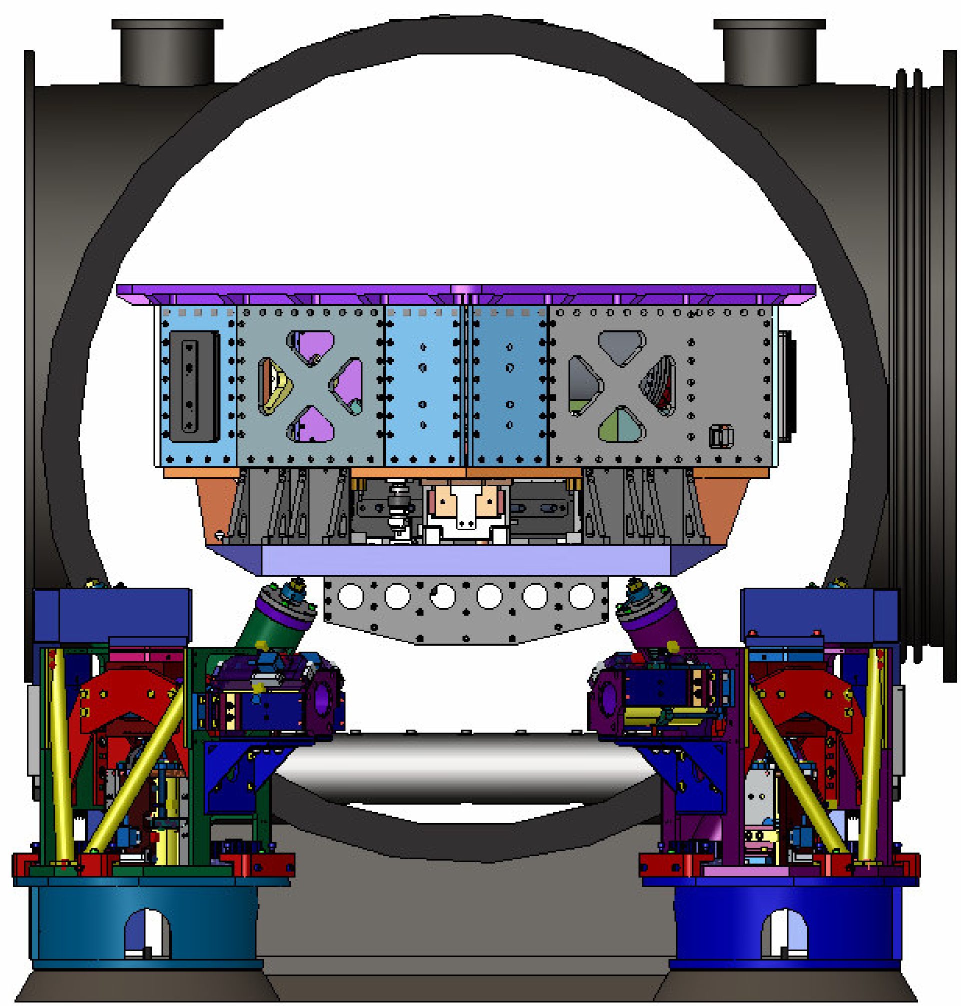
HPD

- Dan Bryce
- Charlie Danaher
- Bill Hollander
- Dave Senders
- Jonas Waterman

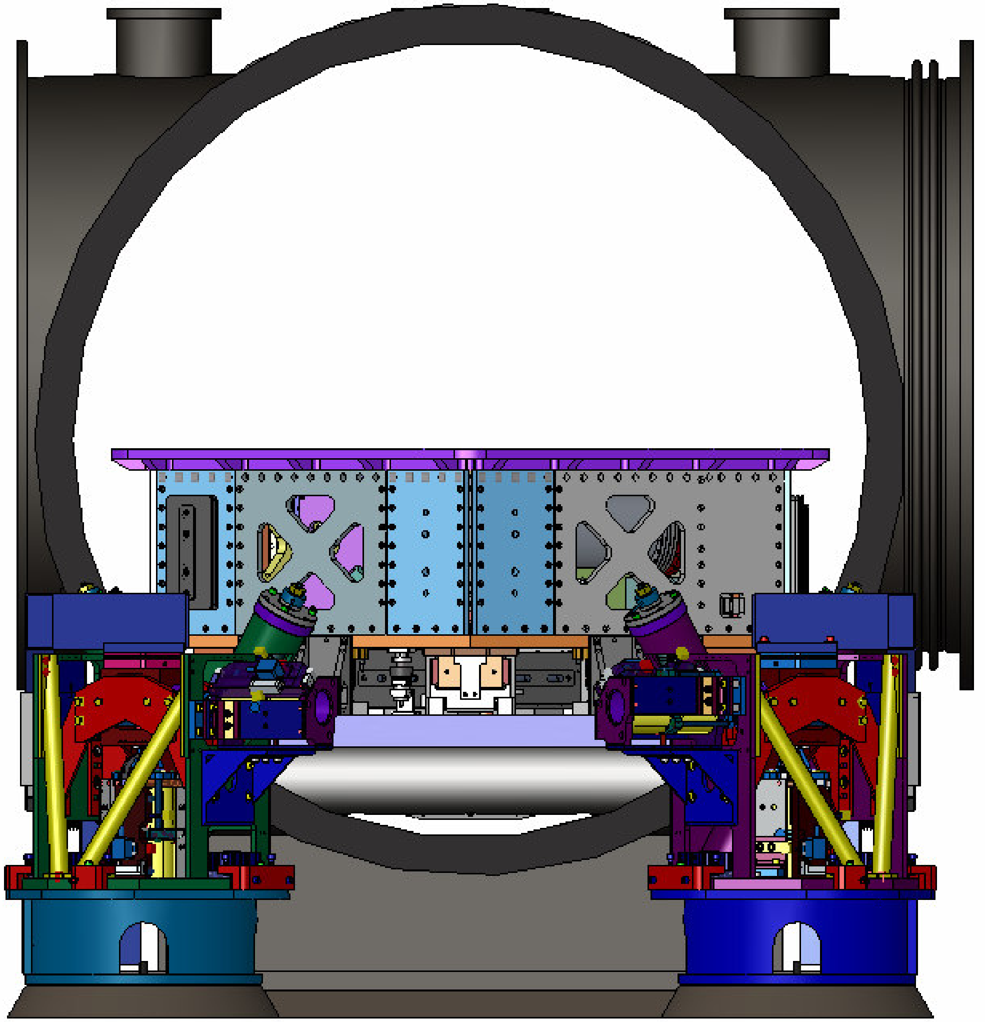
Agenda

1. **System Design**
    1. Layout and Section Views
        1. System in HAM Chamber
        2. System Overview
        3. Components and Sub-Assemblies
    2. Critical Component Locations
    3. Fastener Plan
2. **Technical Review**
    1. Overall Approach
    2. Stage 1 FEA
    3. System Dynamics
    4. Spring & Flexure Assembly
        1. Spring Design & FEA
        2. Flexure Design & FEA
        3. Uncertainty & Sensitivity Analysis
        4. Adjustment Masses
    5. Payload Scenarios
    6. Stage 0 FEA
    7. Kinematic Analysis
    8. Bolted Connection Analyses
3. **Assembly Sequence**
    1. Dirty Assembly Plan
    2. Framework Assembly
    3. Spring Compression
    4. Flexure Assembly
    5. Component Adjustment & Alignment
4. **Design Requirement Compliance**
5. **Risk Analysis & Mitigation**
6. **Fabrication Cost Estimate**
7. **Project Schedule**

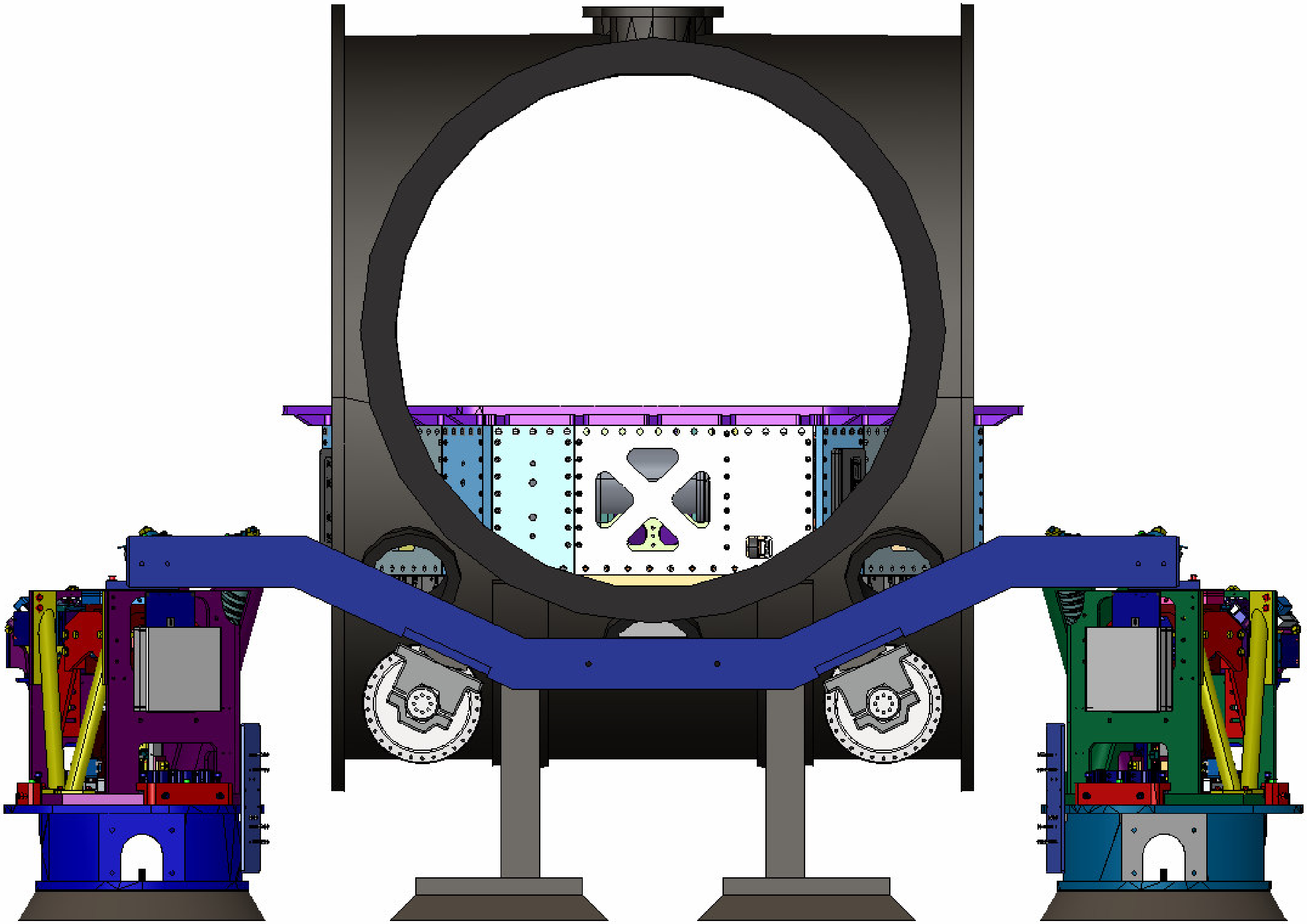
System in Chamber, over HEPI



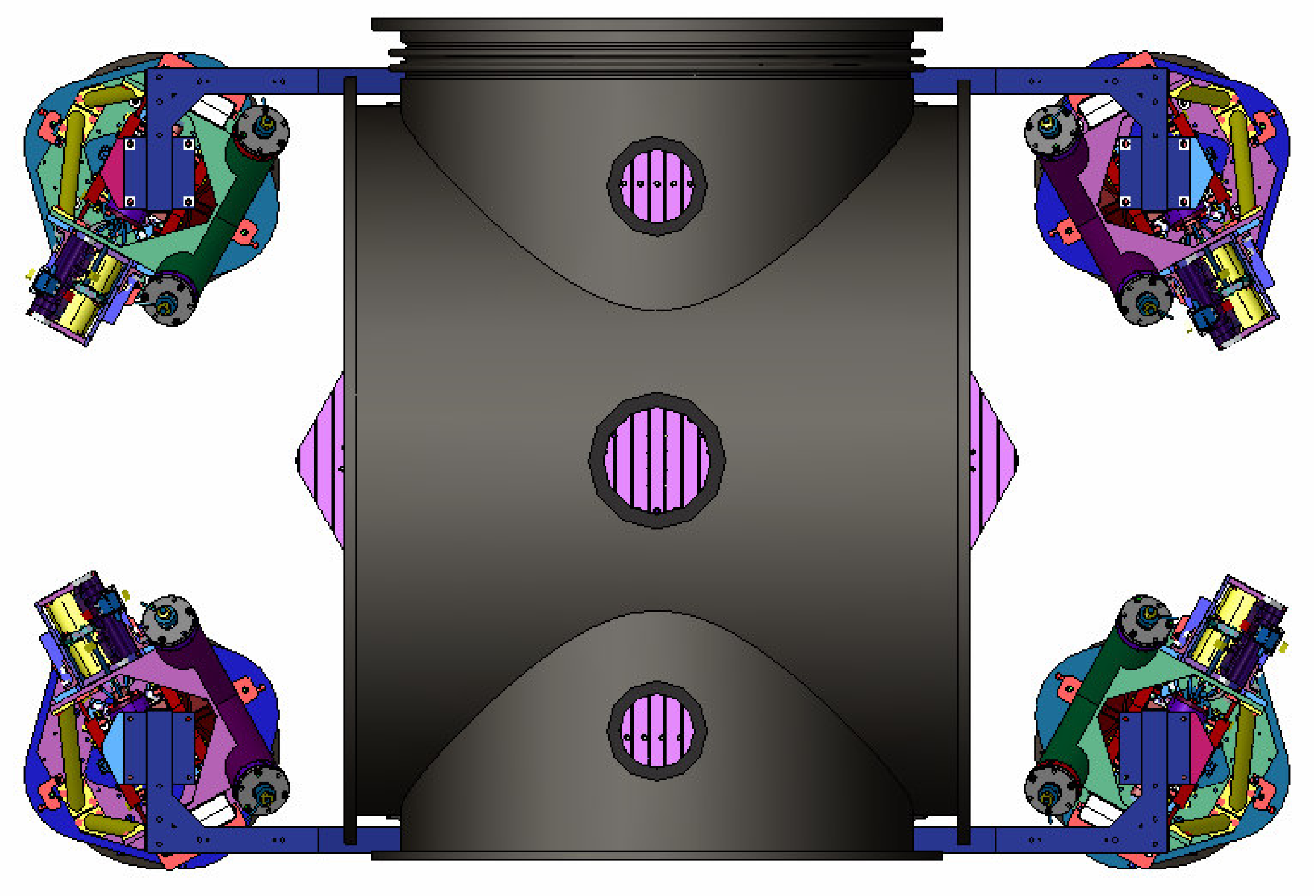
System in HAM Chamber, Door view, with HEPI



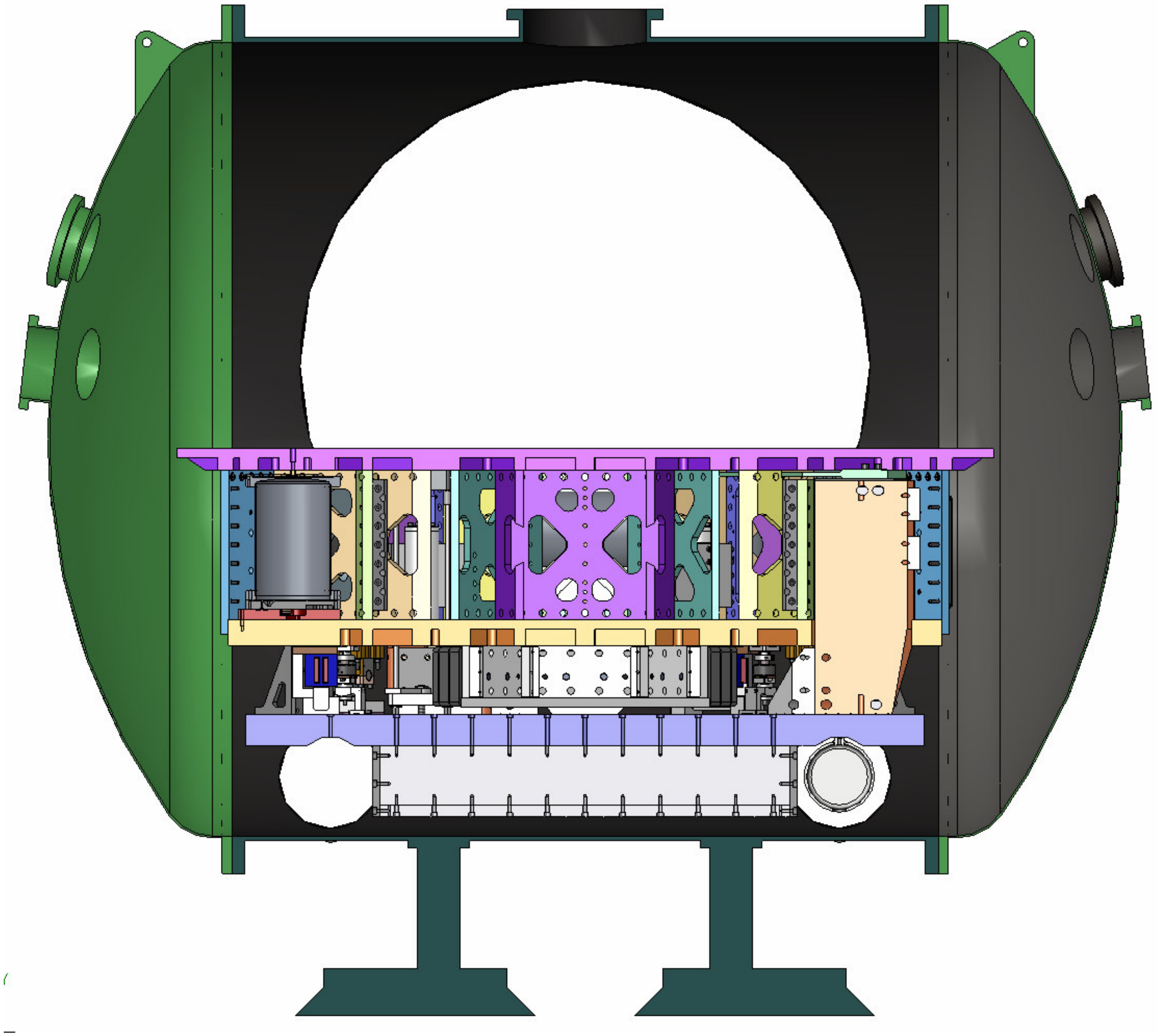
System in HAM Chamber, Beam Axis view, with HEPI



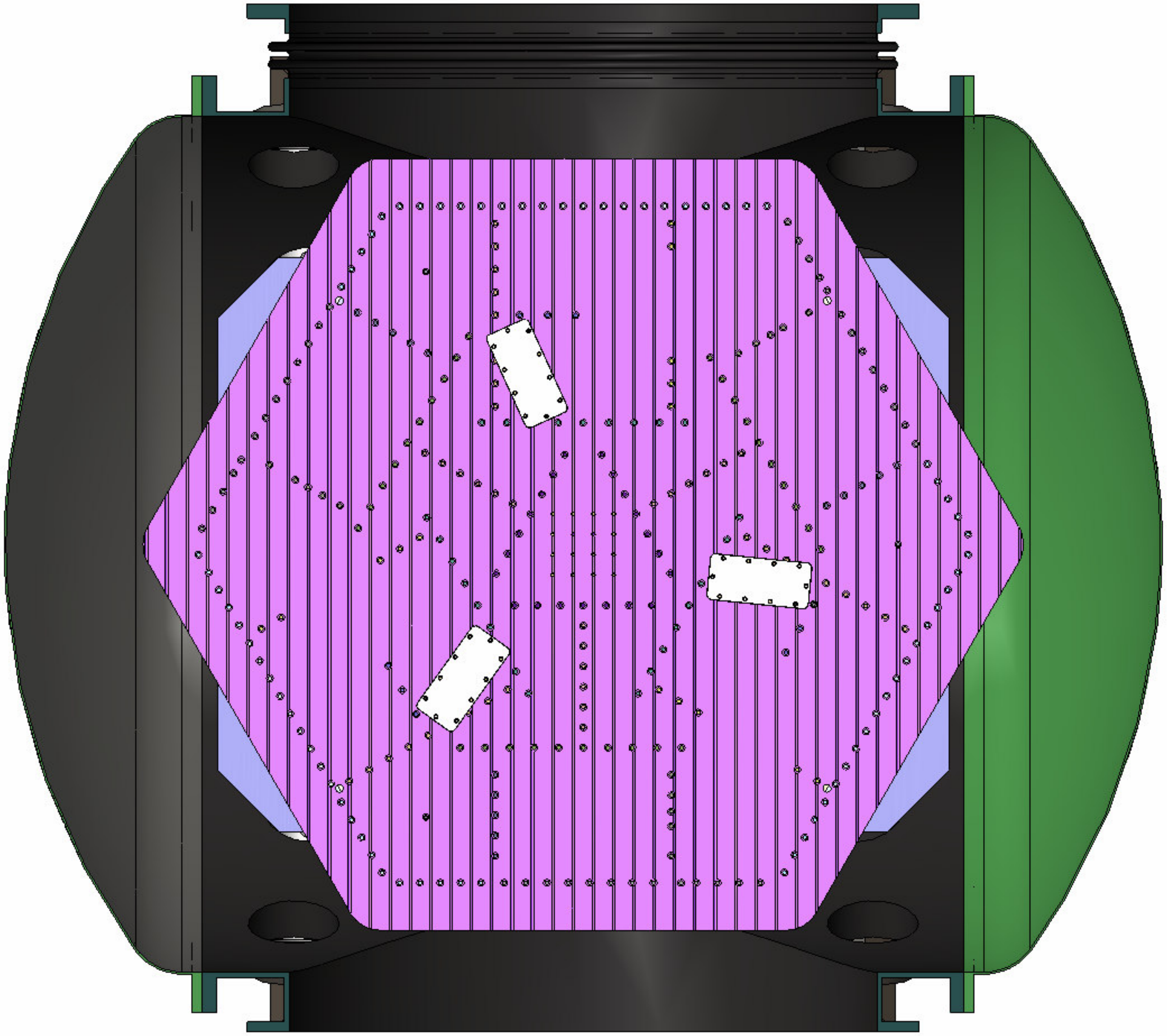
System in HAM Chamber, Top view, with HEPI



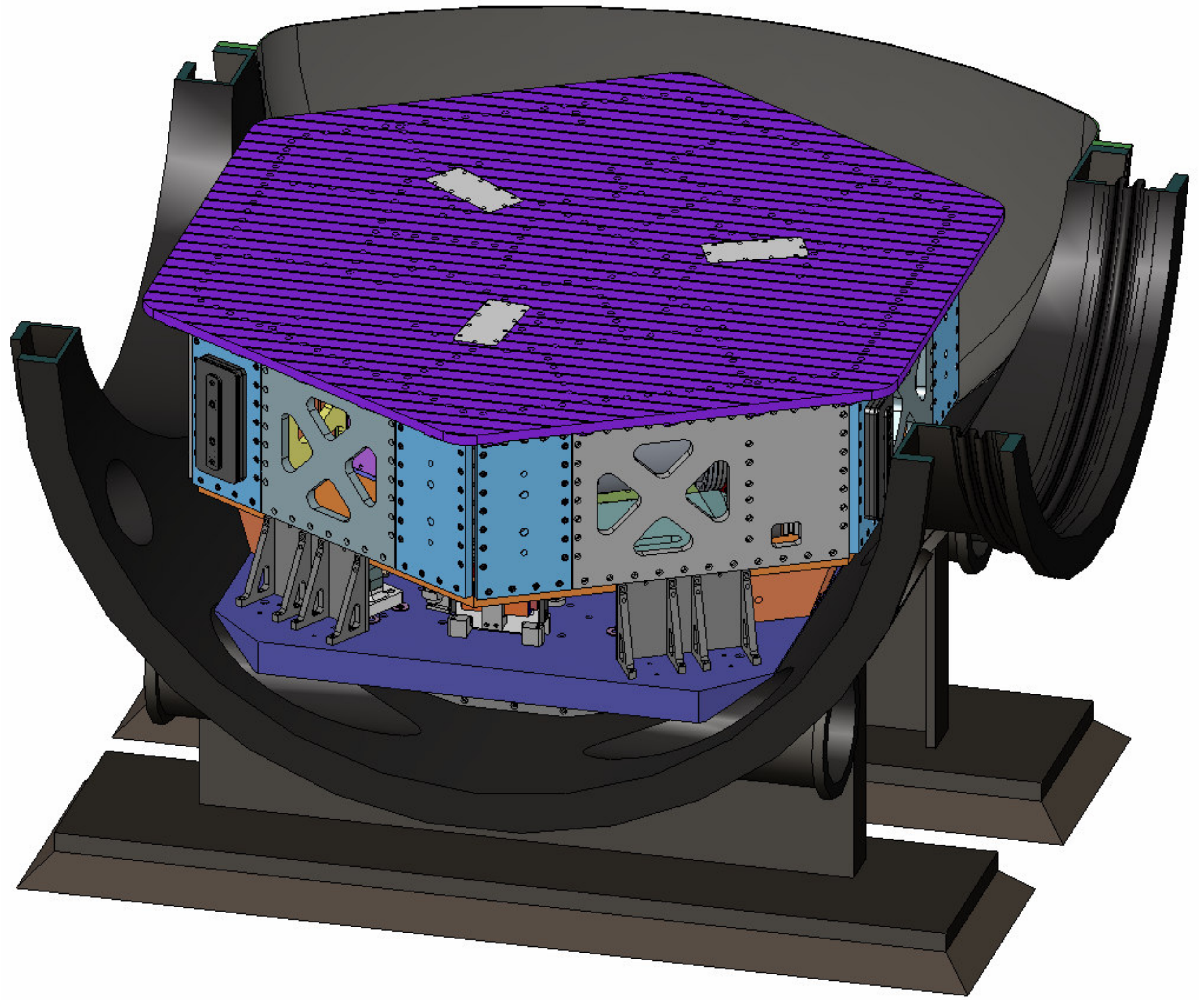
System in HAM Chamber, Beam Axis view, Sectioned



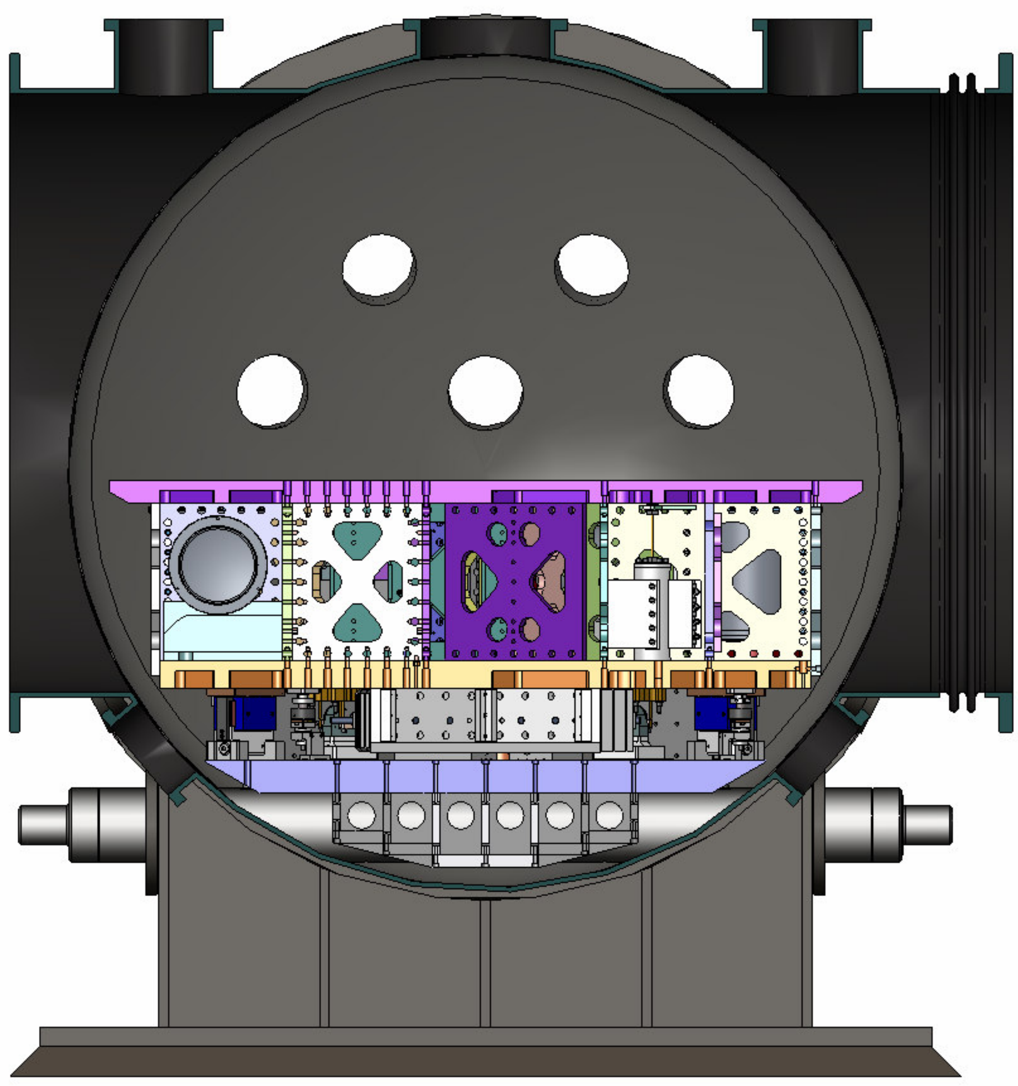
System in HAM Chamber, Top view, Sectioned



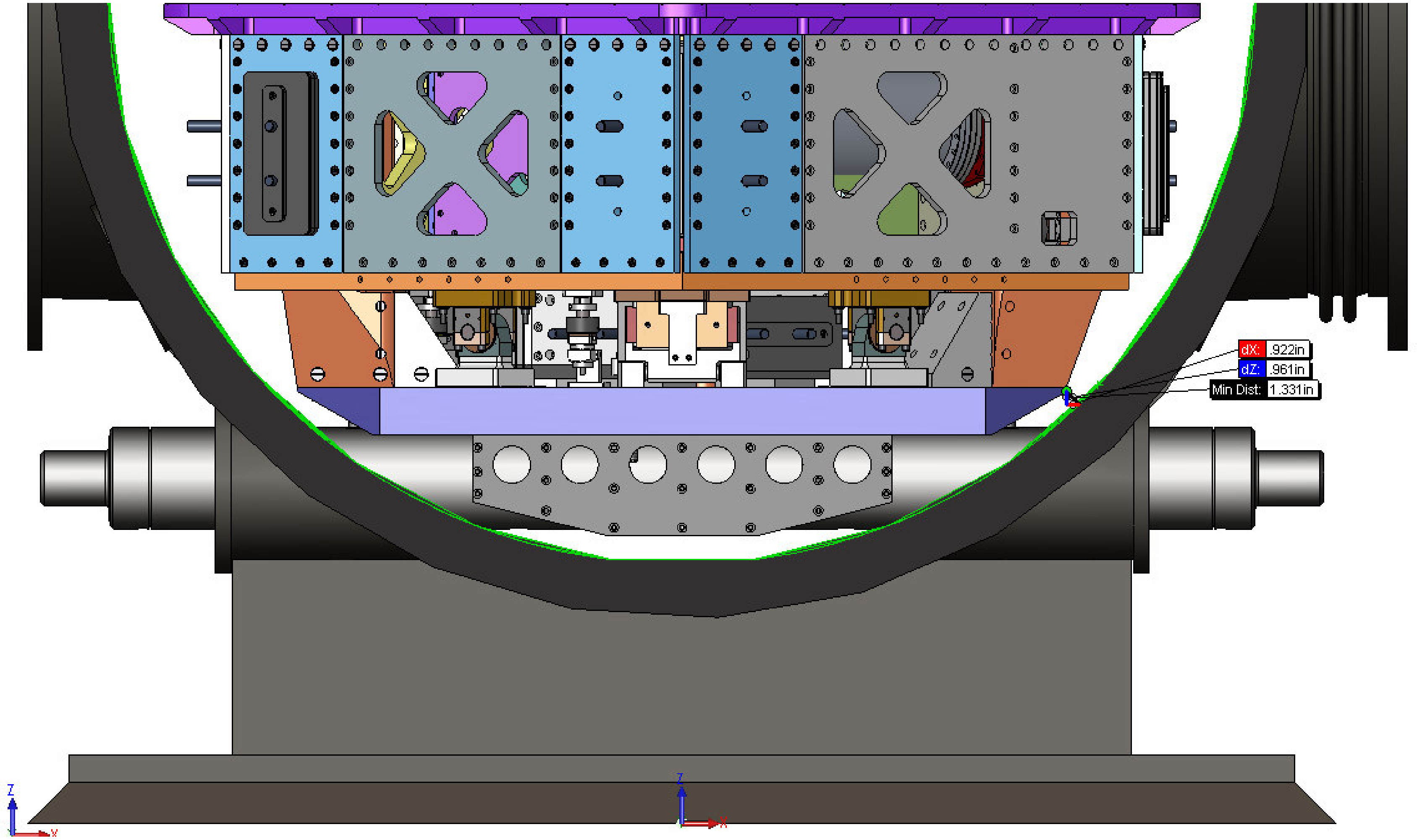
System in HAM Chamber, ISO view, Sectioned



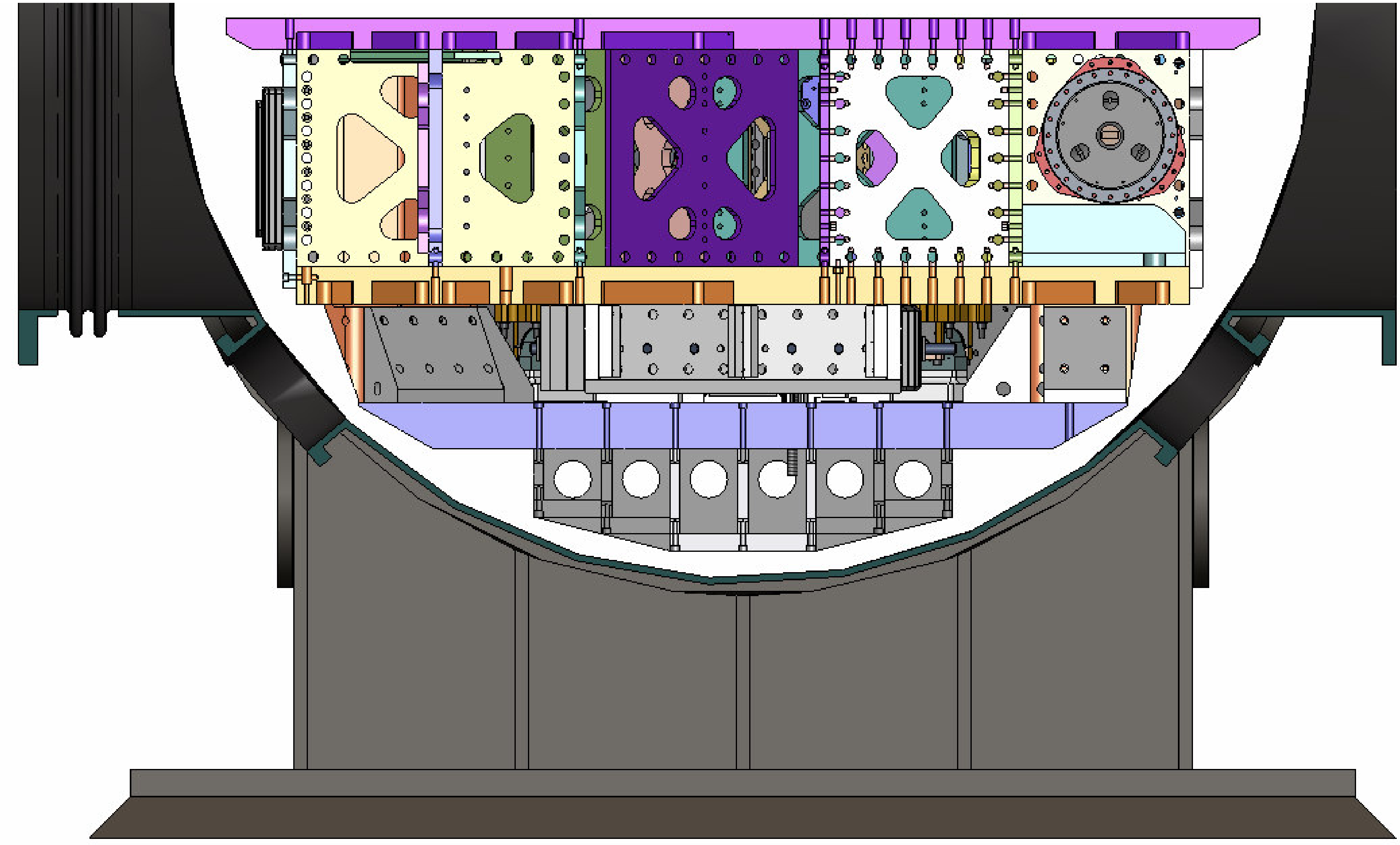
System in HAM Chamber, Door view, Sectioned



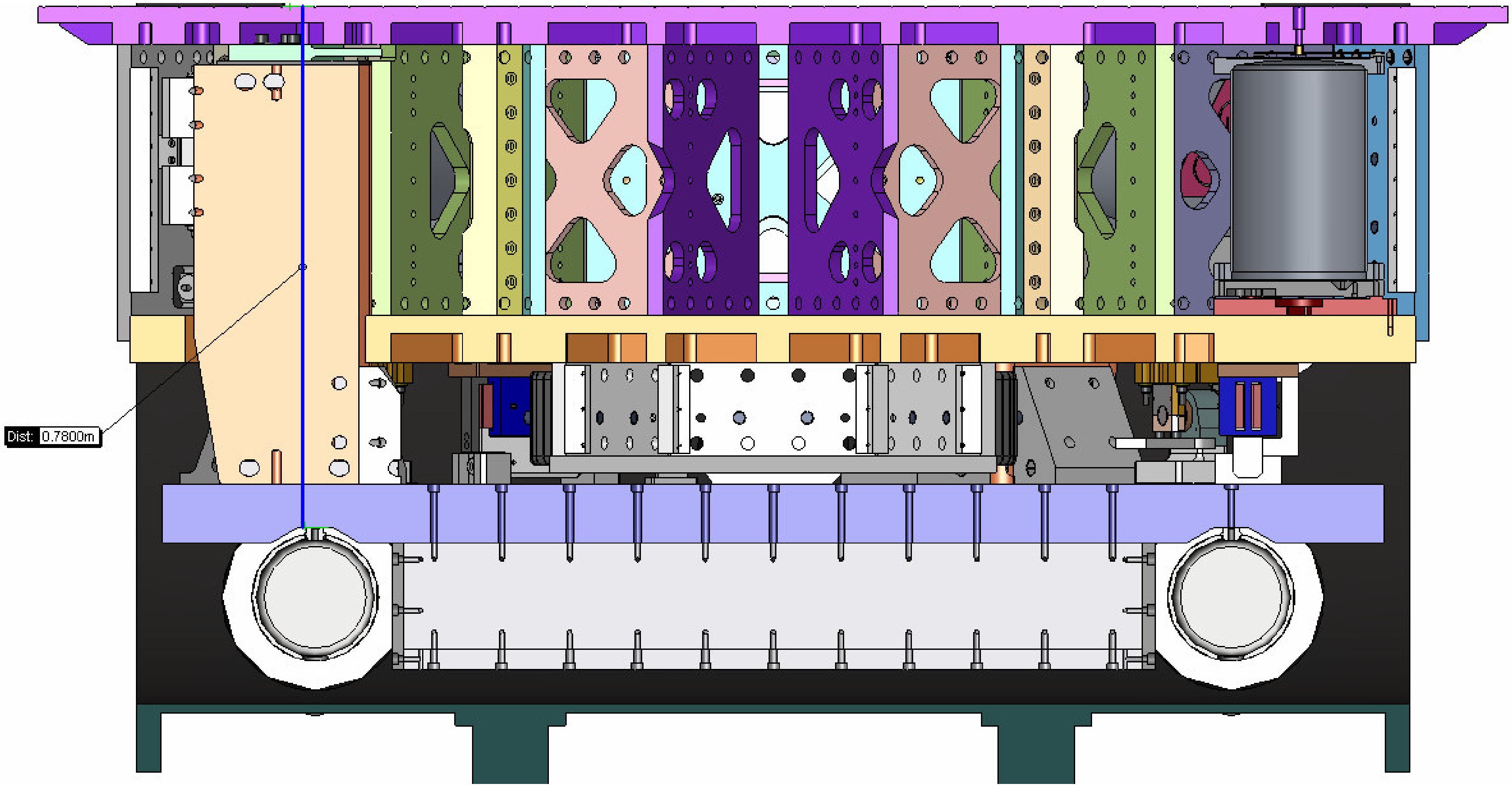
System in HAM Chamber, Door view, Minimum Clearance



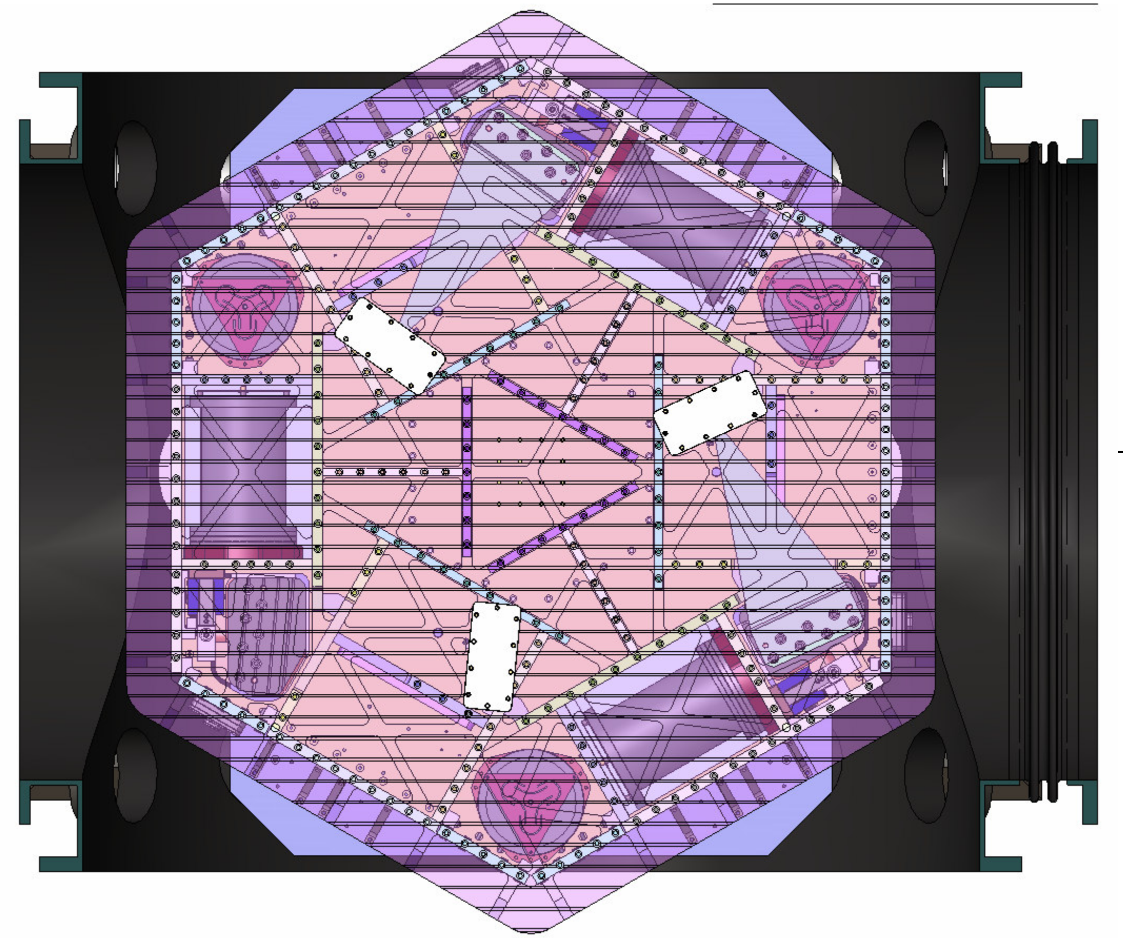
System in HAM Chamber, Door view, Sectioned



System in HAM Chamber, Beam Axis view, Sectioned, Optics Table Position

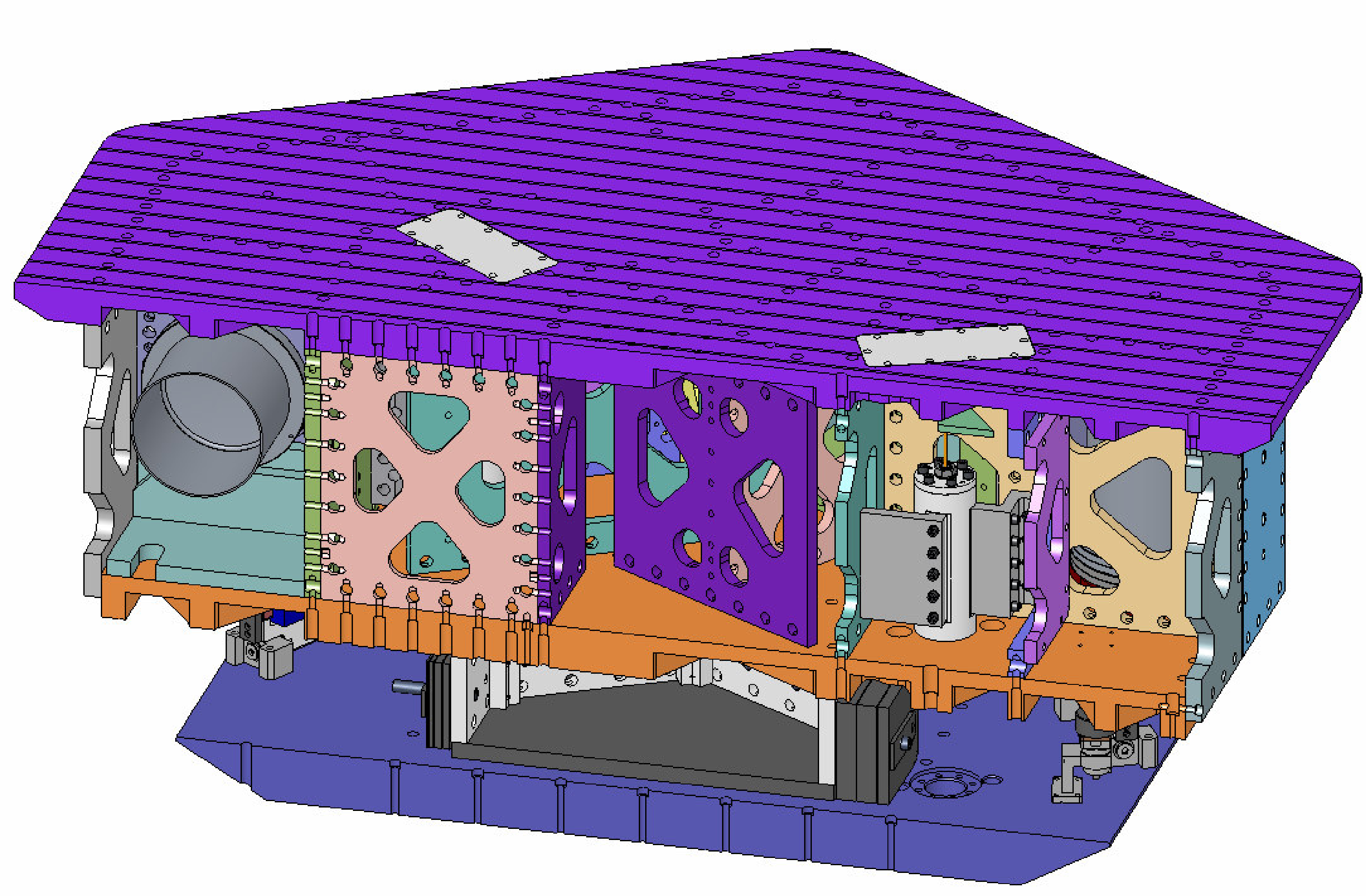


Top view, Showing locations of GS-13s

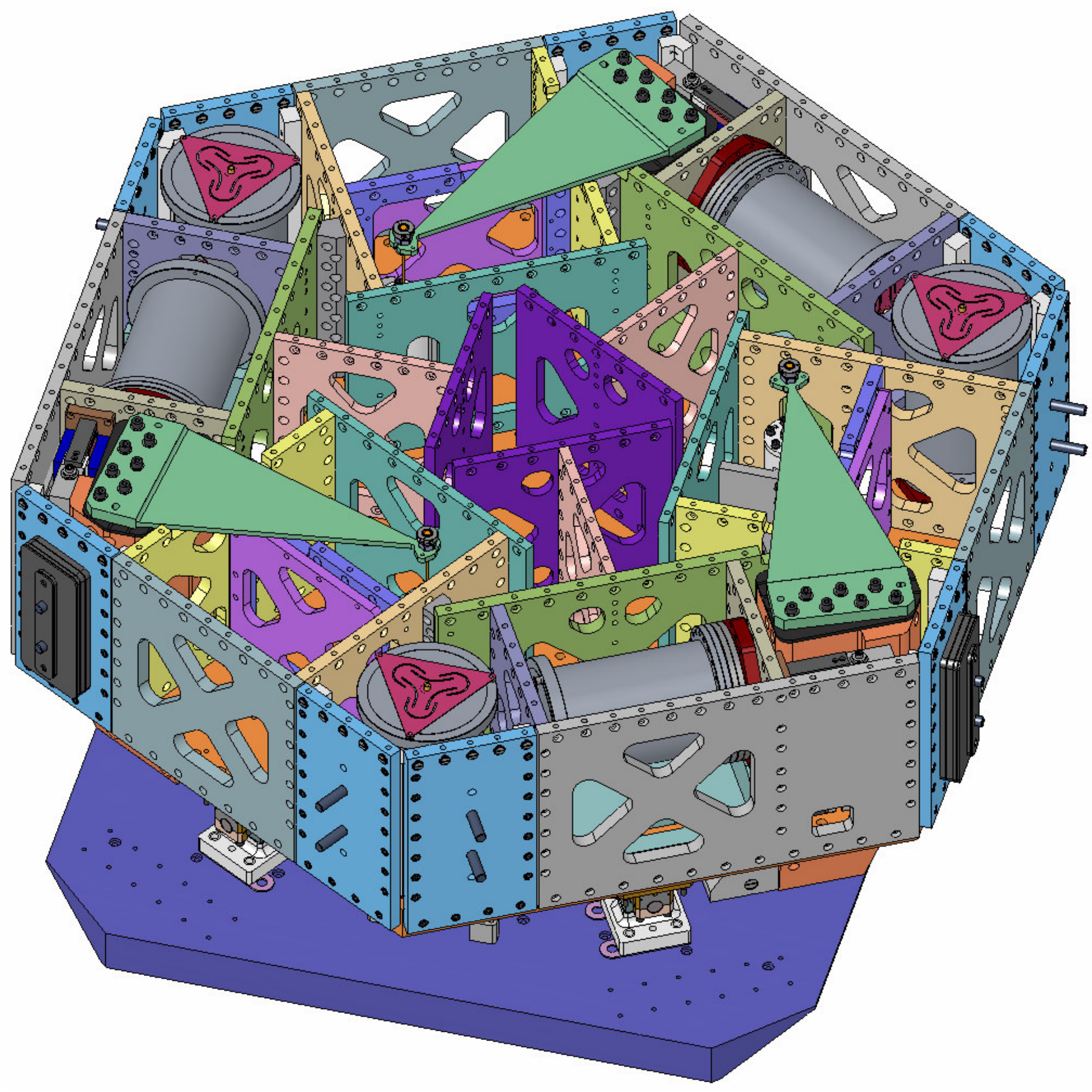


Beam path

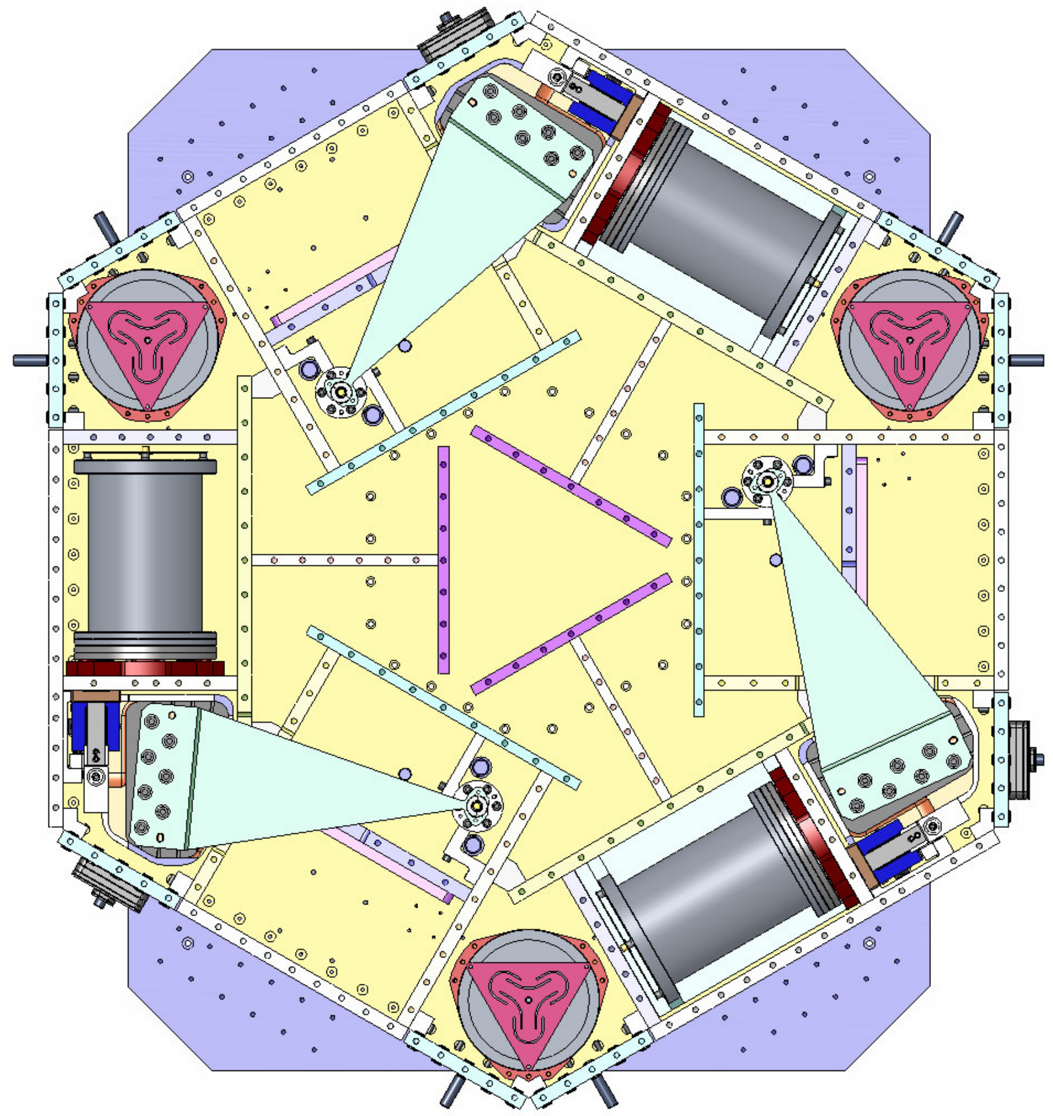
System, ISO Door View, Sectioned



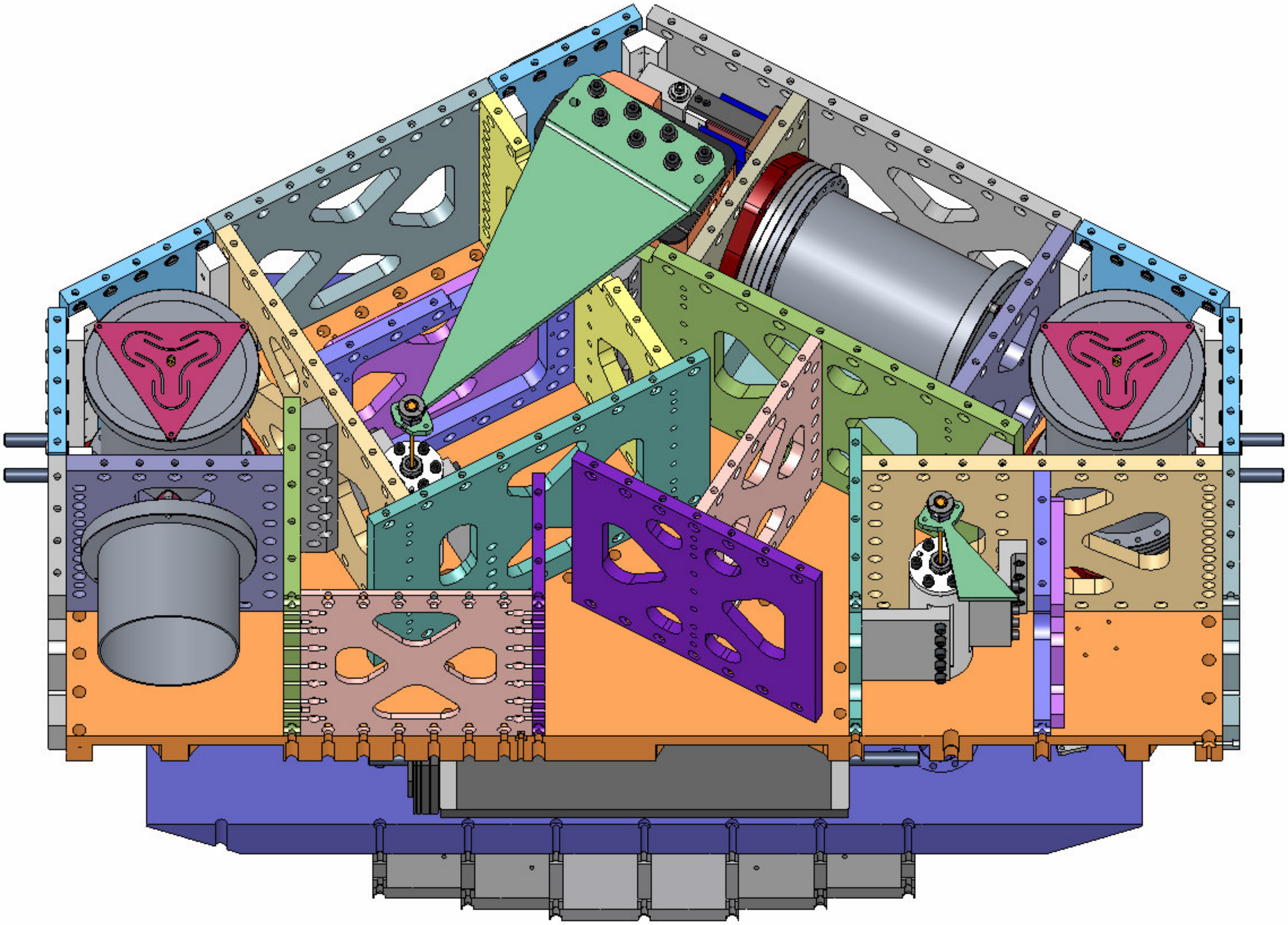
System, ISO View, Table Hidden



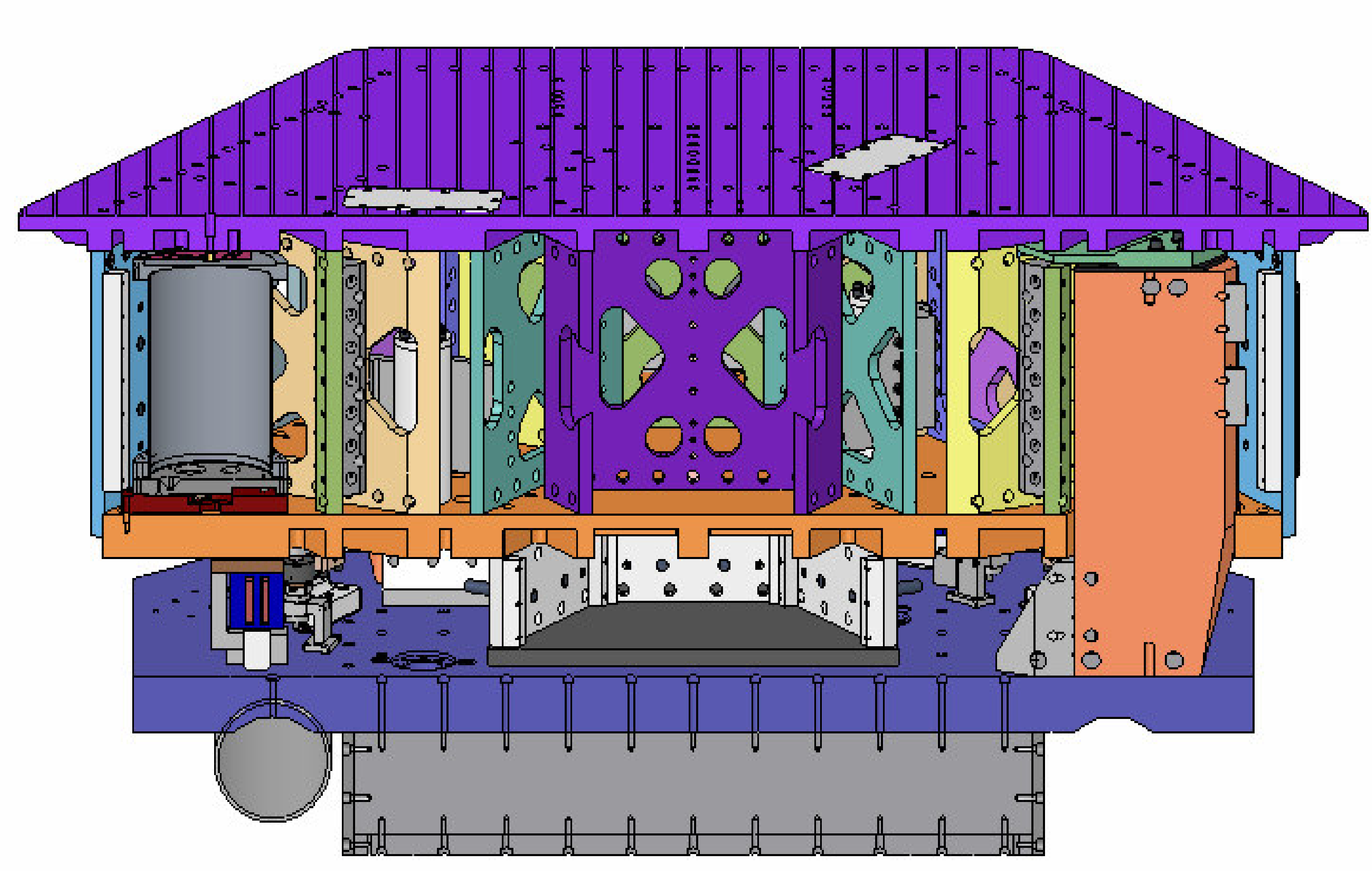
System, Top View, Table Hidden



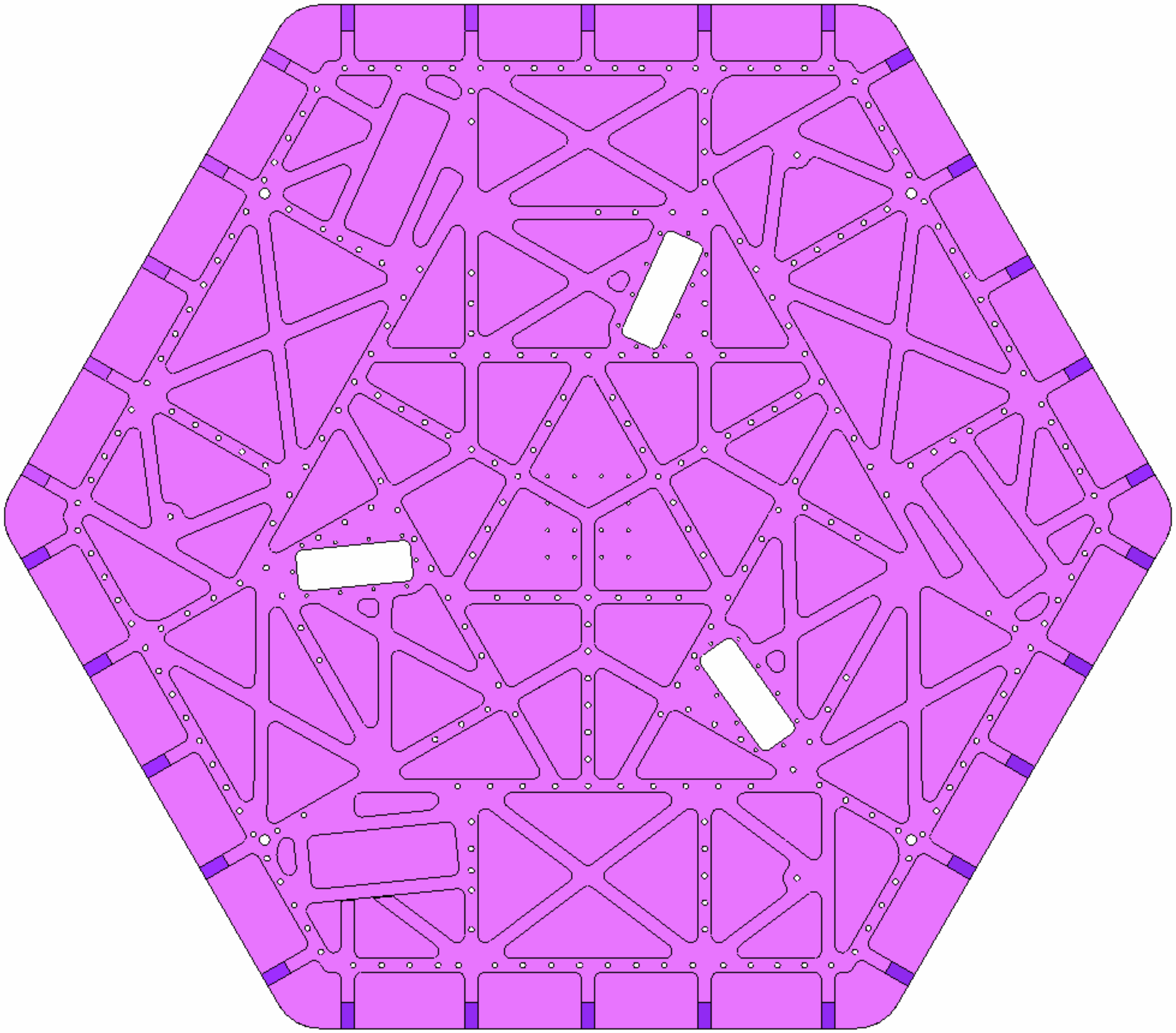
System, ISO view, Sectioned, Table Hidden



System, ISO view, Sectioned



Optics Table, Bottom View



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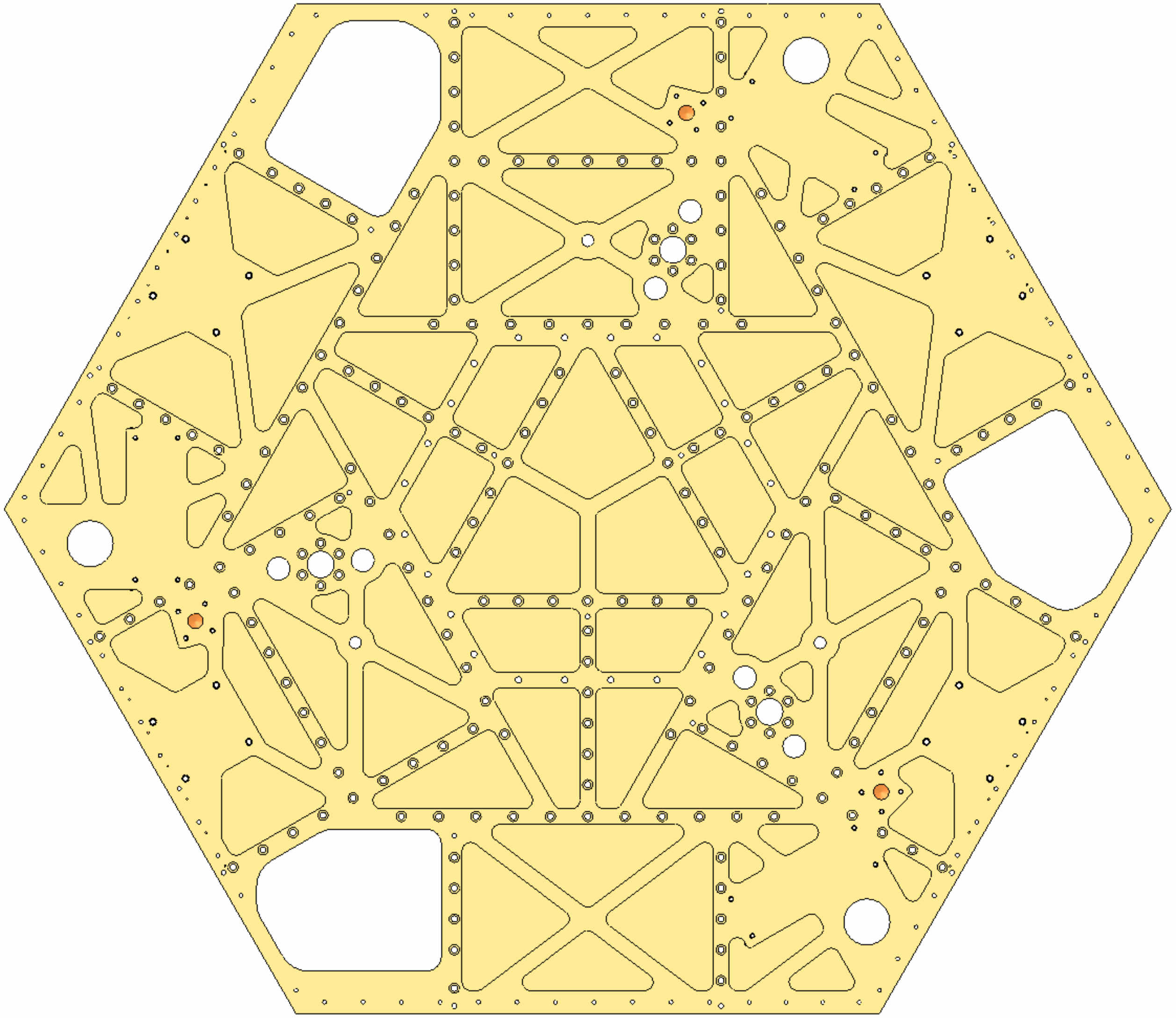
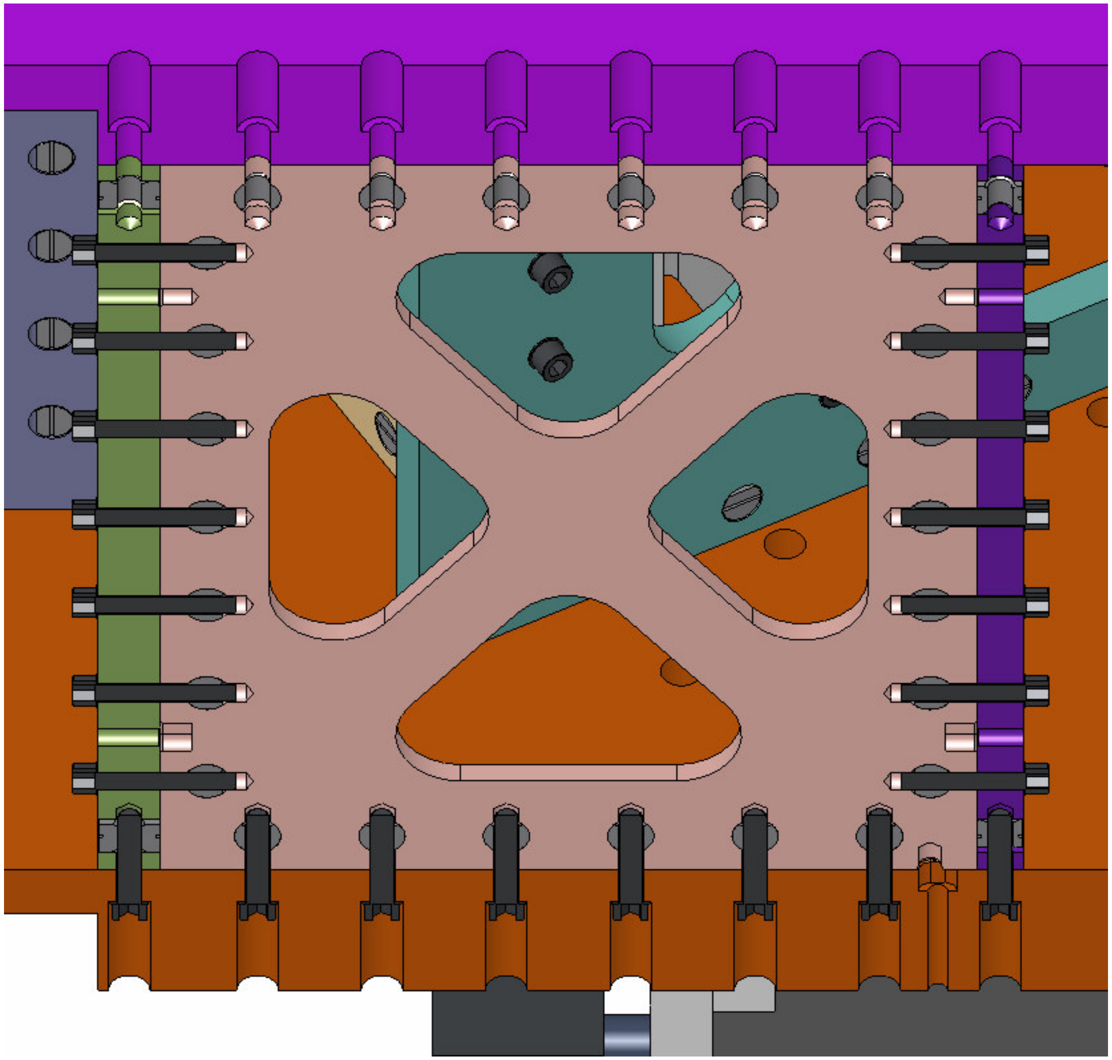
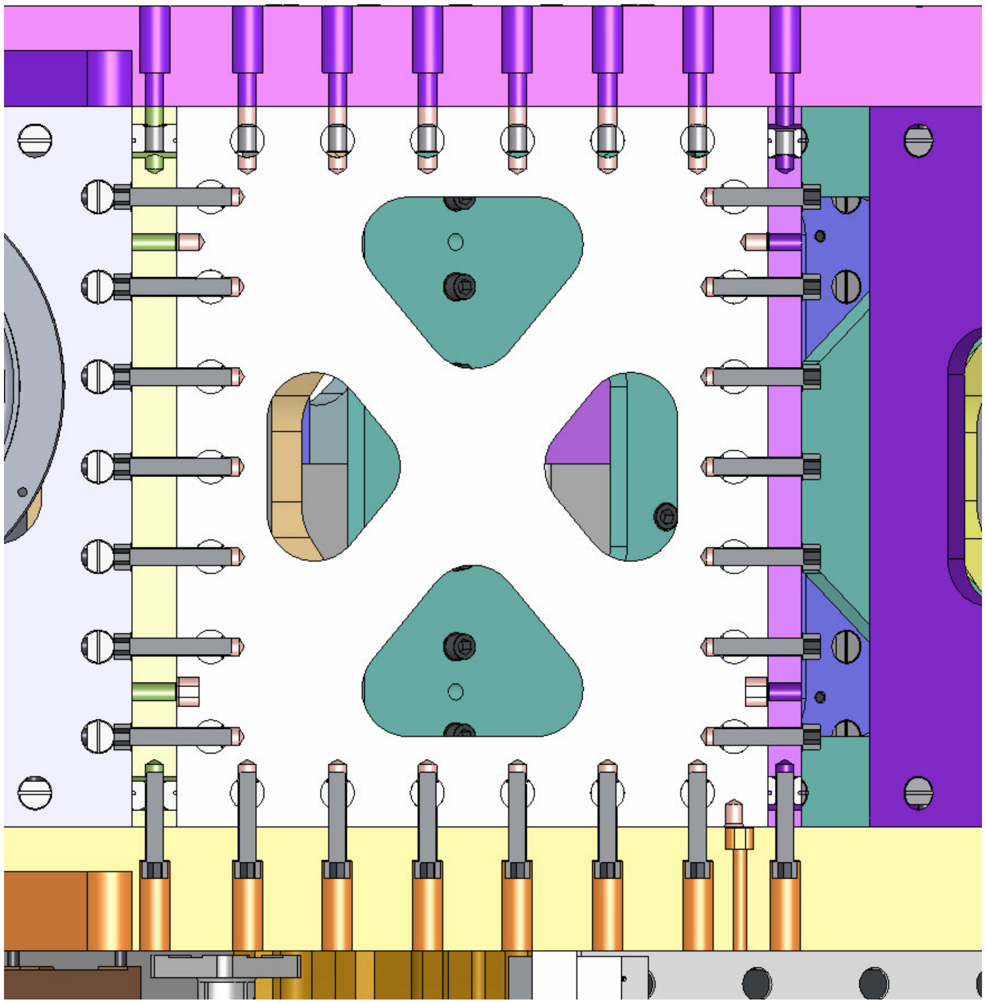
Stage 1 Floor, Bottom View



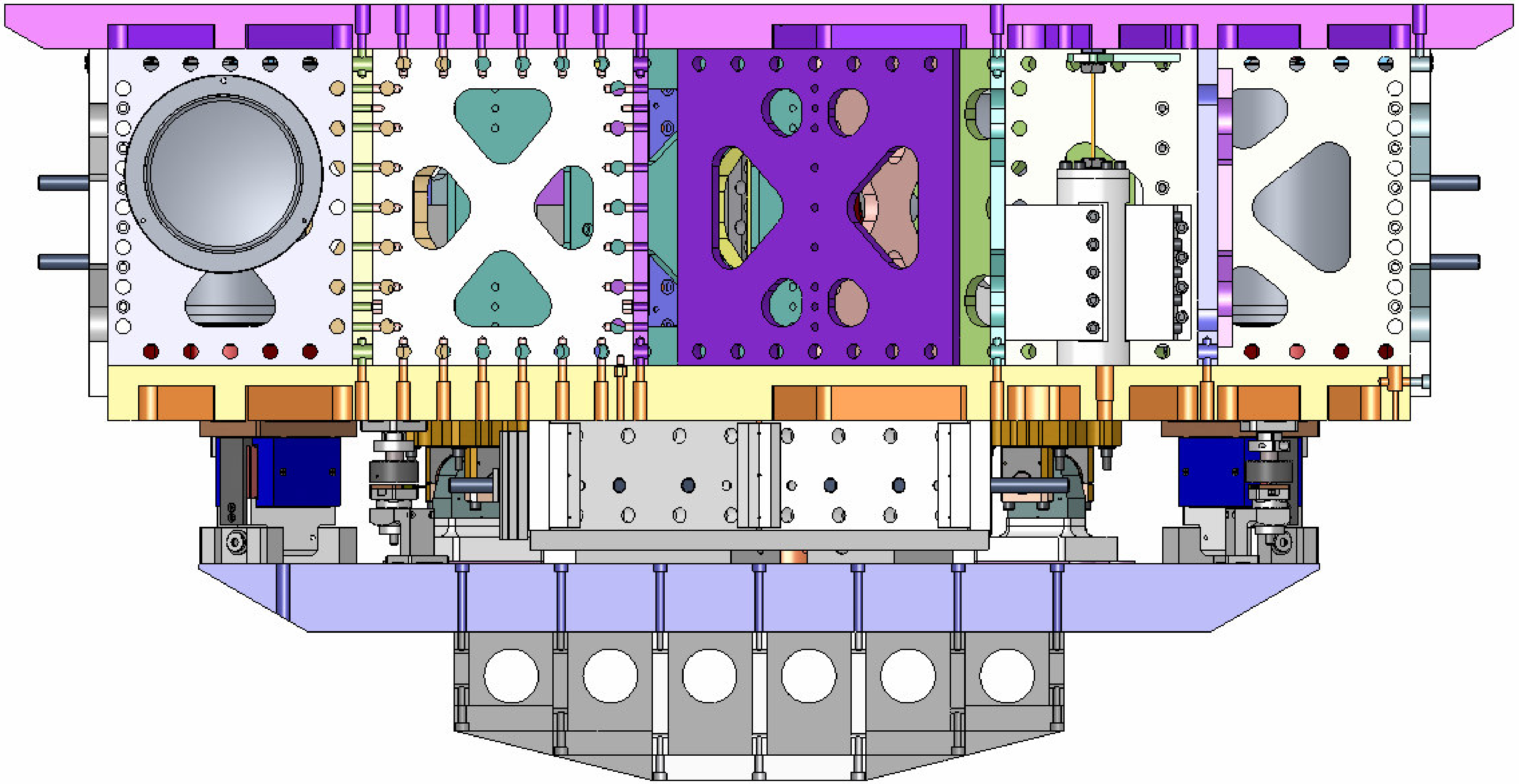
Screws & Barrel Nuts in Vertical Plates



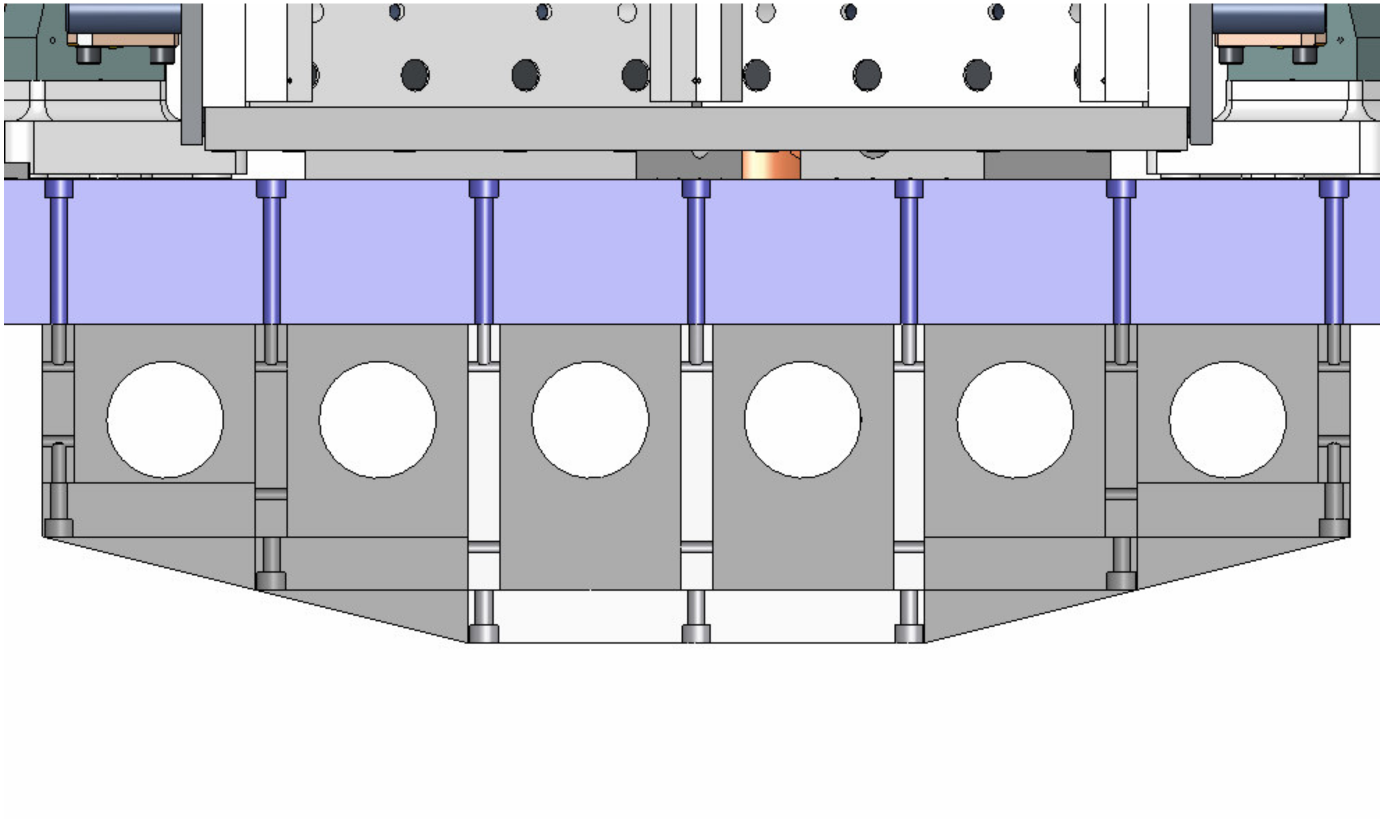
Screws & Barrel Nuts in Vertical Plates



System, Door View, Sectioned

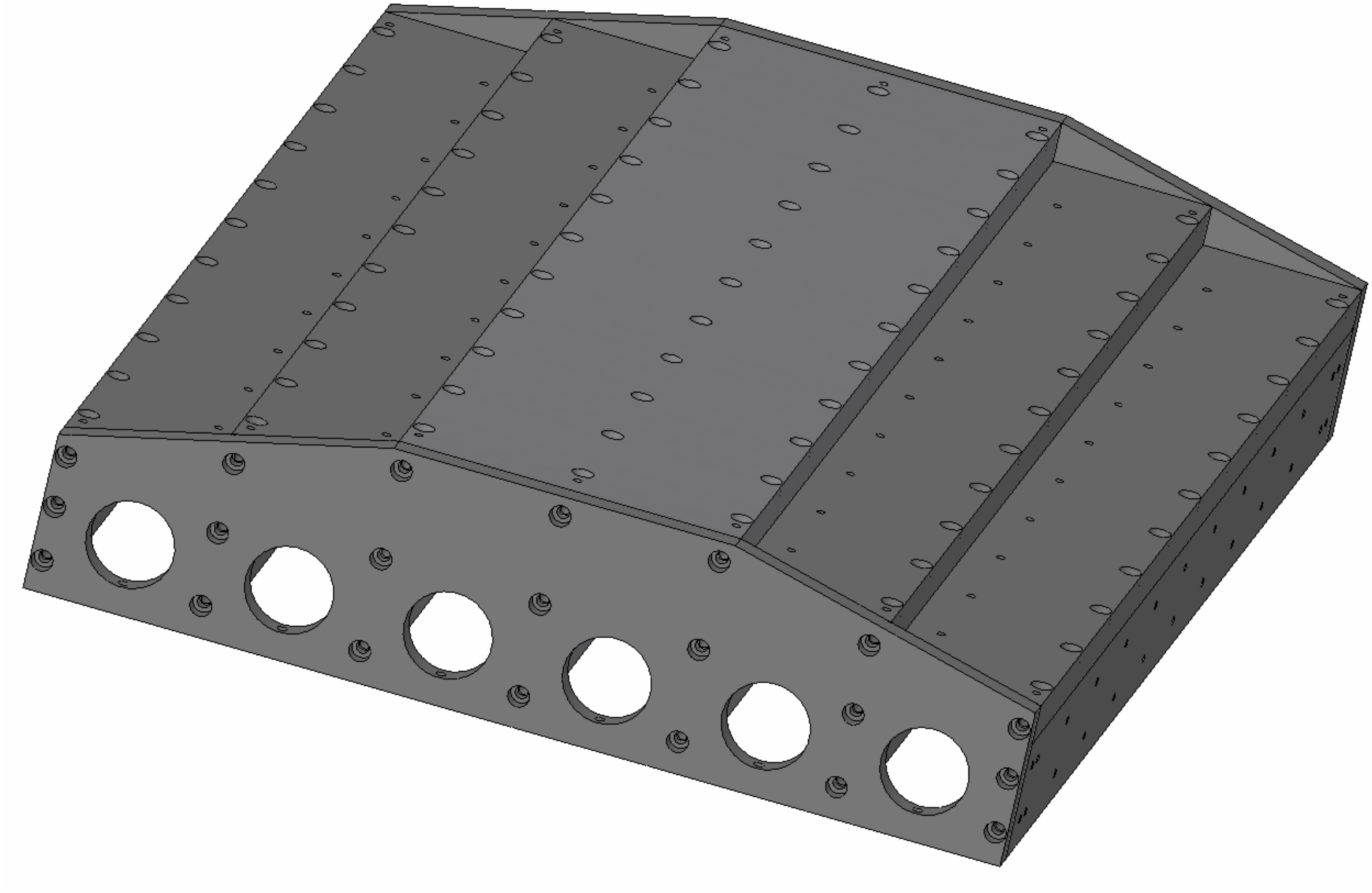


Stage 0 Stiffener, Door View, Sectioned

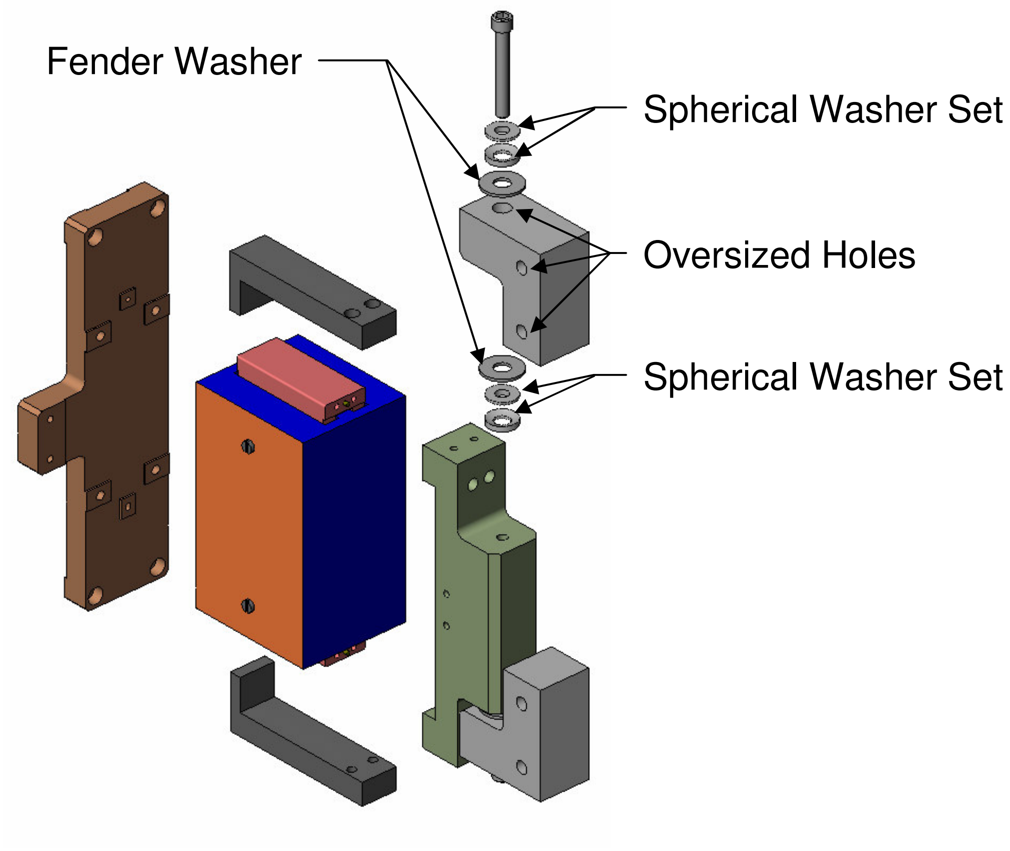


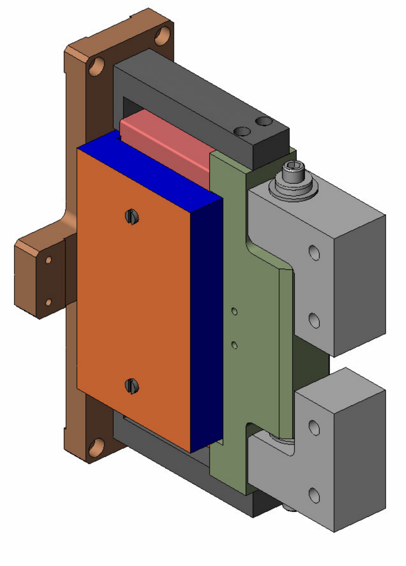
Stage 0 Stiffener

Stage 0 Stiffener

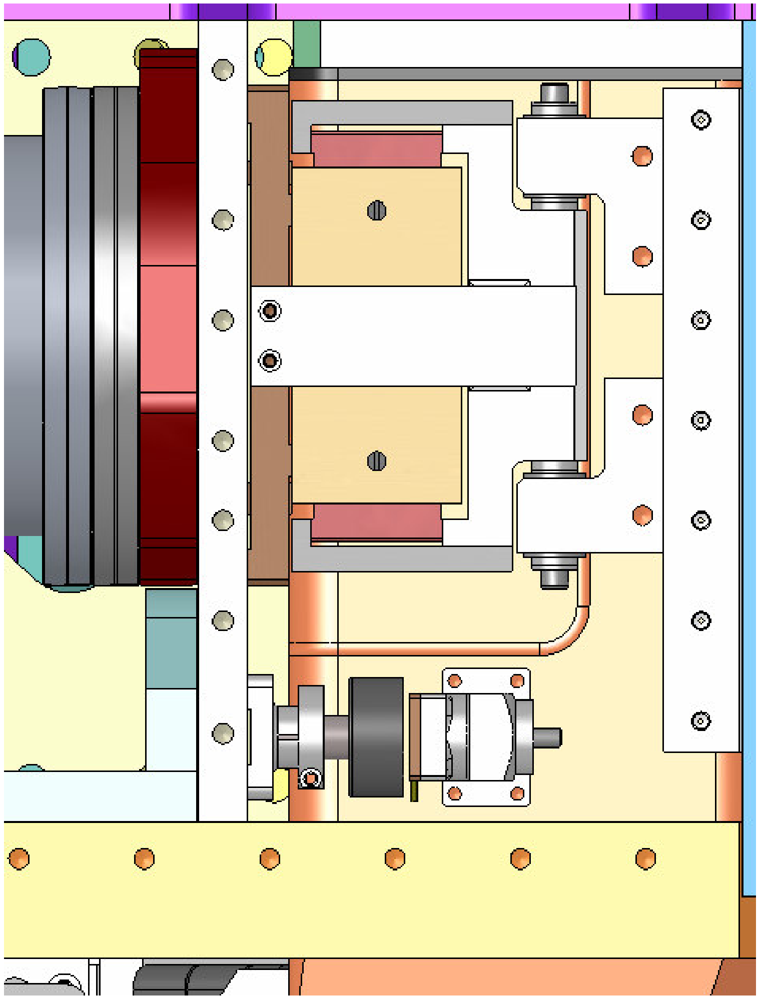


Horizontal Actuator with Mounting Hardware

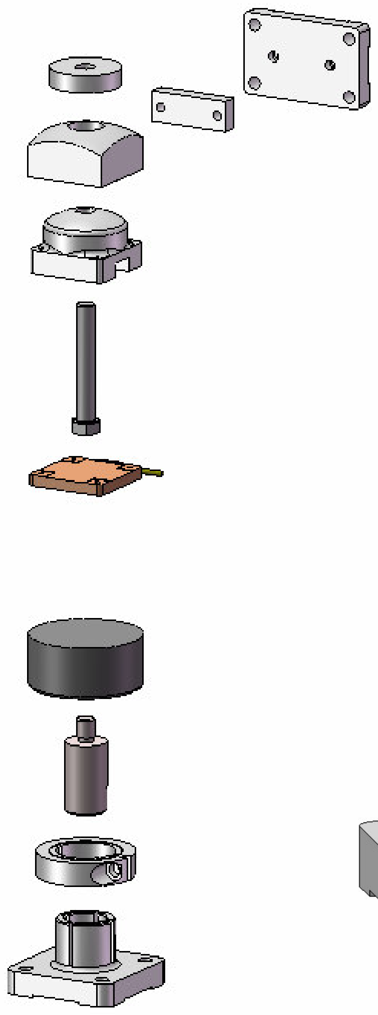




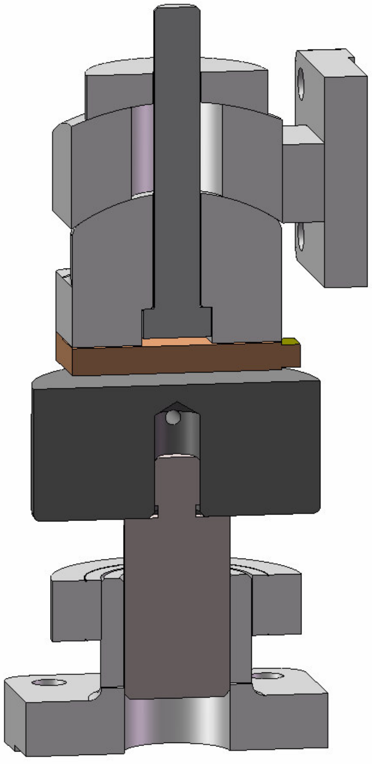
Horizontal Sensor Concept



Horizontal Sensor, mounted on Support Post

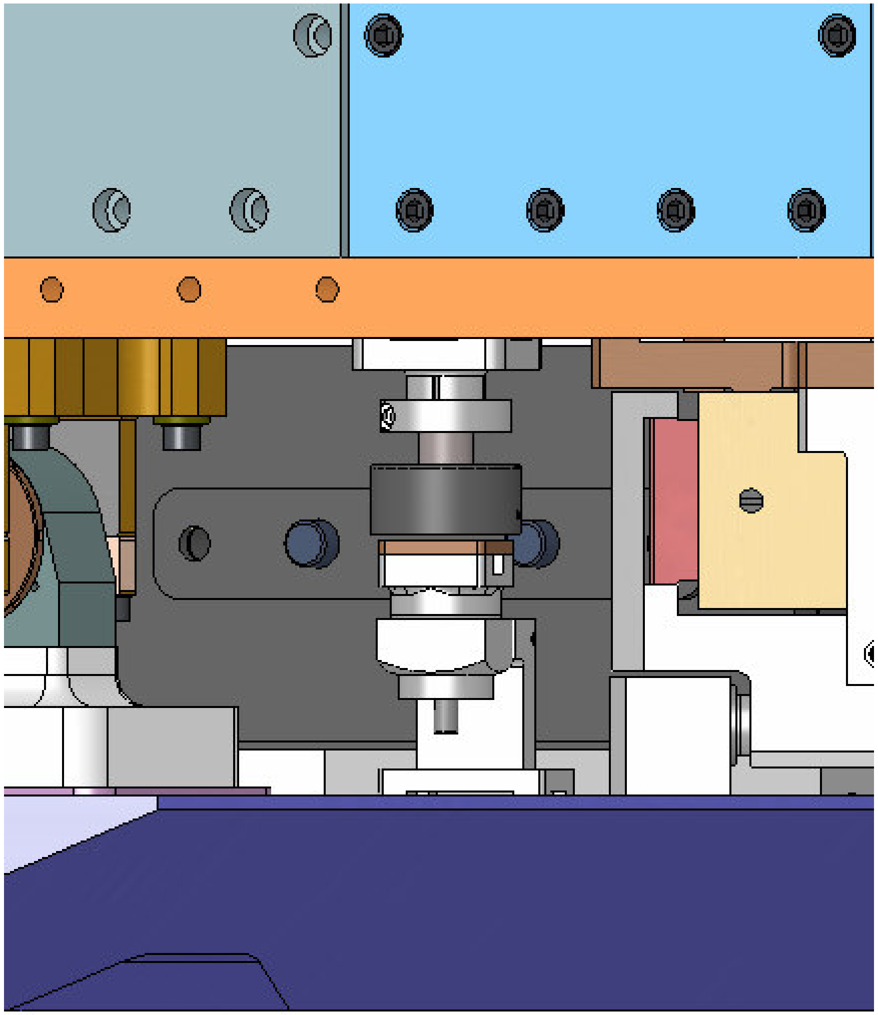


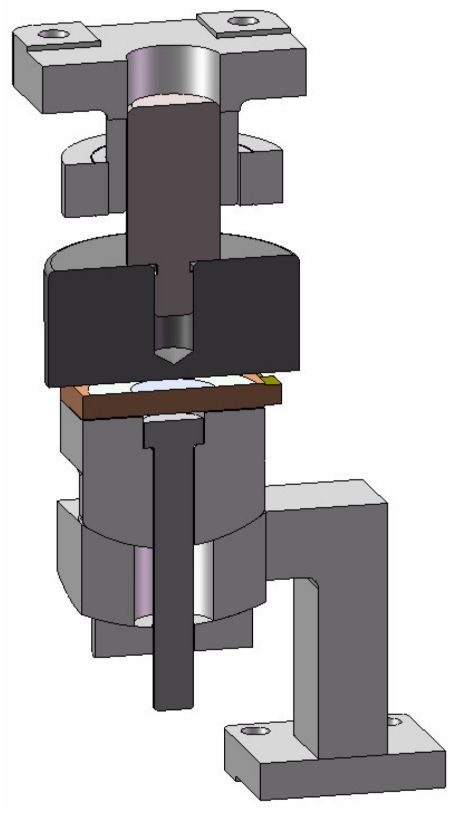
Exploded



Sectioned

Vertical Sensor Concept



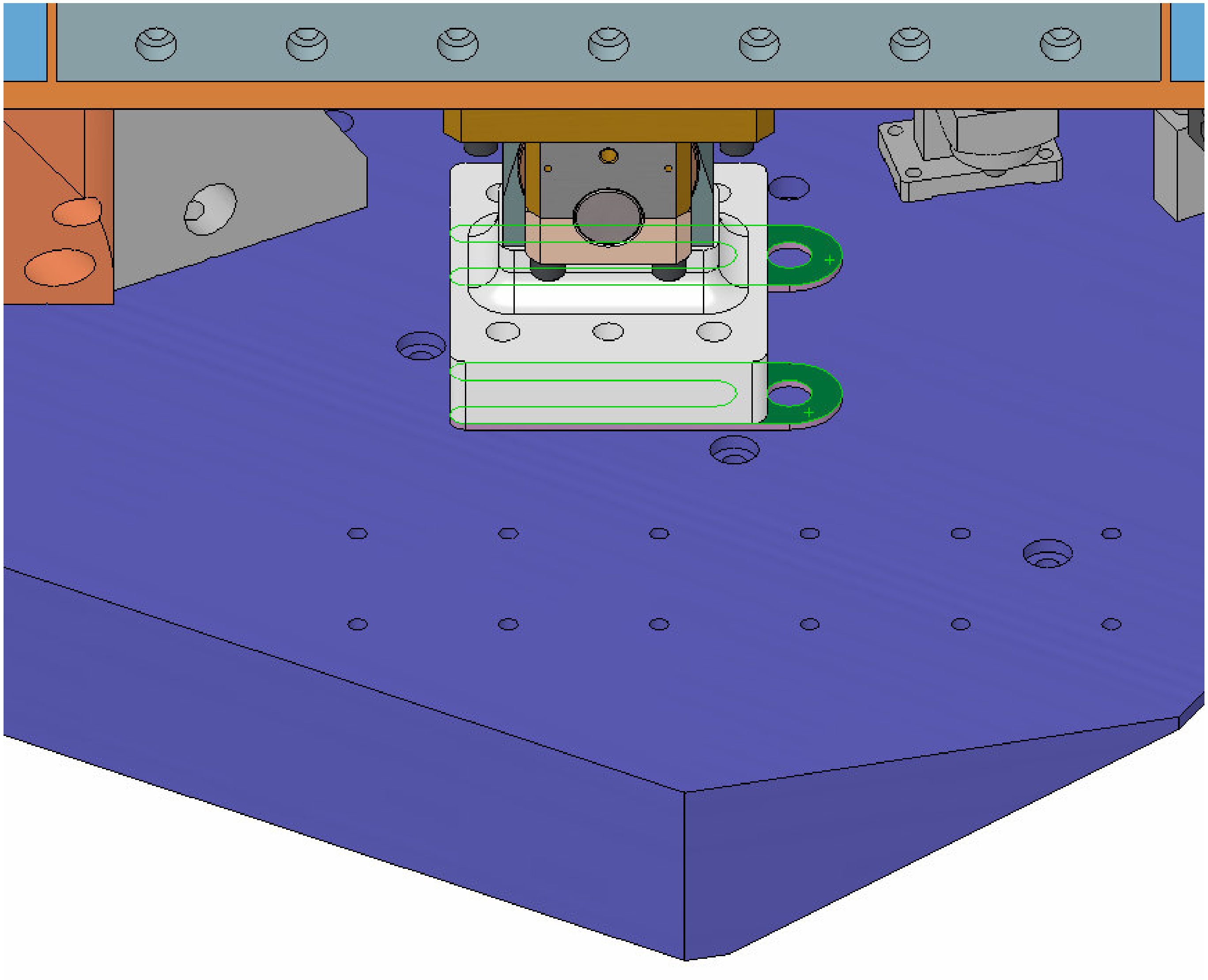


Horizontal Sensor, mounted on Support Post

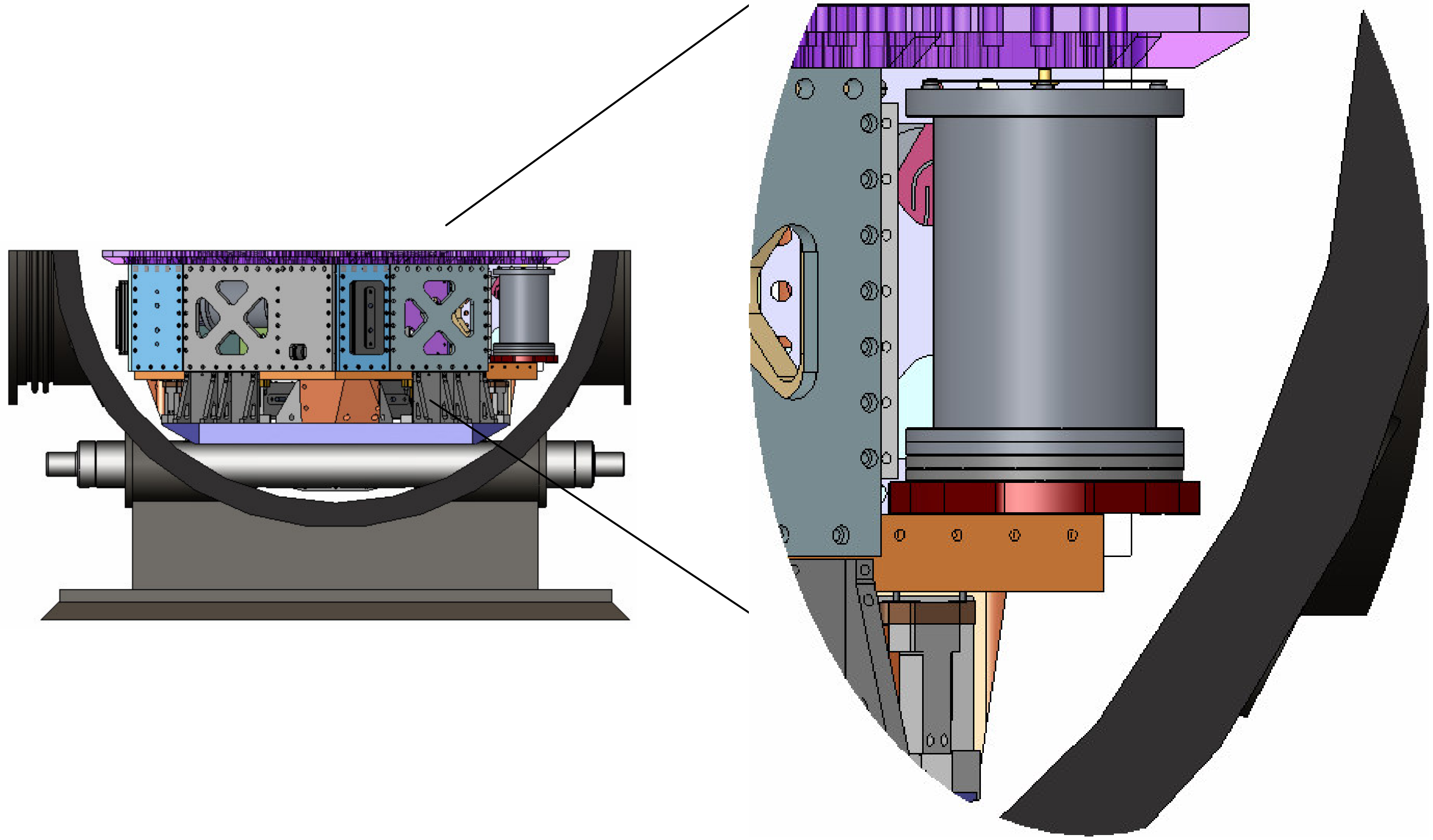
Exploded

Sectioned

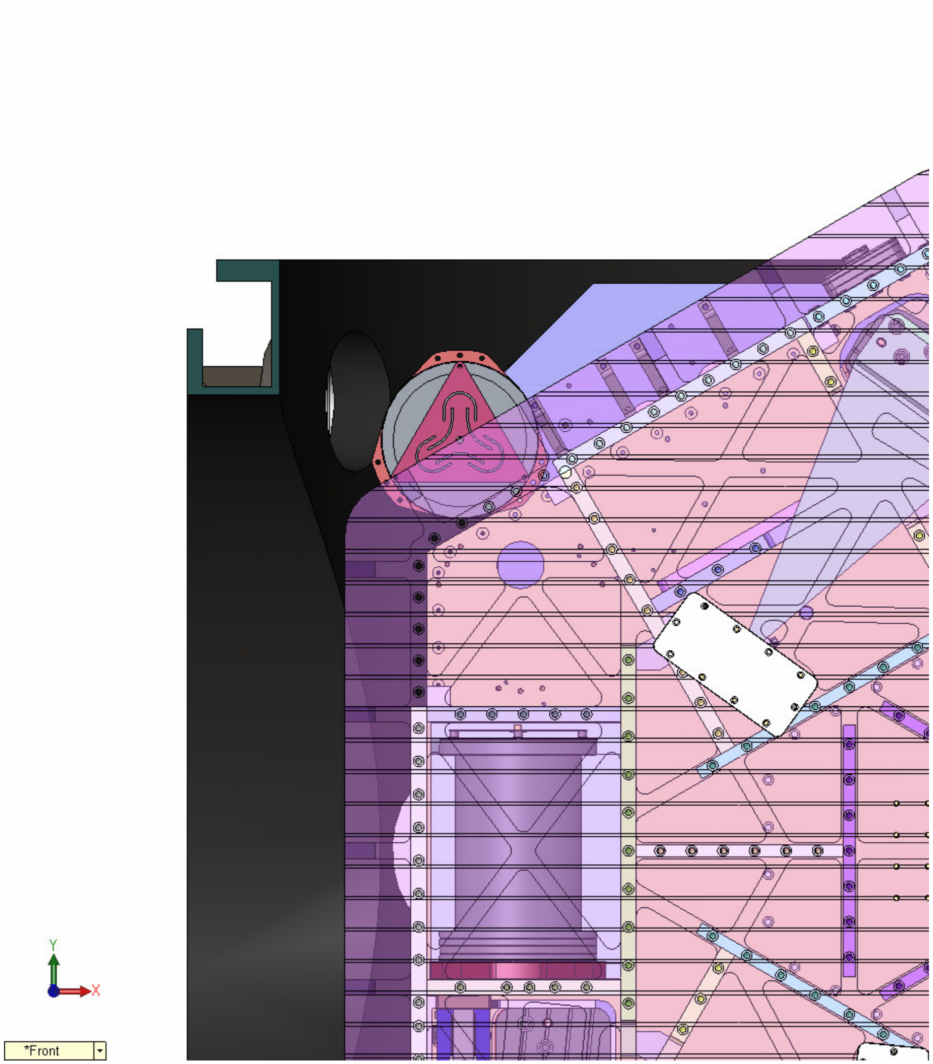
Modifications To Locker/Locator Base



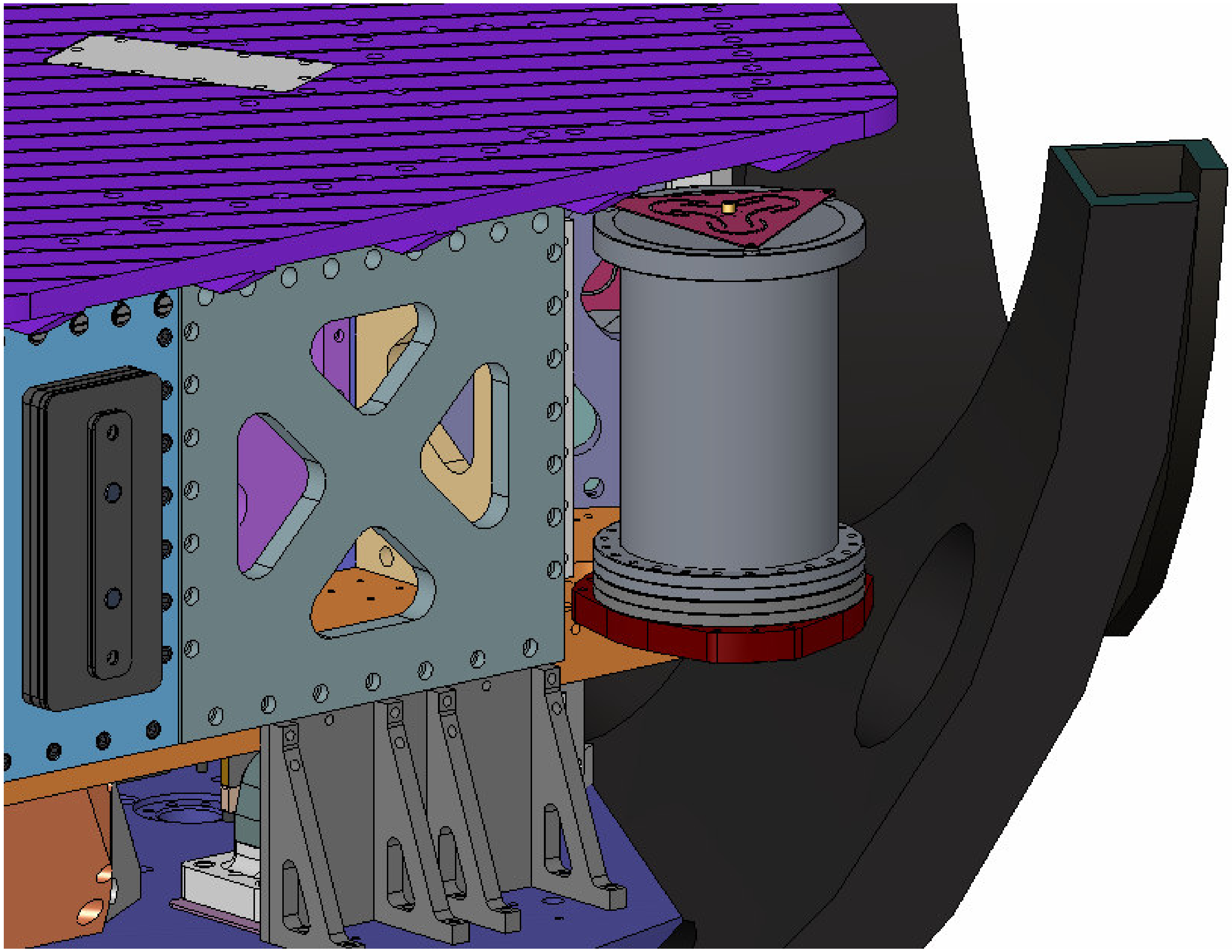
Side View, Worst-Case removal of Vertical GS-13



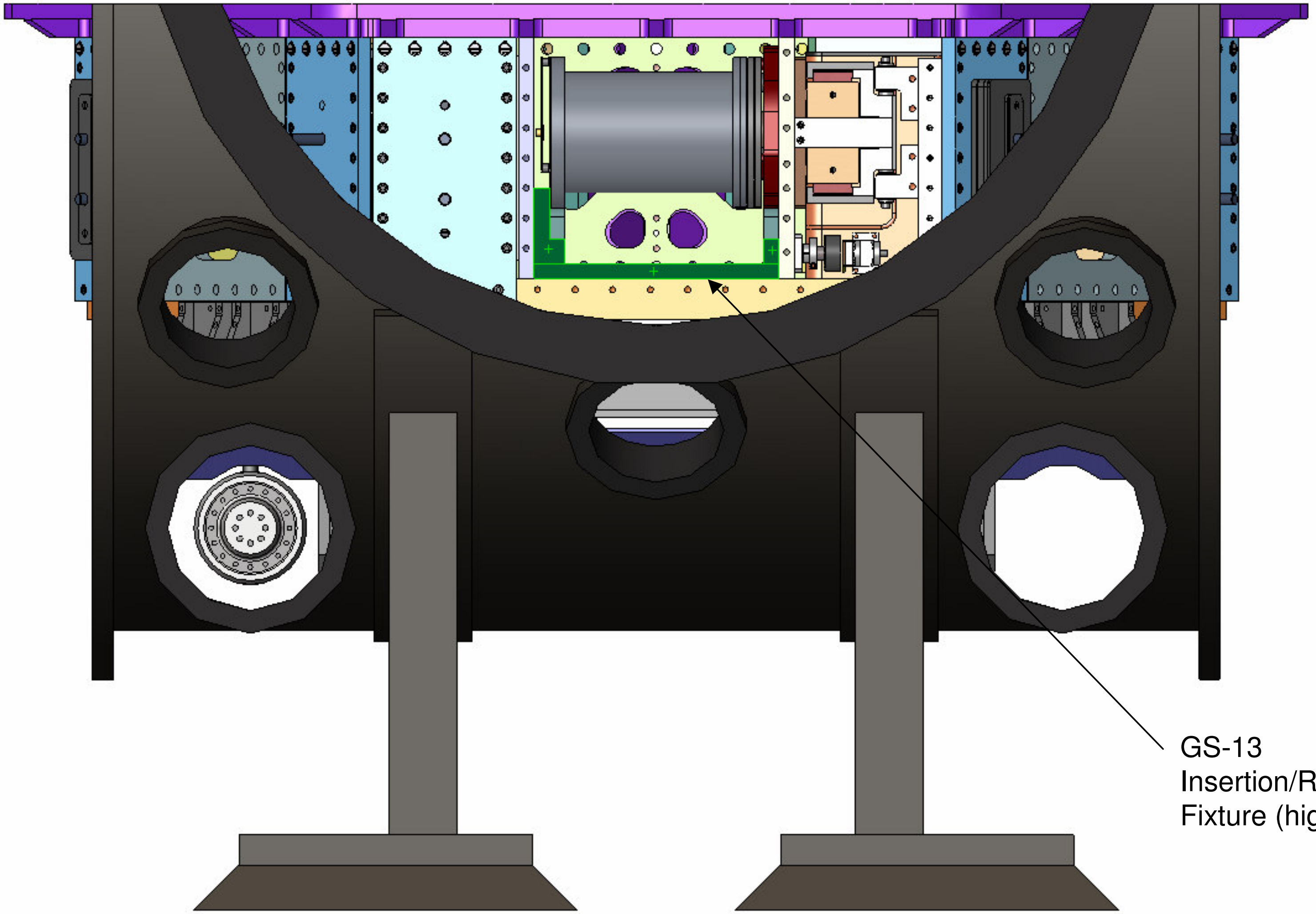
Top View, Worst-case Vertical GS-13 Access



ISO View, Worst-case Vertical GS-13 Access

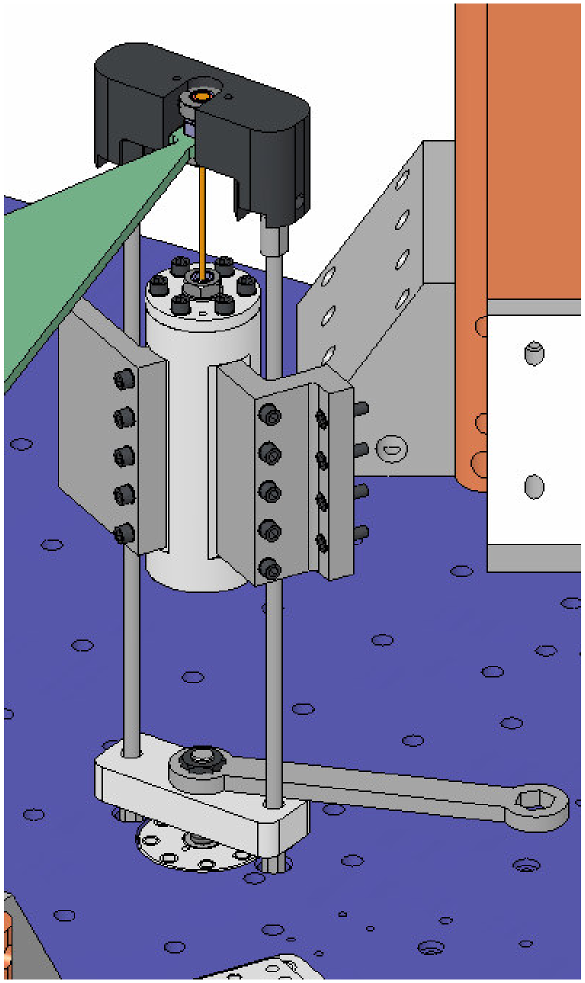


Worst-Case Horizontal GS-13 Access (via beam tube)

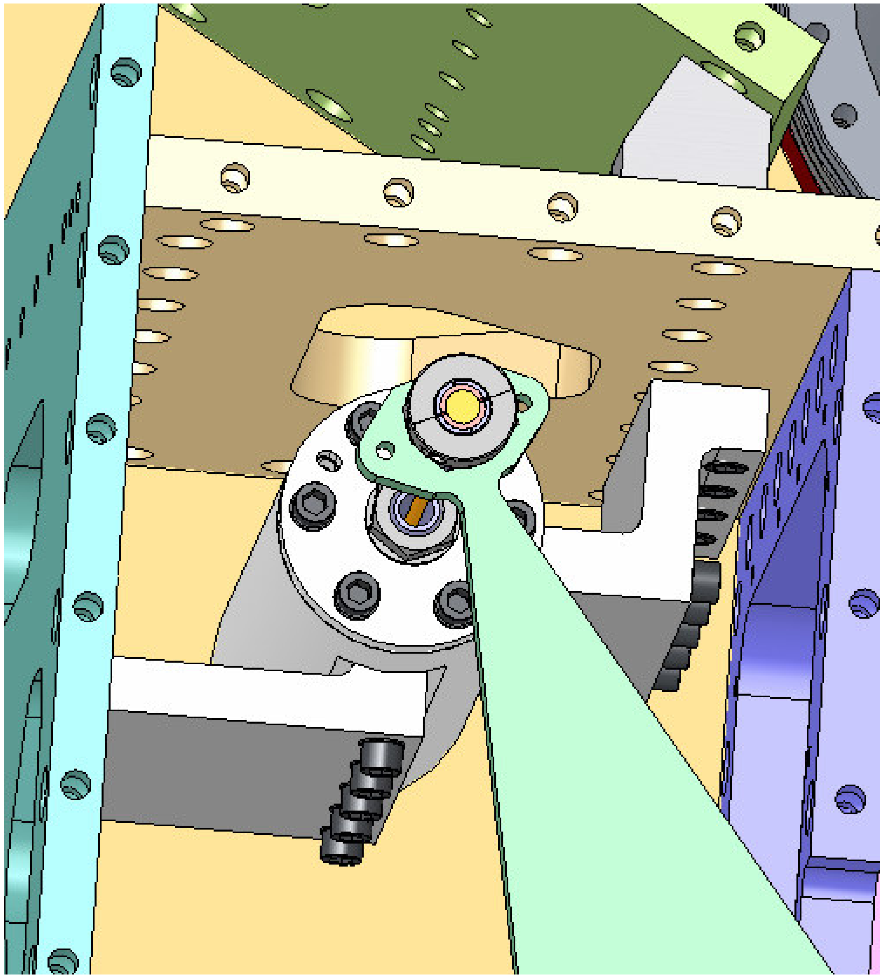


GS-13 Insertion/Removal Fixture (highlighted)

Spring Pull-Down

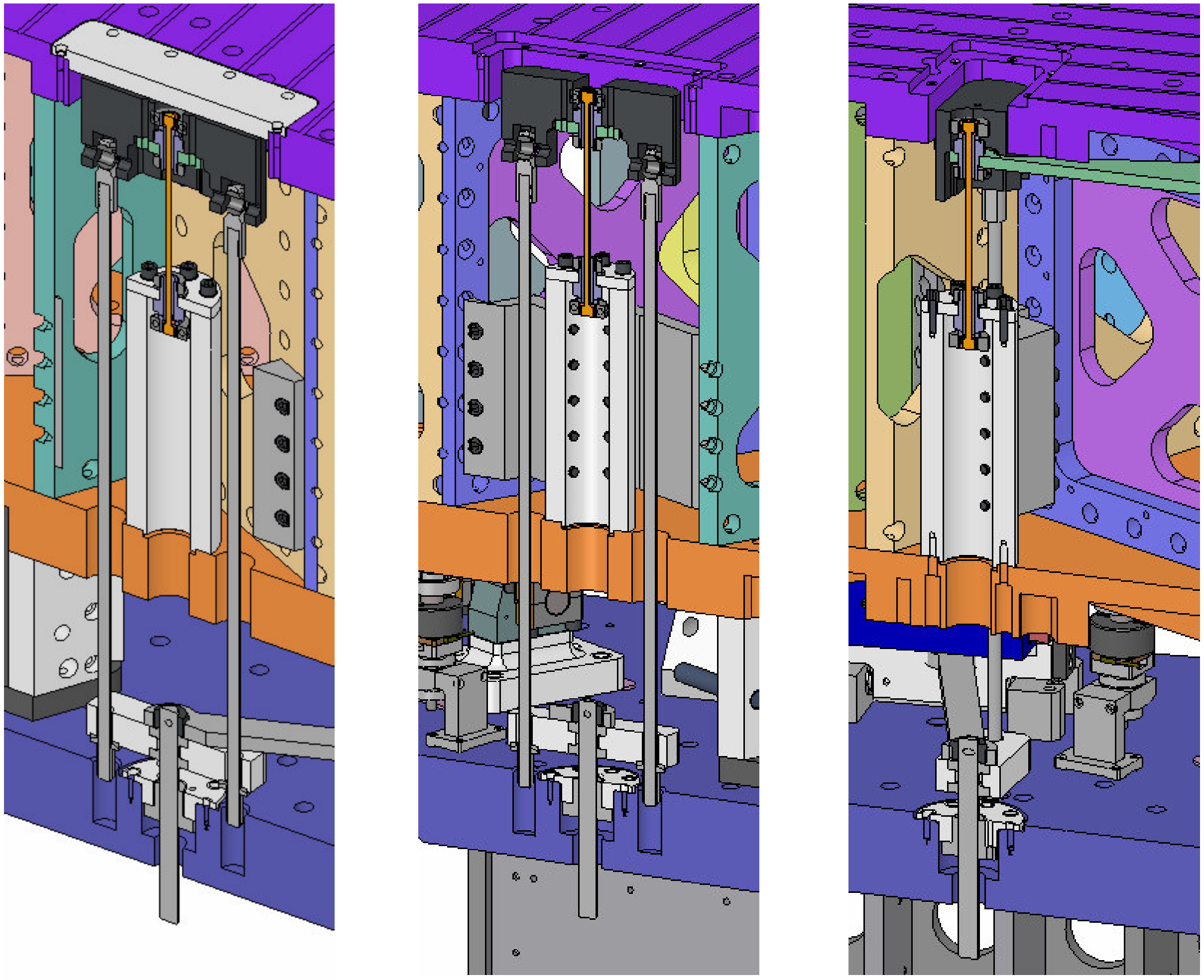


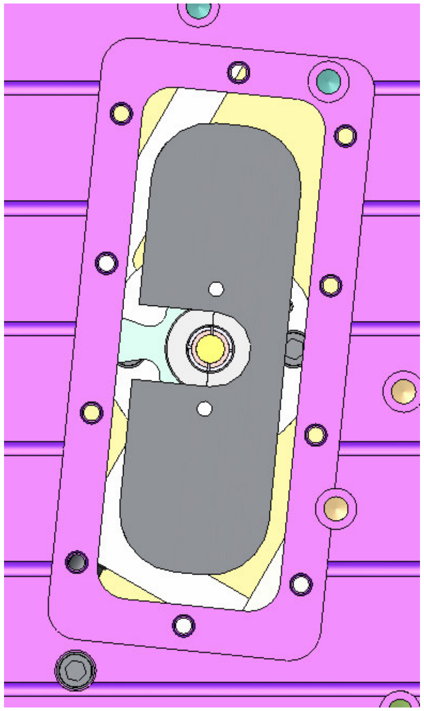
Pull-Down with surrounding structure removed



Top View, Table Hidden

Spring Pull-Down



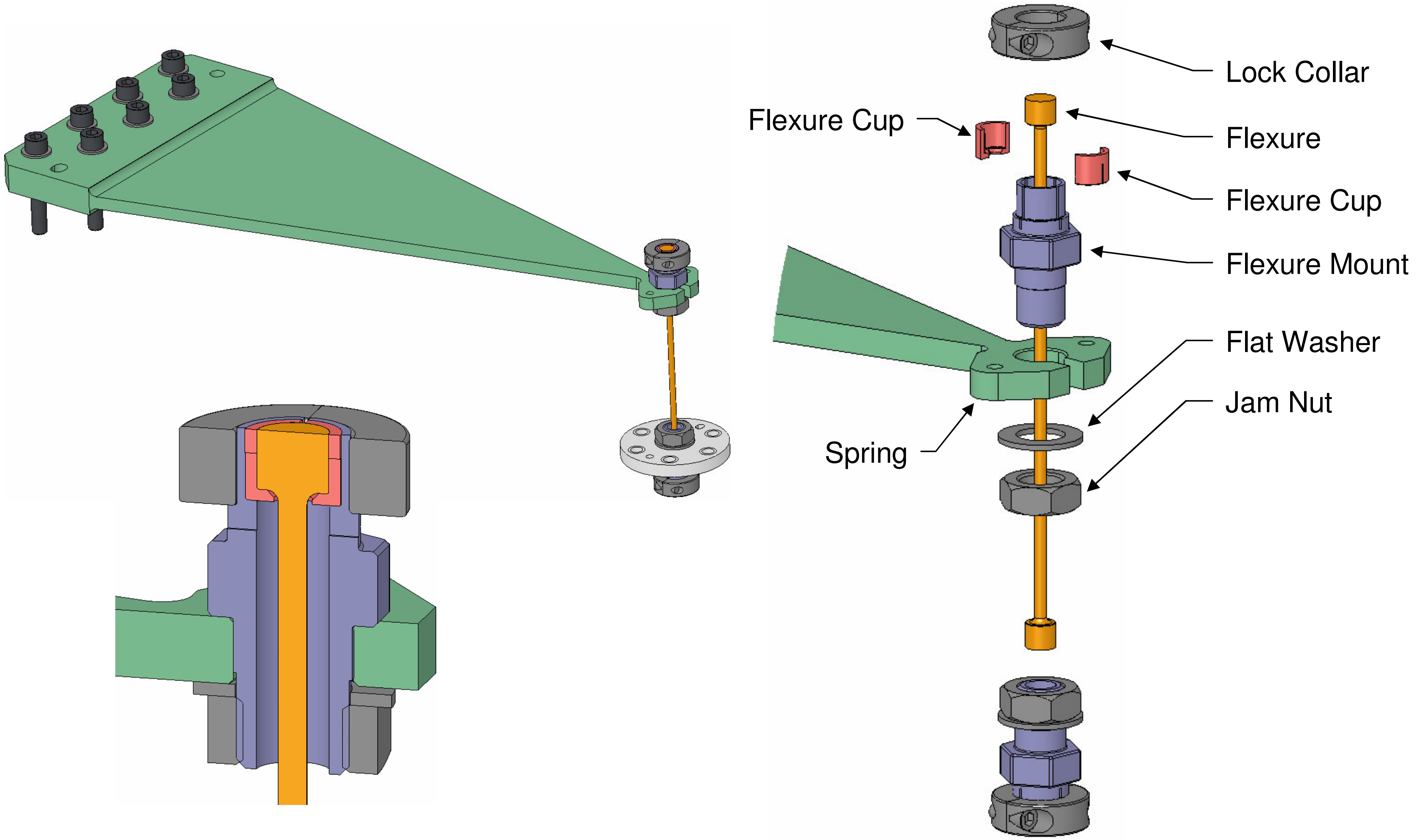


Top View, Thru Table

Section Views

Sectioned Along Spring

Flexure Installation



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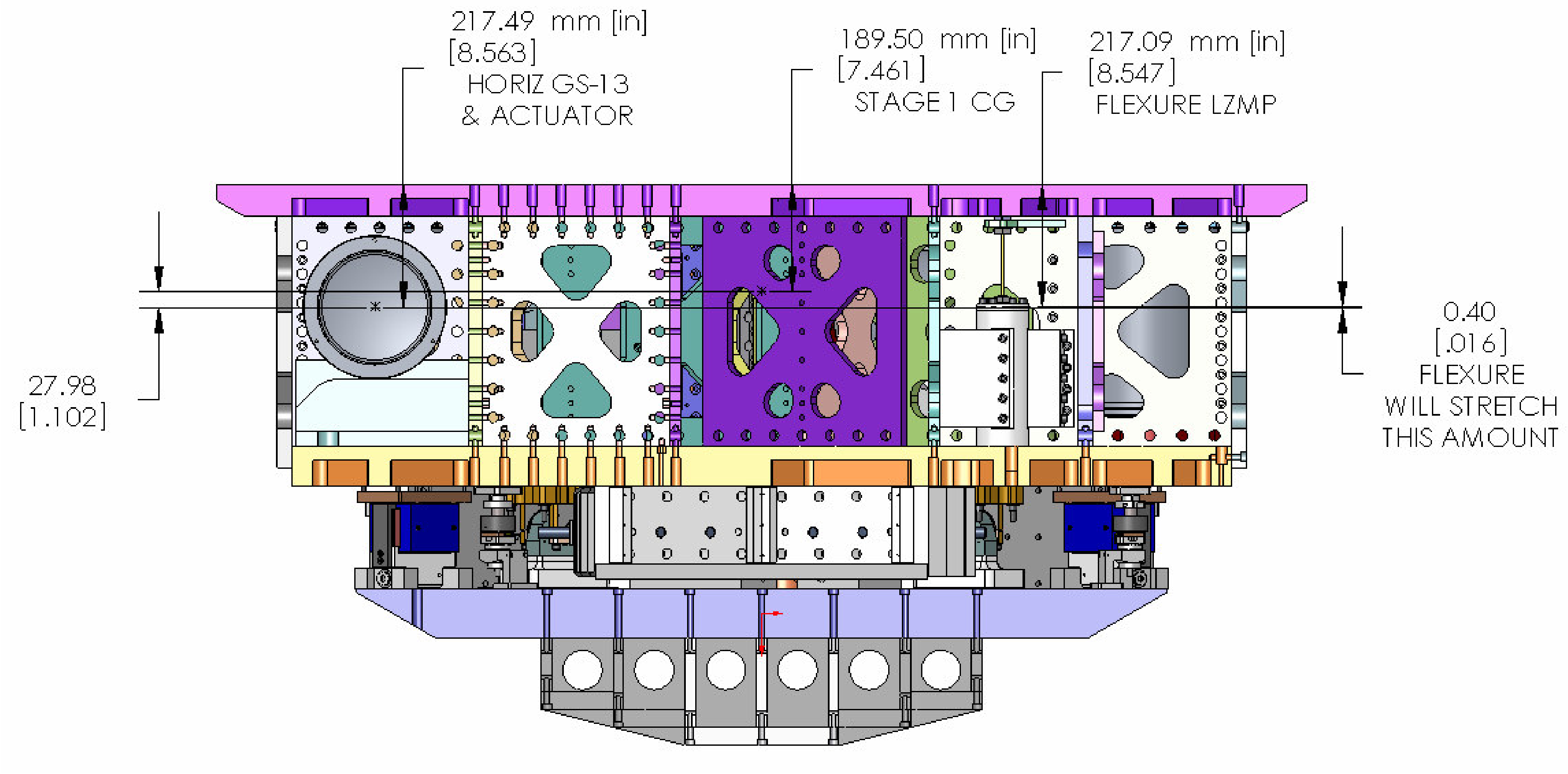
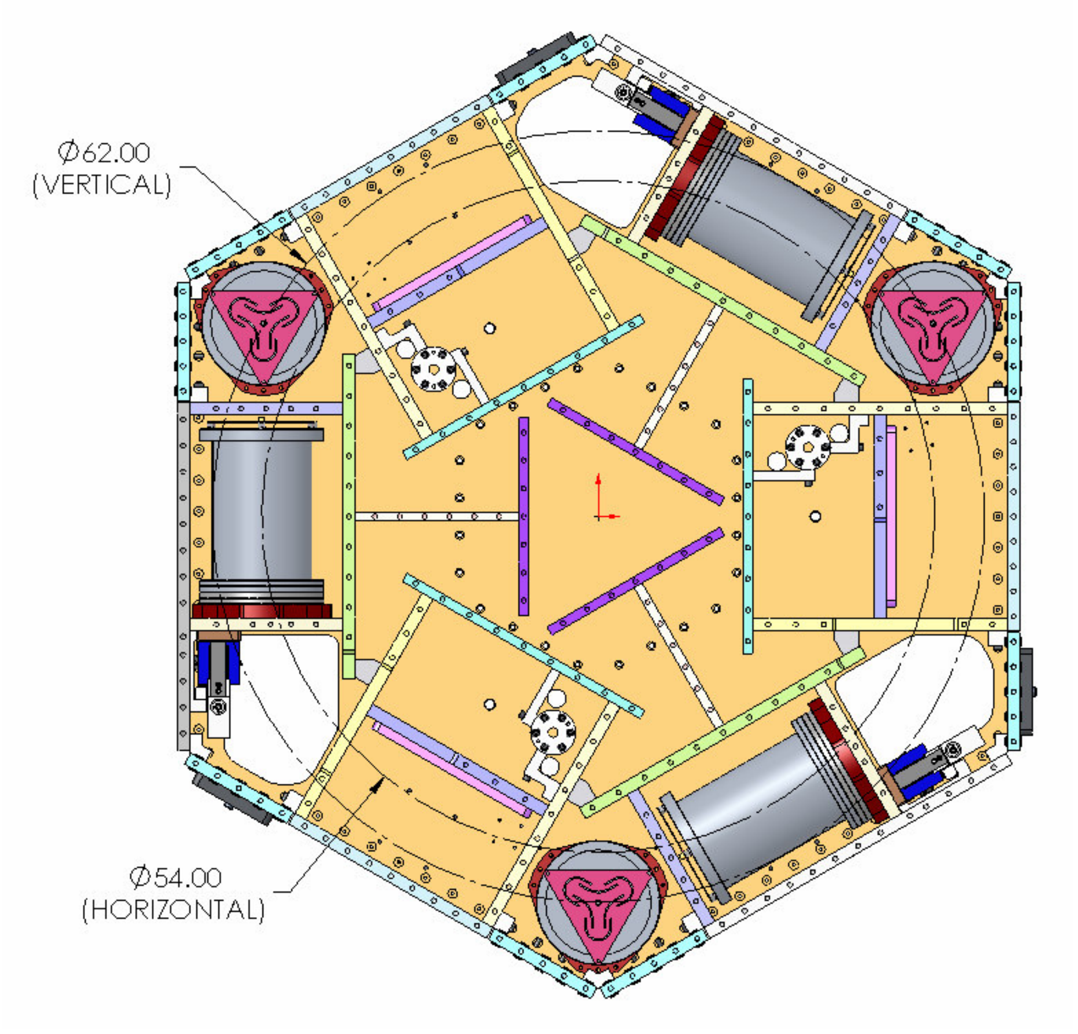
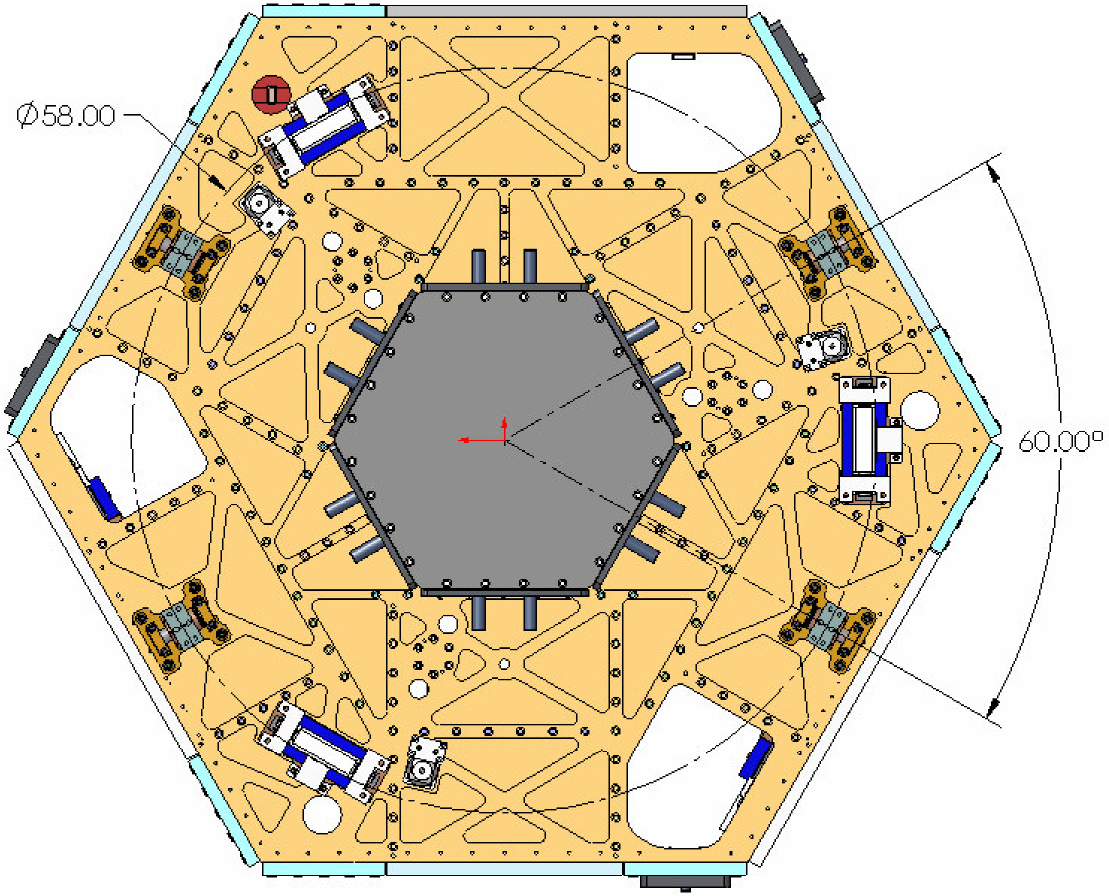
Stage 1 – CG, LZMP, Actuators, GS-13 Locations



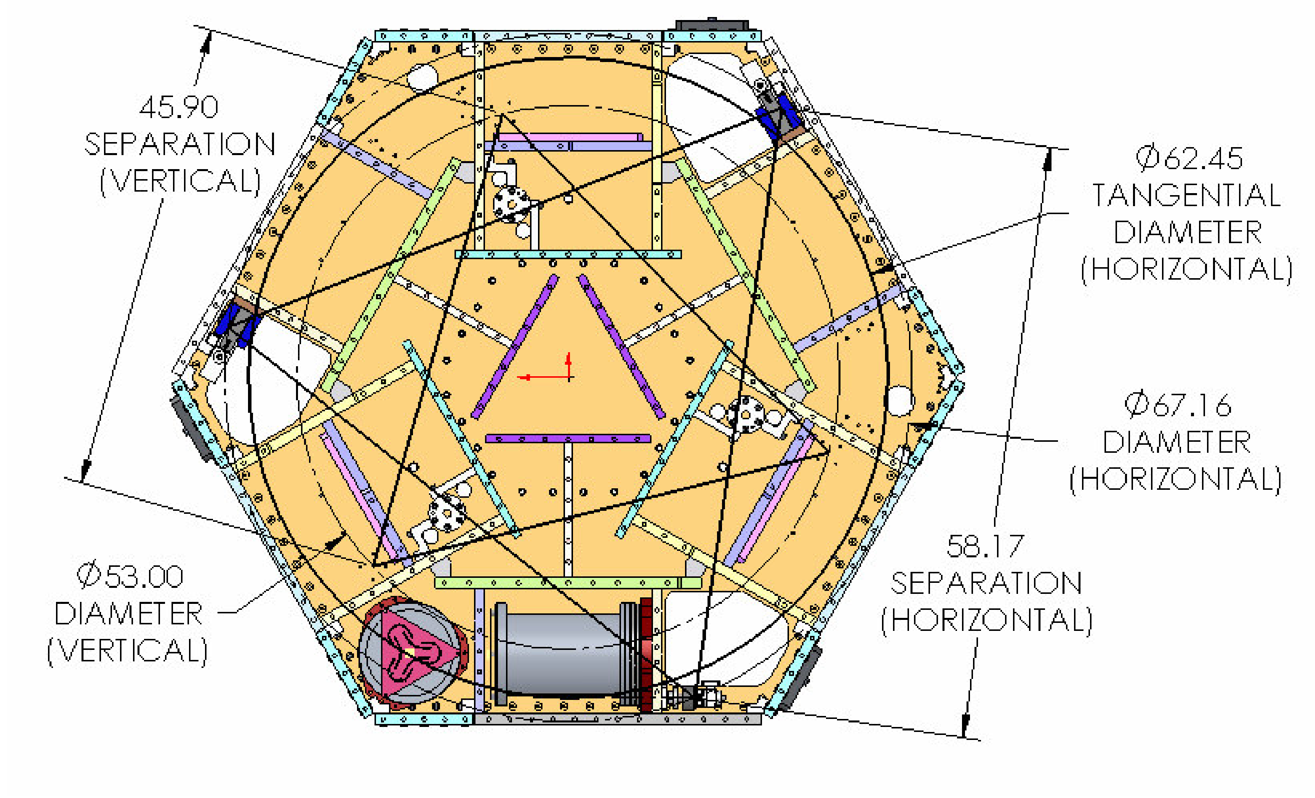
Seismometer Locations – Top View



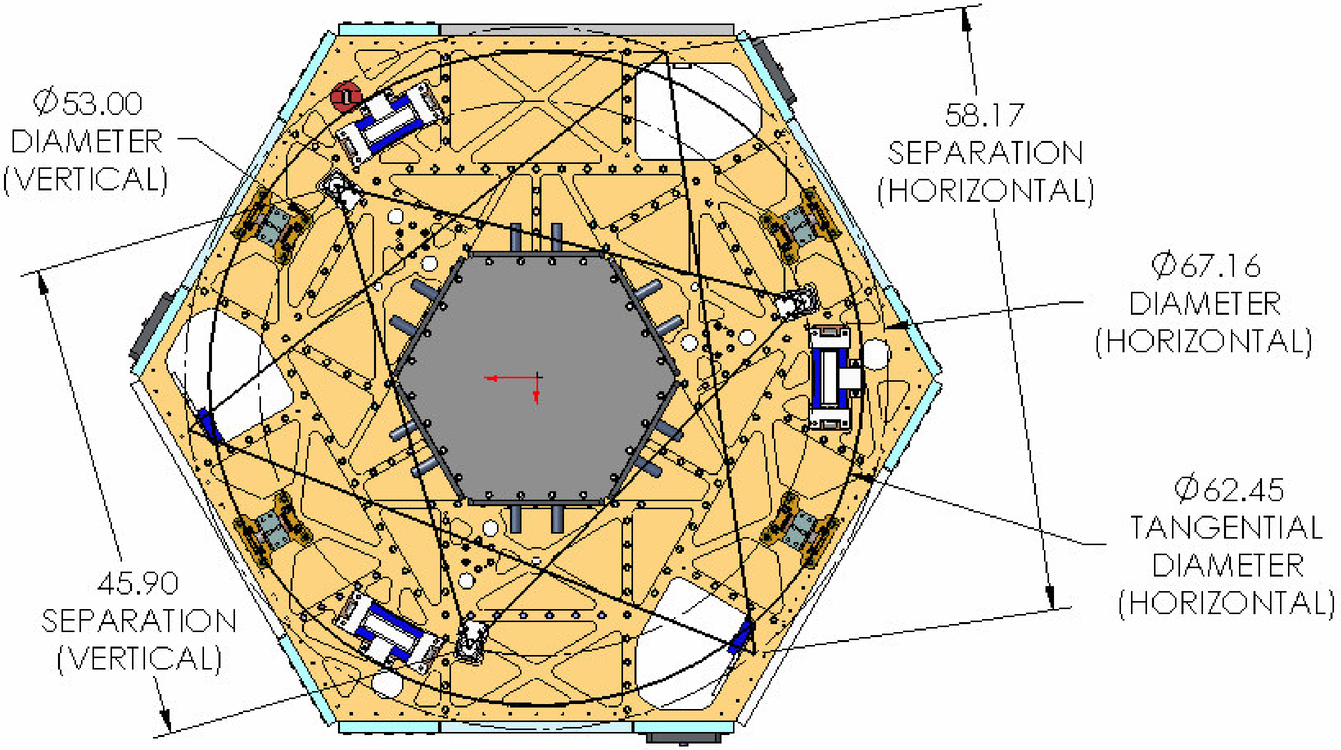
Locker/Locator Positions – Bottom View



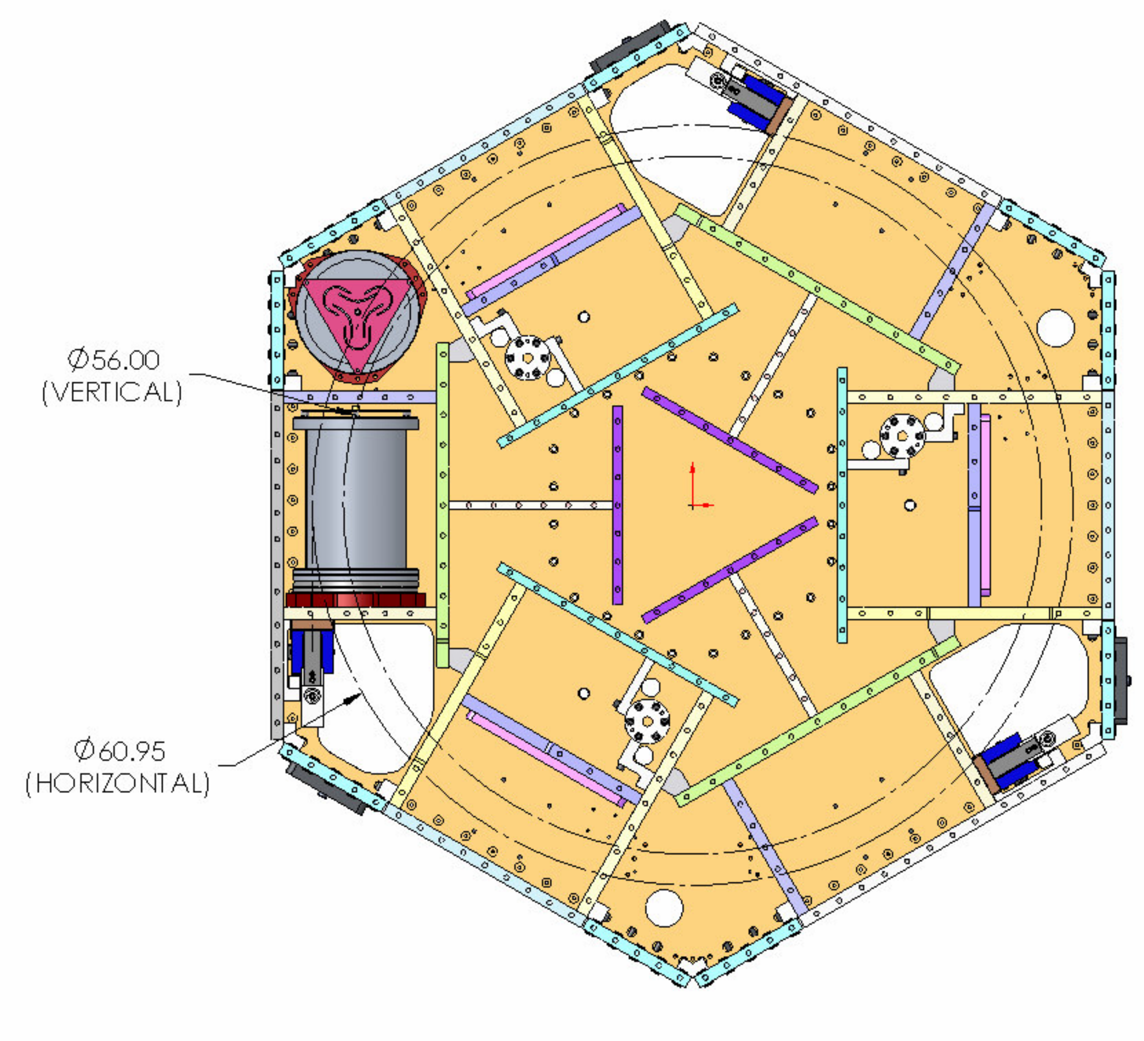
Position Sensor Locations – Top View



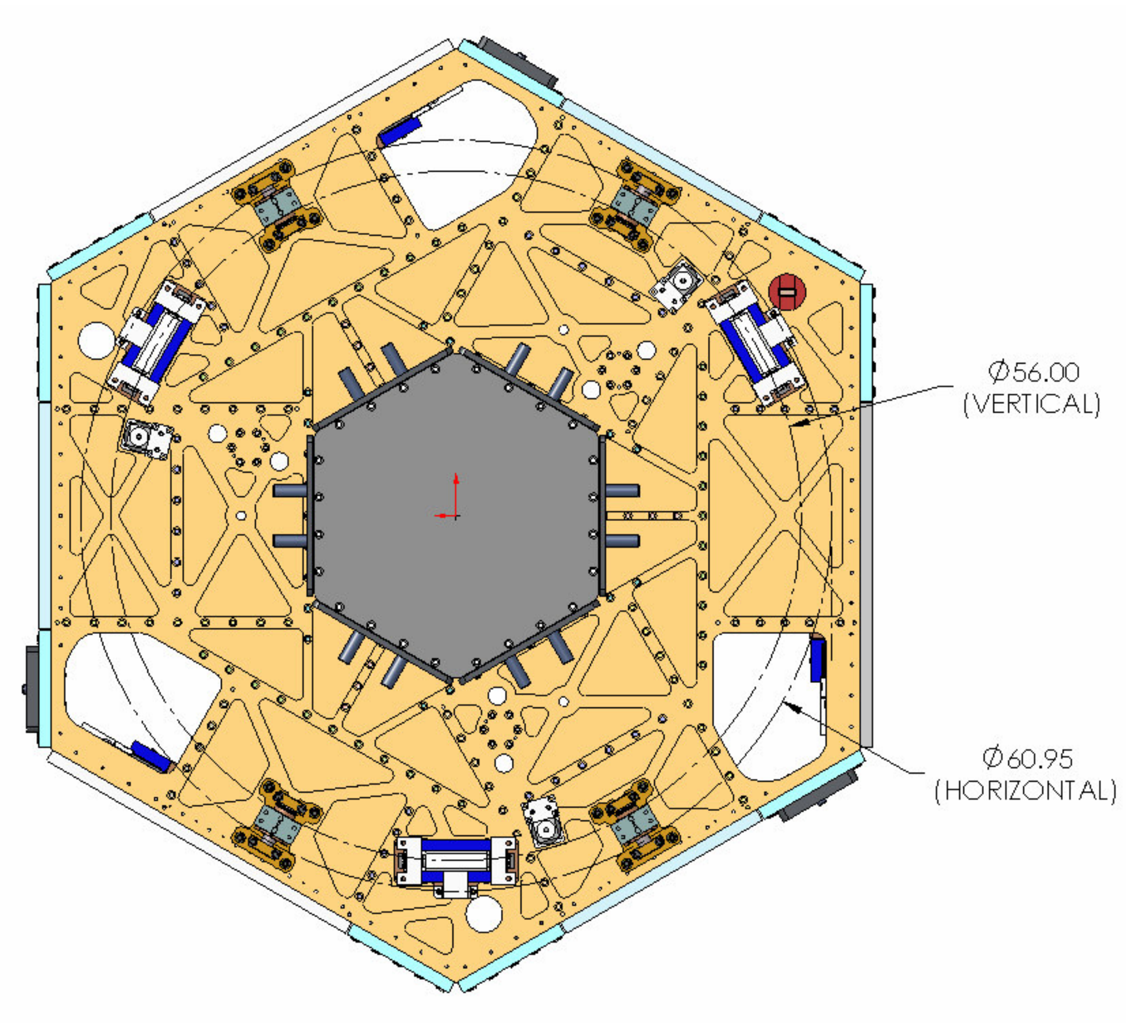
Position Sensor Locations – Bottom View



Actuator Locations – Top View



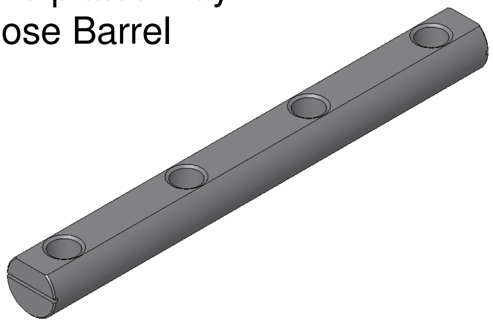
Actuator Locations – Bottom View



Fastener Plan

Non-Retained Barrel Nut: Most Locations. 6061-T6 with Nitronic 60 Helicoil insert.

Retained Barrel Nut: Used only in locations where plates may be removed and possibility exists of dropping loose Barrel Nuts. 6061-T6 with Nitronic 60 Helicoil insert.



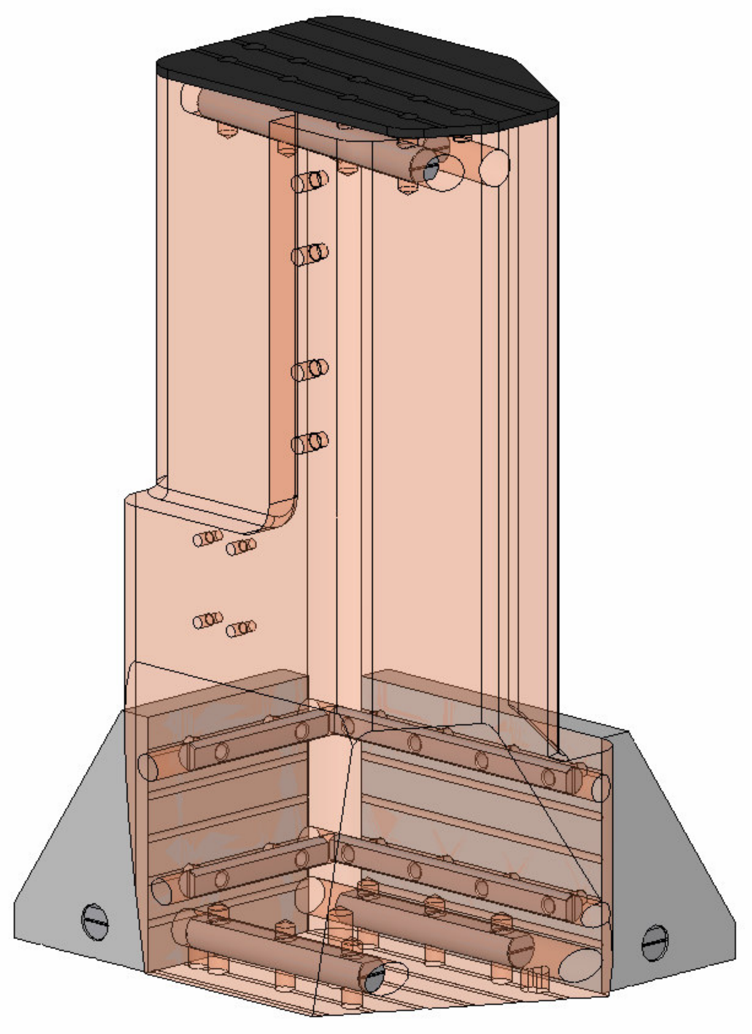
Gang Barrel Nut: Used only in Support Post and Gussets, where access is too limited for individual Barrel Nuts. 17-4 H1150 Stainless with Nitronic 60 Helicoil inserts.

Nitronic 60 Helicoil Only: Used only in places where Barrel Nuts are infeasible due to size or space constraints. Preferential use is in smaller brackets, etc. that are easily replaced whole if thread is damaged.

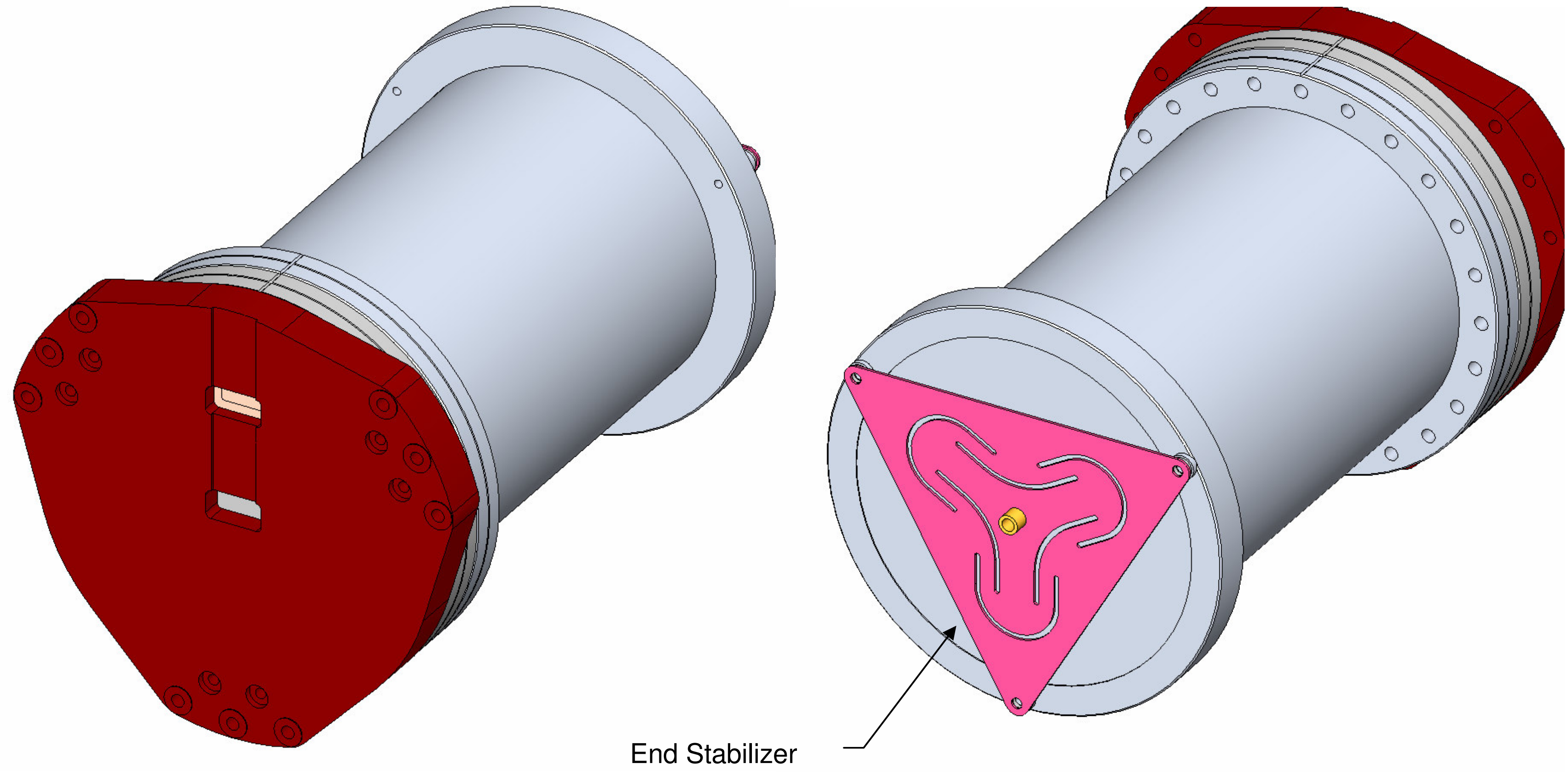
Oversized tapped holes in aluminum: Used on Stage 0 stiffener assembly (for permanent connections in areas where particulates are less likely to cause problems).

Socket Head Cap Screw with Vented Washer: Used in most locations. 18-8 stainless steel. No silver-plated or A286 hardware is required.

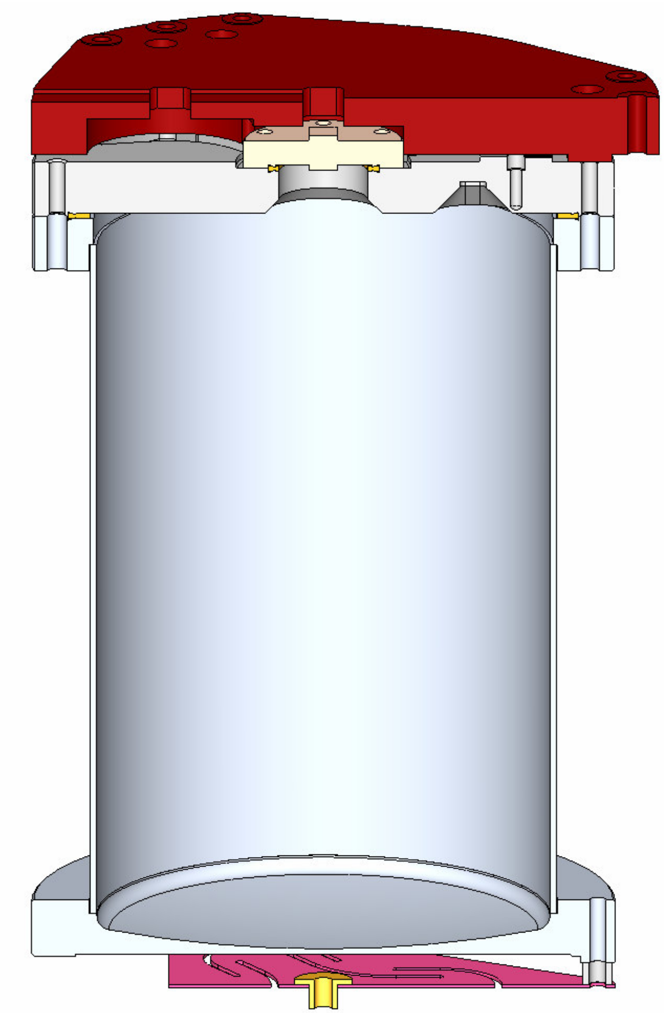
Gang Barrel Nuts in Support Post



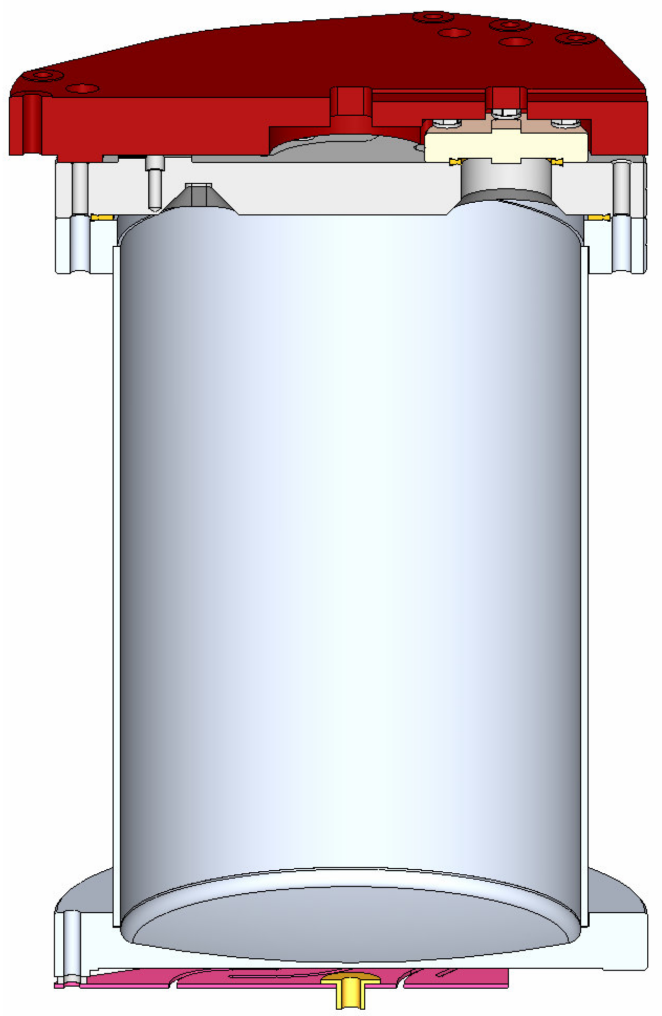
GS-13, Adapter Plate, and Stabilizer



End Stabilizer

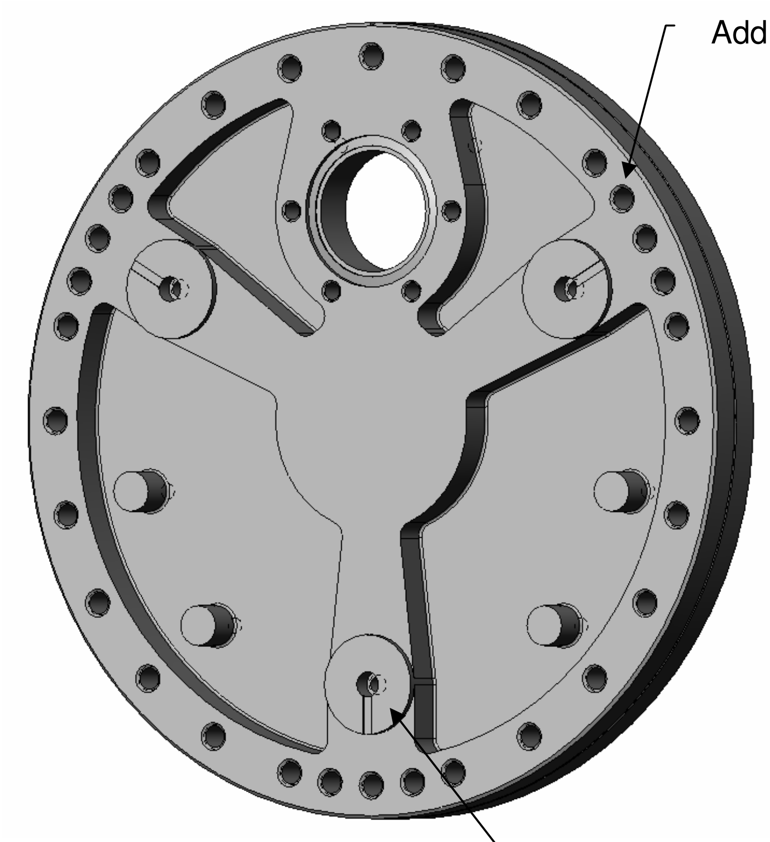


Horizontal

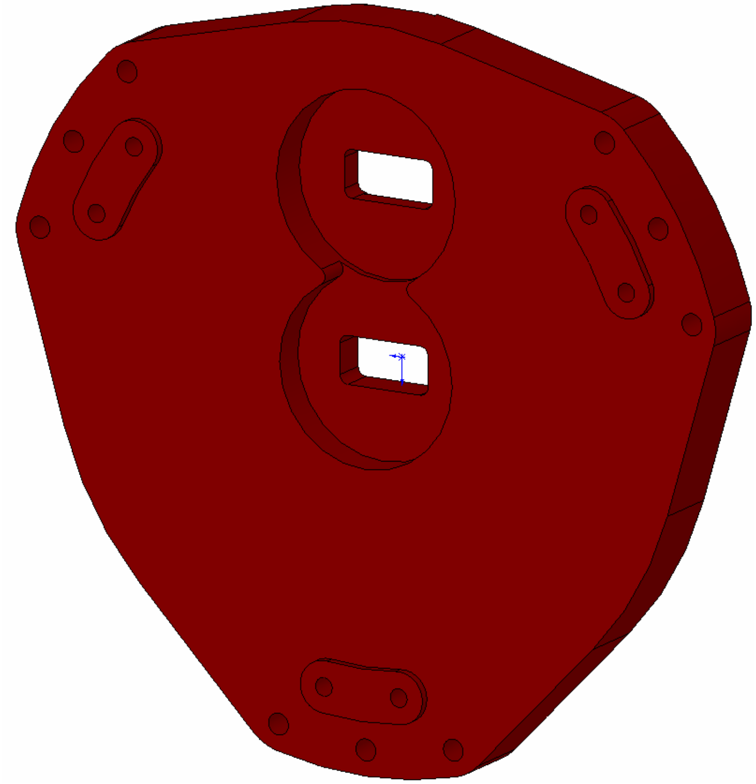


Vertical

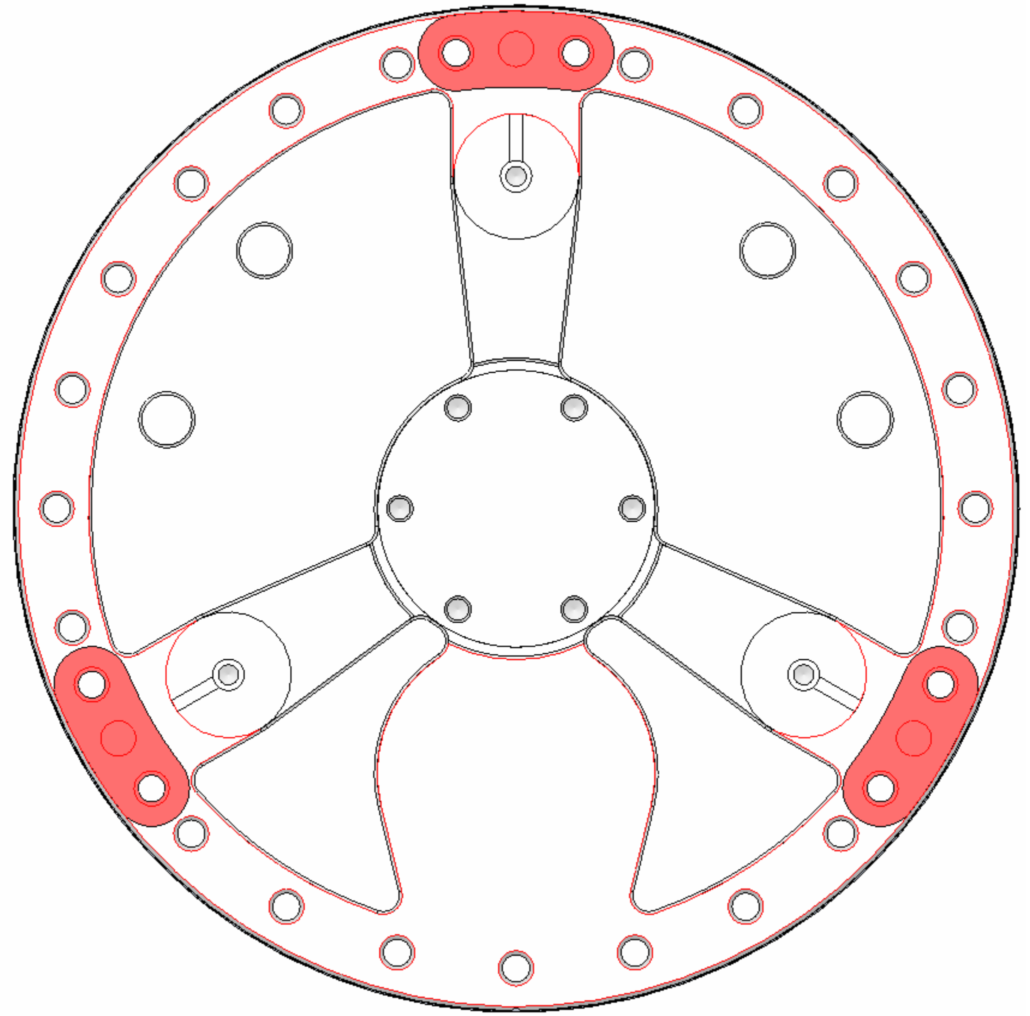
GS-13 Flange Modifications & Adapter Plate


Additional Mounting Holes

(3) Mounting pads are identical - Not used



GS-13 Flange With Adapter Plate Pads



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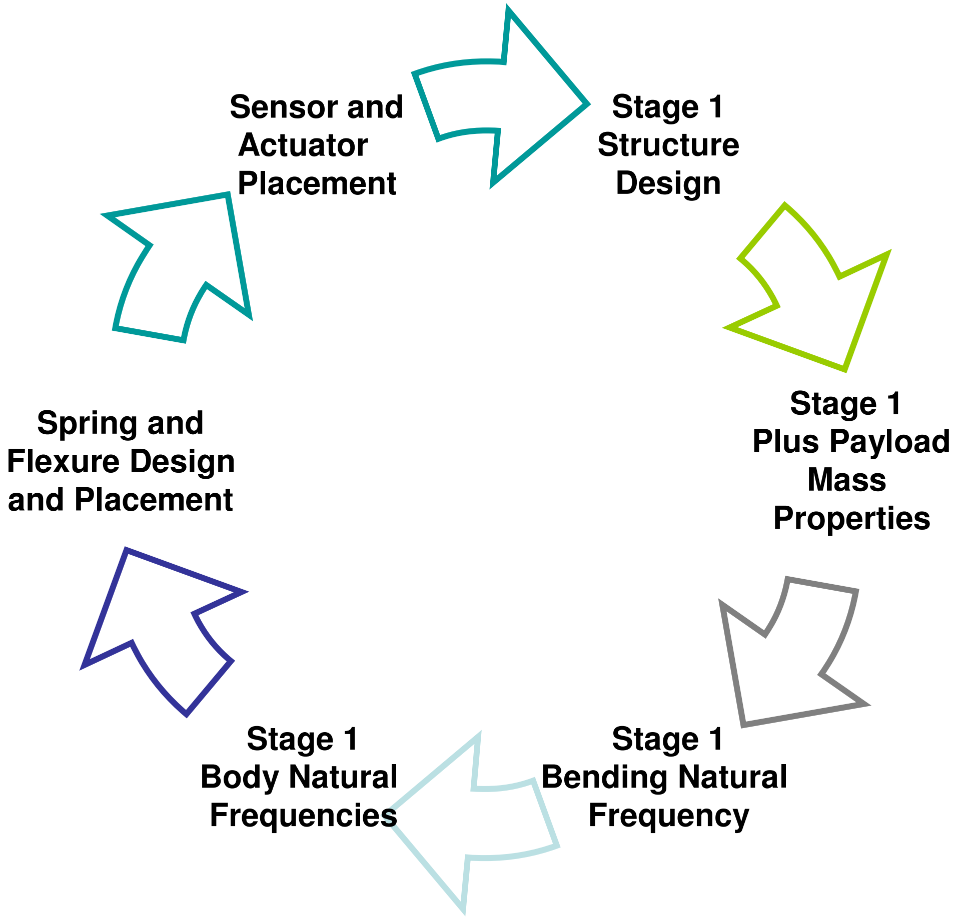
System Design – Overall Approach



Sensor and Actuator Placement

Stage 1 Structure Design

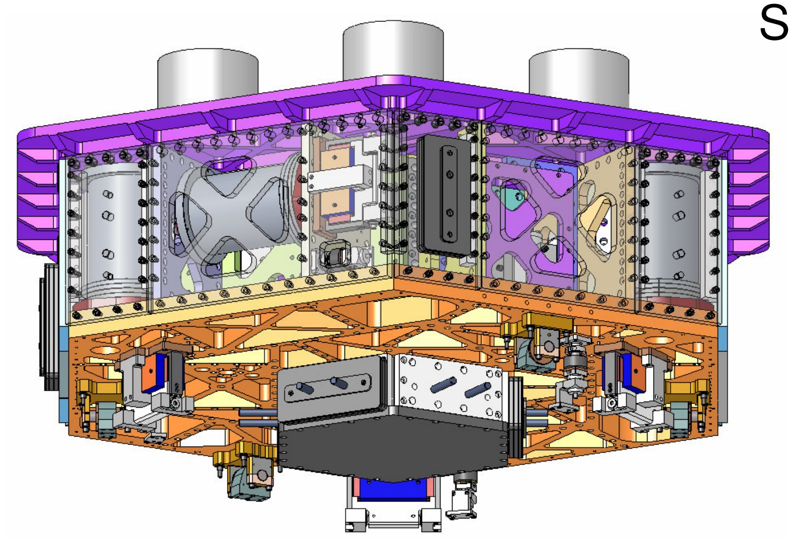
Stage 1 Plus Payload Mass Properties

Stage 1 Bending Natural Frequency

Stage 1 Body Natural Frequencies

Spring and Flexure Design and Placement

Stage 1 Masses



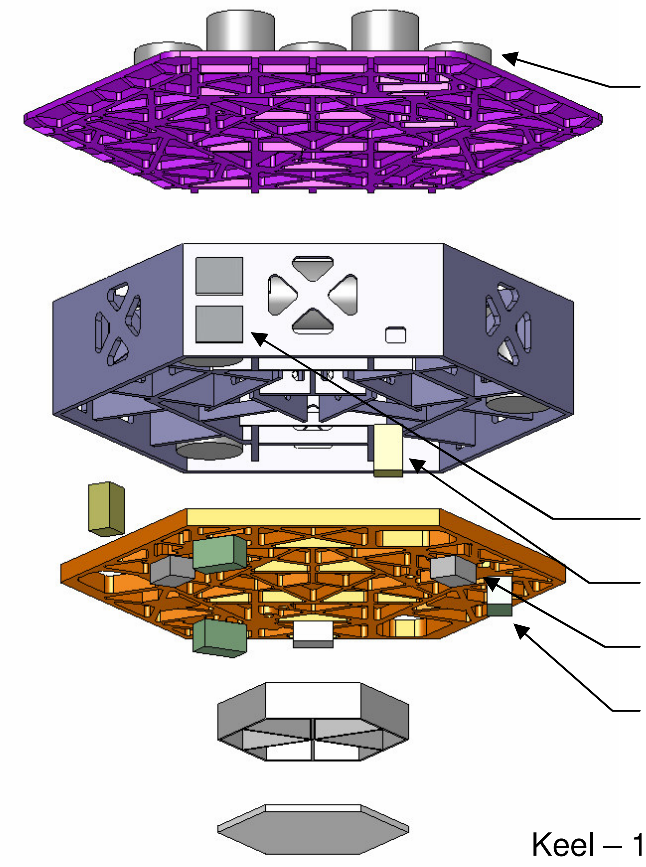
Color Key For All Spreadsheets	
🟩	Entered Value
🟦	Calculation
🟪	Design Value
🟥	Solver - Equation = 0
🟧	Solver - Target Cell
🟨	SW Design Table Values

Mass Properties

CAD model includes sensors, actuators, lockers, and fasteners

Mass and Inertia Properties - From CAD and Estimates			
Gravitational Acceleration (m/s^2)	g	9.81	
Stage 1 Mass (kg) (w/ sensors, actuators, lockers, fasteners) From CAD	ms1	1400	
Adjustment Mass (kg)	mtrim	63	
Additional Mass (GS-13 screws, flexures, pins, helicoils, cables, etc.)	madd	0	
Nonsuspended Payload Mass (kg)	mp	435	
Total Unsuspended Mass (kg)	mu	1898	
Suspended Payload Mass (kg)	ms	75	Payload Scenario 2 150 Kg of mp on keel
Total Mass, Stage 1 With Payload (kg)	mtot	1973	
S1 Polar Moment of Inertia, Tip and Tilt, about CG (Kg*m^2)	Jxx, Jyy	530	
S1 Polar Moment of Inertia, Yaw, about center	Jzz	824	
Center of Gravity from optical table (m)	CG	-0.190	-0.249
LZMP distance from optical table (m)	LZMP	-0.217	-0.217
CG - LZMP offset (positive: CG above LZMP)	h	0.0272	-0.0319
Height of suspended payload above optical table (m)	hs	1	

Stage 1 FEA – Model Setup



Payload – 435 Kg total

Balance/Trim masses – 60 Kg total

Horizontal actuators – 15 Kg each

Lockers/Locators – 3 Kg each

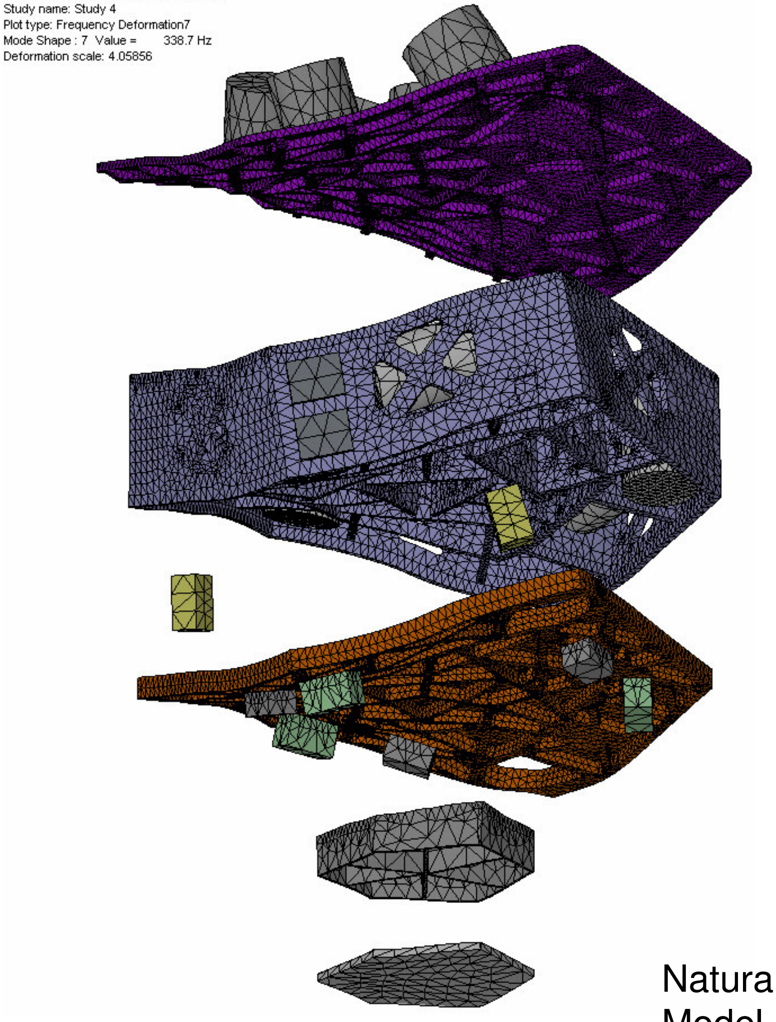
Vertical actuators – 14 Kg each

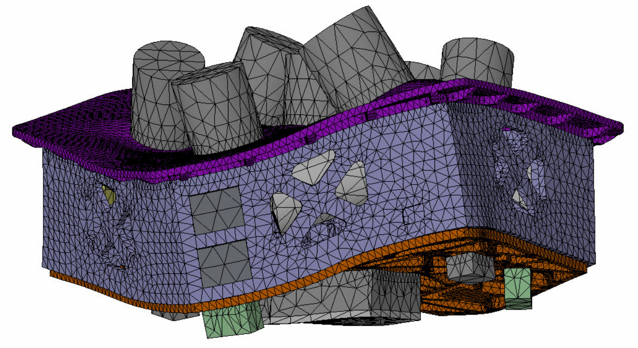
Keel – 101 Kg total

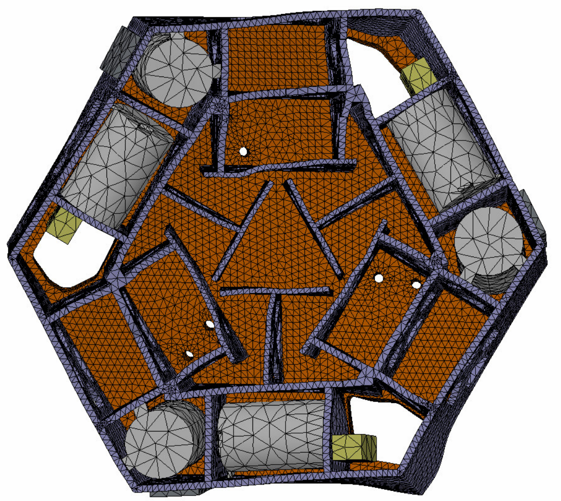
FEA frequency analysis model

- Simplified model – not completely accurate
- Material properties
    - Table, Vertical Plates, Floor, Keel
    - 6061-T6 aluminum
- Balance/Trim masses
    - Stainless steel
    - Modeled with 10% of stiffness (not rigidly mounted)
- GS-13s are connected with tabs at free ends
- Solid mesh
- All parts are globally bonded

Stage 1 FEA – Bending Modes
Nearly current model

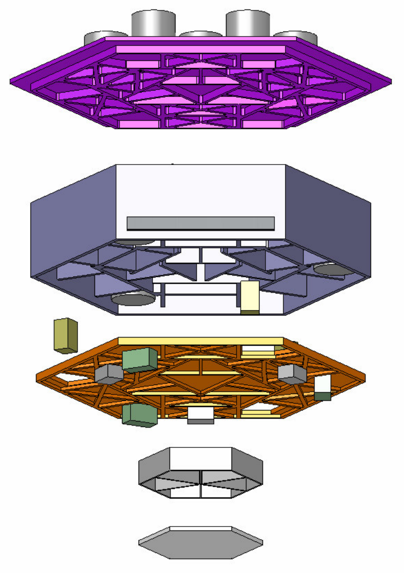


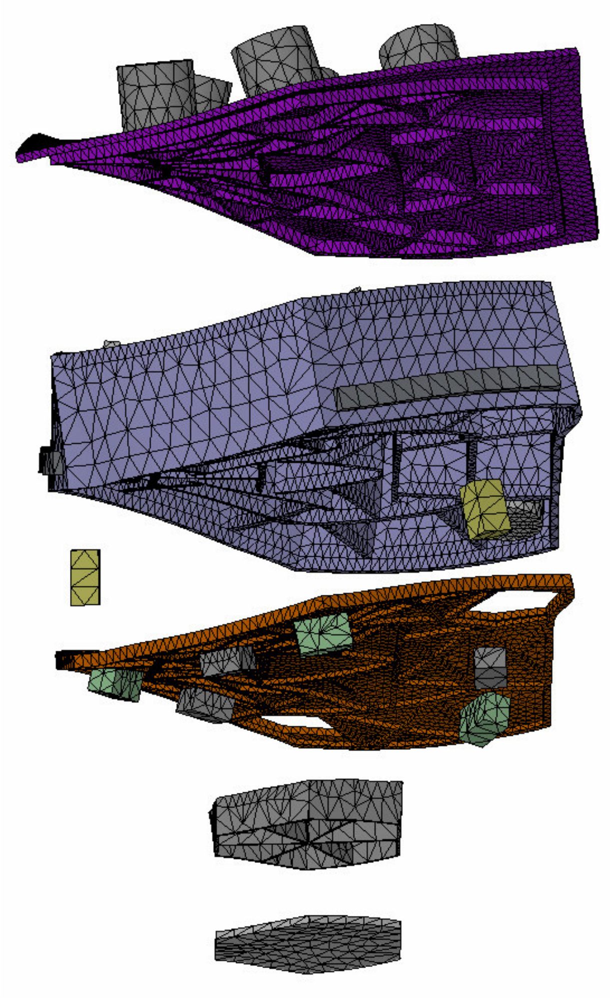




Natural Frequency: 339 Hz
Model mass: 1796 Kg

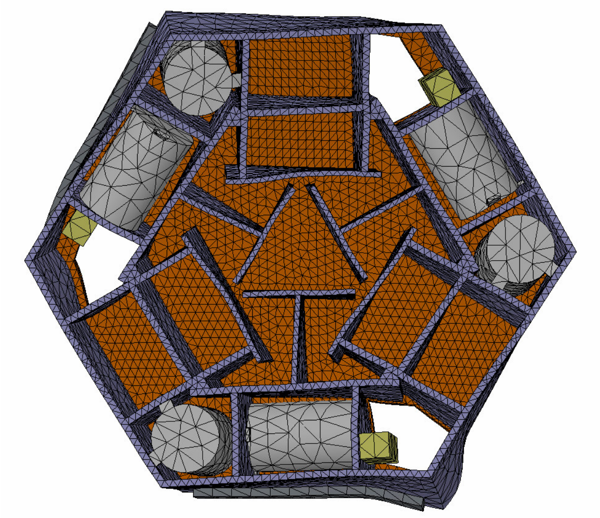
Payload Scenario 1

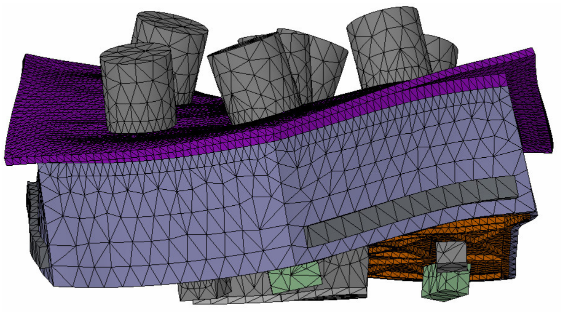




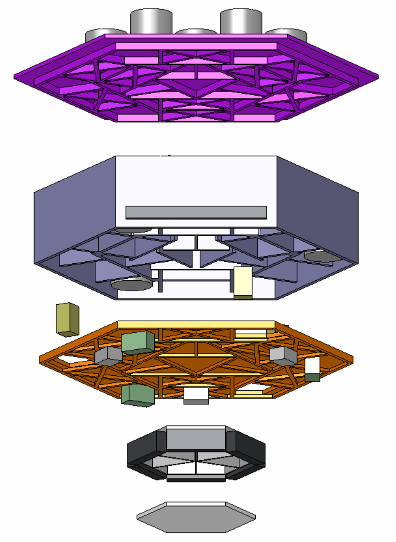
OUTDATED MODEL

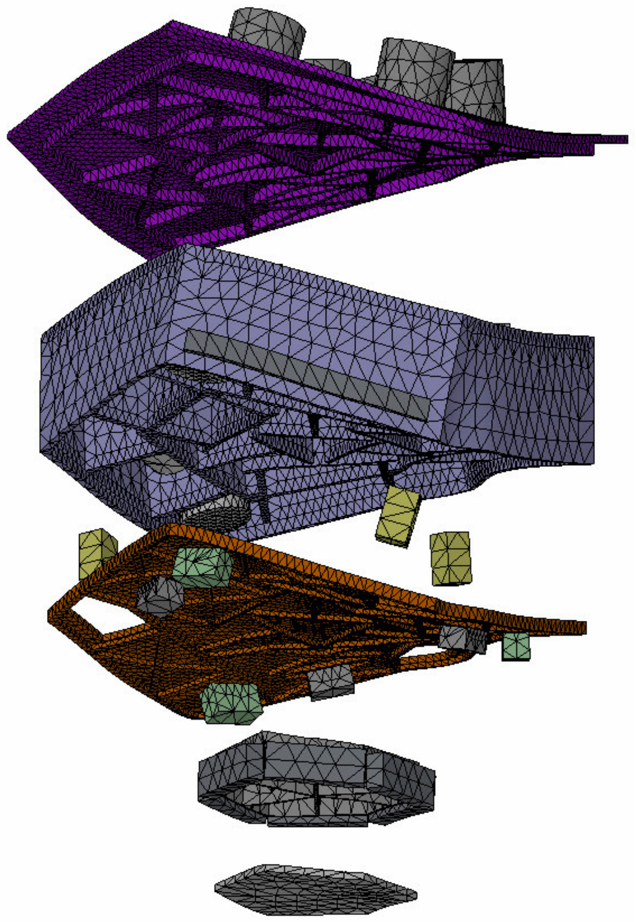
- 435 Kg Payload
- 0 Kg Ballast
- Model Mass: 2014 Kg
- Natural Frequency: 362 Hz
- CG – LZMP offset: 27 mm (CG above LZMP)





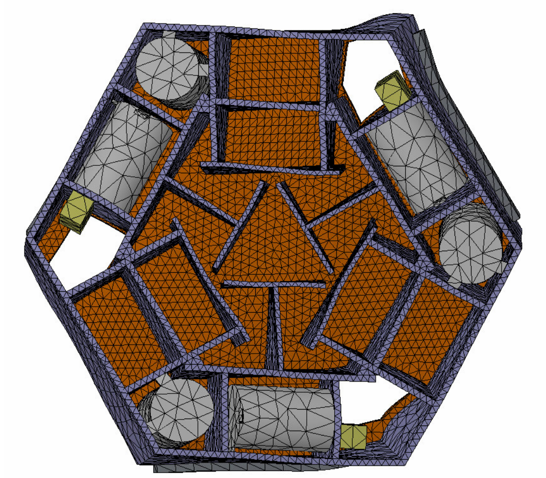
Payload Scenario 2

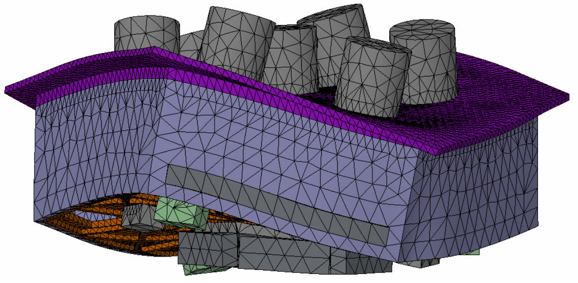




OUTDATED MODEL

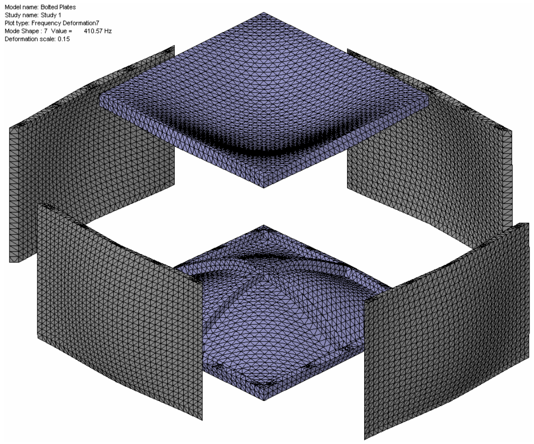
- 285 Kg Payload
- 150 Kg Ballast
- Model Mass: 2014 Kg
- Natural Frequency: 382 Hz
- CG – LZMP offset: -32 mm (CG below LZMP)



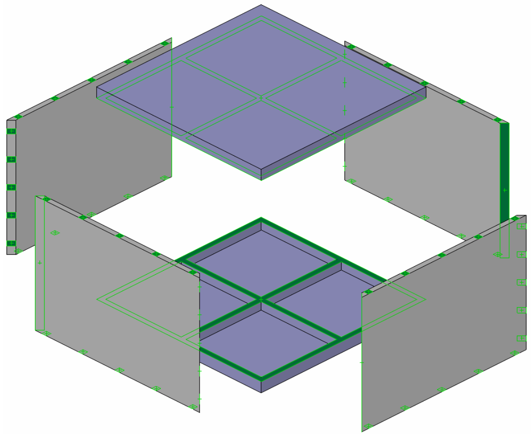


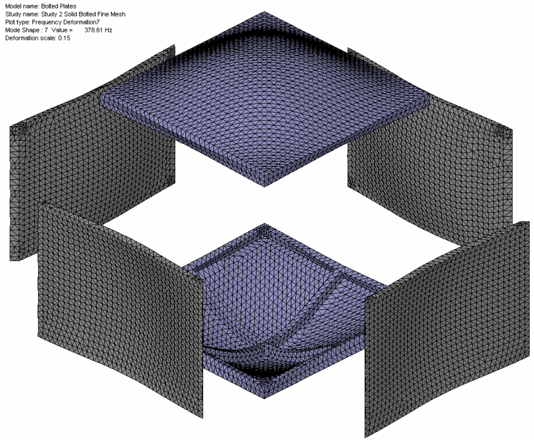
Stage 1 FEA – Modeling Bolted Connections

Frequency analysis validation with solid mesh



Model 1: Globally bonded connections
- 410 Hz Natural frequency
- 8% Higher than Model 2
- 23% Higher than Model 3

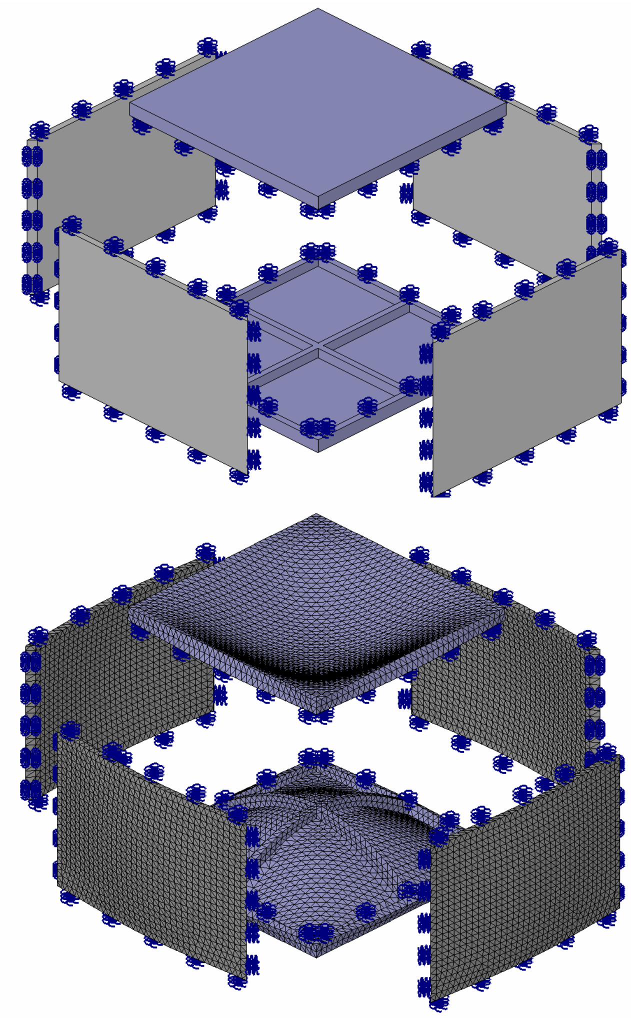




Model 2: Discrete bonded connections
- Represent bolt locations
- 379 Hz Natural frequency

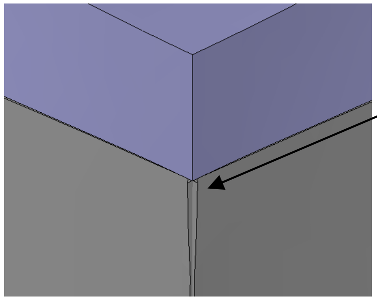
Stage 1 FEA – Modeling Bolted Connections

Frequency analysis validation with solid mesh



Model 3: Discrete spring elements represent bolts

- "No Penetration" contact restraint is not available for COSMOS frequency analysis – part interference reduces natural frequency
- Stiffness equal to that of 3/8" bolt with 1" grip
- 333 Hz Natural frequency
- 19% Reduction from globally bonded Model 1



Part interference is allowed in model
(reduces natural frequency)

Decision (LIGO + HPD 1/23/2007):

Design with 25% margin for bolted connection rigidity + 10% margin for good measure (FEA accuracy, etc.)

Therefore, FEA model must exceed 250 x 1.35 = 338 Hz

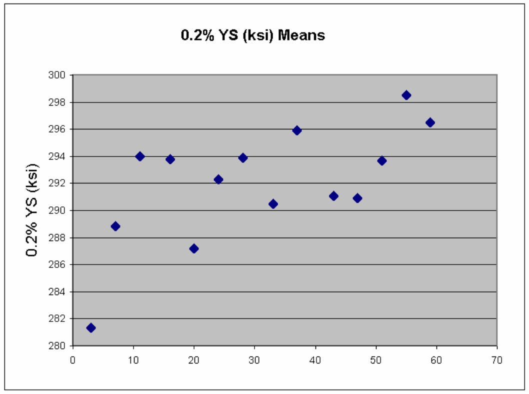
Maraging Steel Material Properties

Vascomax C-300 Tensile Data
Test Data from Allvac, Mark Zaun 803-789-4308, 2/2/2007

ALL YIELD STRENGTH DATA	
Mean (ksi)	292.03
STDEV (ksi)	4.32
N	14
Uncertainty of Mean (%)	0.01%
1σ Uncertainty (%)	1.48%

WITHIN HEAT YIELD STRENGTH DATA	
Mean of Uncertainties	0.70%
STDEV of Uncertainties	0.40%
1σ Uncertainty (%)	1.10%

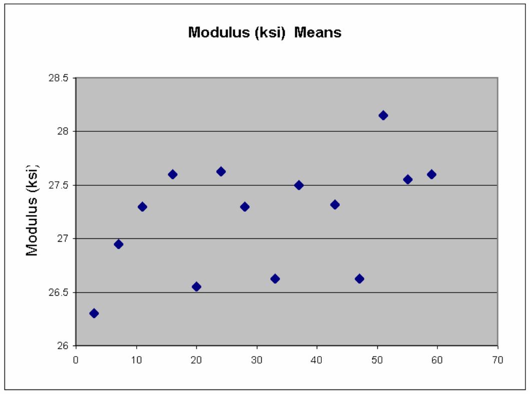
1σ Uncertainty equals 84% confidence that variation is less than this value


0.2% YS (ksi) Means

ALL MODULUS DATA	
Mean (ksi)	27.2137
STDEV (ksi)	0.53
N	14
Uncertainty of Mean (%)	0.01%
1σ Uncertainty (%)	1.93%

WITHIN HEAT MODULUS DATA	
Mean of Uncertainties	1.34%
STDEV of Uncertainties	0.53%
1σ Uncertainty (%)	1.87%

1σ Uncertainty equals 84% confidence that variation is less than this value


Modulus (ksi) Means

Spring and Flexure Material Properties - Maraging 300 steel - AMS6514		
Elastic Modulus (pa) (from VascoMax C300 datasheet)	E	1.876E+11
Poisson Ratio	nu	3.00E-01
Shear Modulus (pa)	GG	7.22E+10
Yield Strength (pa)	Sy	2.014E+09

System Design – Dynamics

Design approach – body vibrational modes

1. Determine stage 1 mass and inertia properties from CAD

2. Choose translational uncoupled natural frequencies, calculate spring and flexure stiffnesses

$$f_{xx} = f_{yy} = 1.32Hz \qquad f_{zz} = 1.80Hz \qquad \omega = 2\pi f$$

$$\text{spring stiffness}: \; k_{zz} = \frac{m_u \omega_{zz}^2}{3} \qquad \text{flexure stiffness}: \; k_{xx} = k_{yy} = \frac{m_u \omega_{xx}^2}{3} = \frac{m_{tot}\, g}{3 l_z}$$

$m_s \equiv$ suspended payload mass

$m_u \equiv$ dynamic mass (stage 1 + unsusp. payload)

$m_{tot} = m_u + m_s$ (static mass)

$l_z \equiv$ effective flexure length

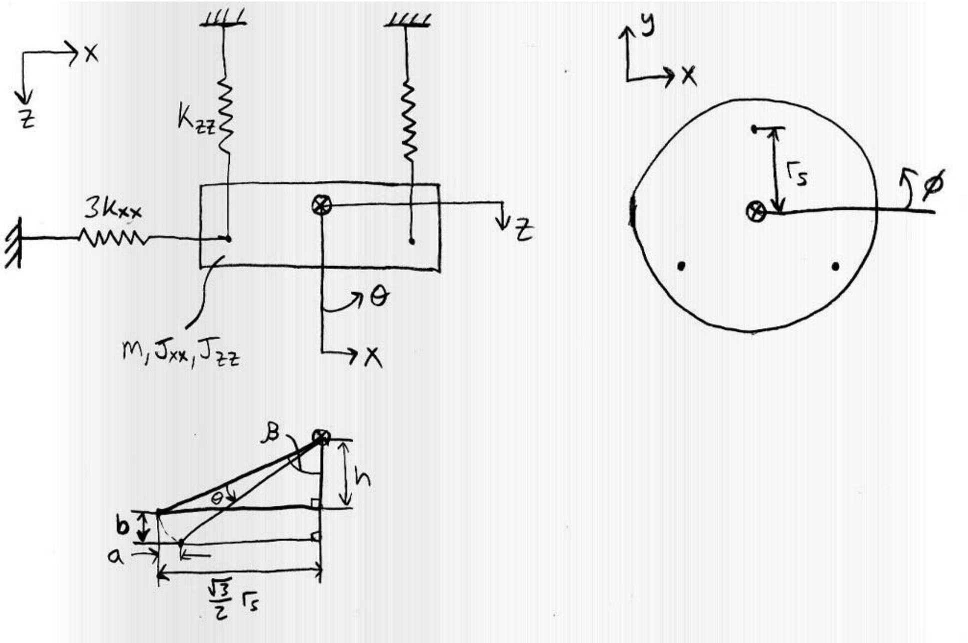
System Dynamics		
Vertical Translation, Z (Hz) **(1.3 - 1.9)**	fzz	1.8
Horizontal Translation, X & Y (Hz) **(1.0 - 1.4)**	fxx	1.32
Spring Tip Radial Position (m)	rs	0.45
Tip and Tilt, RX & RY (Hz) **(0.8 - 1.1)**	frxx	1.07
Yaw, RZ (Hz) **(0.8 - 1.2)**	frzz	0.90
Z Stiffness (N/m)	Kzztot	242773
XY Stiffness (N/m)	Kxxtot	130558
RXY Stiffness (N*m/rad)	Krxxtot	24173
RZ Stiffness (N*m/rad)	Krzztot	26457

3. Choose spring thickness and flexure diameter for allowable stress
   1. Spring and flexure lengths are determined by thicknesses and required stiffnesses

4. Choose spring tip radius r_s such that the rotational natural frequencies are acceptable

6-DOF simplified equation of motion

- Linearized for small displacements
- Assumes massless springs and flexures
- Flexures designed to parallel translate
- Ignores Z – RZ coupling (corkscrew)
- Incorporates S1 CG to LZMP offset (h)
- Includes suspended payload affect on tip/tilt stiffness
- Includes flexure rotational stiffness



$$\mathbf{M}\ddot{\mathbf{U}}+\mathbf{K}\mathbf{U}=\mathbf{0}, \text{ where}$$

$$\mathbf{M}=\begin{bmatrix} m_u & 0 & 0 & 0 & 0 & 0 \\ 0 & m_u & 0 & 0 & 0 & 0 \\ 0 & 0 & m_u & 0 & 0 & 0 \\ 0 & 0 & 0 & J_{xx} & 0 & 0 \\ 0 & 0 & 0 & 0 & J_{yy} & 0 \\ 0 & 0 & 0 & 0 & 0 & J_{zz} \end{bmatrix} \qquad \mathbf{U}=\begin{Bmatrix} x \\ y \\ z \\ rx \\ ry \\ rz \end{Bmatrix}$$

$$\mathbf{K}=\begin{bmatrix} 3k_{xx} & 0 & 0 & 0 & 3k_{xx}h & 0 \\ 0 & 3k_{yy} & 0 & 3k_{yy}h & 0 & 0 \\ 0 & 0 & 3k_{zz} & 0 & 0 & 0 \\ 0 & 3k_{yy}h & 0 & \frac{3}{2}k_{zz}r_s^2+3k_{yy}h^2-m_ugh-m_sgh_s & 0 & 0 \\ 3k_{xx}h & 0 & 0 & 0 & \frac{3}{2}k_{zz}r_s^2+3k_{xx}h^2-m_ugh-m_sgh_s & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{3}{\sqrt{2}}\sqrt{k_{xx}^2+k_{yy}^2}\,r_s^2+3\frac{GJ_f}{l_f} \end{bmatrix}$$

$$h_s \equiv \text{suspended payload height above stage 1 CG}$$

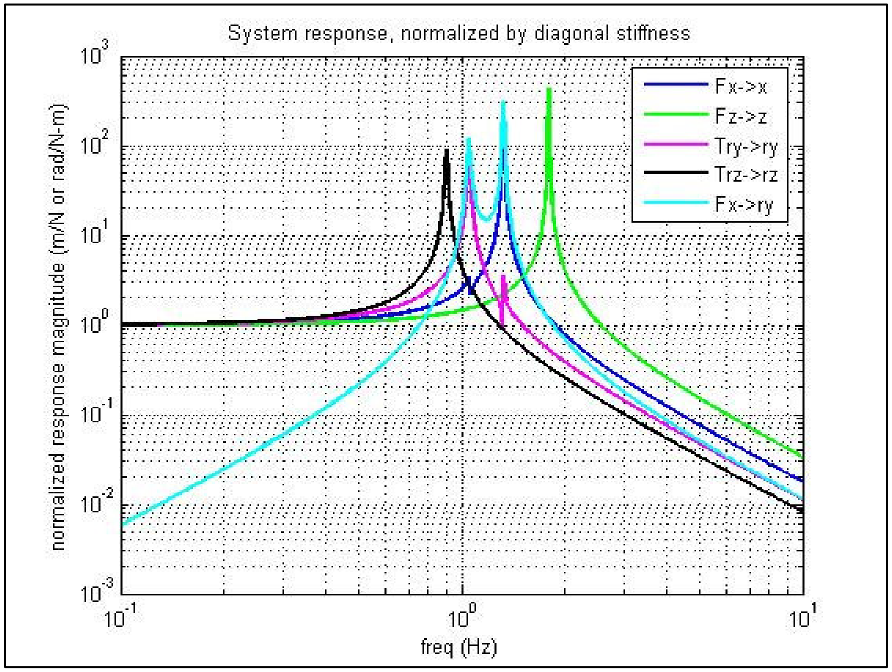
Computation of Natural Frequencies, Mode Shapes, and Frequency Response – Matlab Code

```matlab
% ham_eom_FDR.m
% Program to compute the natural frequencies, mode shapes, and frequency response of the HAM isolation table
% Jonas Waterman, High Precision Devices, 1/12/2007
% Updated with current design values at time of FDR, 3/26/2007
%
% mods by Brian Lantz, Jan 4, 2007
% setup state-space model
% also calculate the tilt-horizontal coupling zero

clear; close all

% System parameters

fzz = 1.8;  % (Hz), Uncoupled natural frequency
mu = 1898;                     % (kg), stage 1 plus "unsuspended" payload mass
ms = 75;   % (kg), "suspended" payload mass
mtot = mu+ms;  % Total static mass
Jxx = 527;                     % (kg*m^2), polar moment of inertia about x (at CG)
Jyy = 533;  % (kg*m^2), polar moment of inertia about y (at CG)
Jzz = 824;                     % (kg*m^2), polar moment of inertia about z (at CG)
g = 9.81;   % (m/s^2), gravitational acceleration

lf = .2032;   % (m), Flexure total length
lz = .1482;   % (m), Flexure effective length
df = .0048;   % (m), Flexure diameter
h = .1;    % (m), Stage 1 plus payload CG offset above flexure LZMP
rs = .45;   % (m), Spring tip radius

E = 1.876E11;    % (N/m^2), Elastic modulus
nu = .3;        % Poisson's ratio
G = E/(2*(1+nu));  % (N/m^2), Shear modulus
Jf = pi*df^4/32;   % (m^4), Flexure area polar moment of inertia
hs = 1;    % (m), Suspended payload height above table

Kzz = mu*(2*pi*fzz)^2/3;  % (N/m), Spring stiffness
Kxx = mtot*g/(3*lz);  % (N/m), Flexure stiffness
Kyy = Kxx;
Krxrx = (3/2)*Kzz*rs^2 + 3*Kxx*h^2 - mu*g*h - ms*g*hs;
Kryry = Krxrx;
Krzrz = 3/2^.5*(Kxx^2+Kyy^2)^.5*rs^2+3*G*Jf/lf;

% Assemble equation of motion matrices and solve eigenproblem

M = diag([mu mu mu Jxx Jyy Jzz]);
K = [3*Kxx 0 0 0 3*Kxx*h 0;
   0 3*Kyy 0 3*Kyy*h 0 0;
   0 0 3*Kzz 0 0 0;
   0 3*Kyy*h 0 Krxrx 0 0;
   3*Kxx*h 0 0 0 Kryry 0;
   0 0 0 0 0 Krzrz];

[V, D] = eig(inv(M)*K);
Natural_frequencies = D.^.5./(2*pi)
Mode_shapes = 1e-5*round(1e5*V)   % truncate the numeric junk
Response_variables = ['X ';'Y ';'Z ';'RX';'RY';'RZ']

num_DOF = length(M);
num_states = 2*num_DOF;
num_inputs = length(M);    % the inputs are forces and torques
```

```matlab
damp = 50*eye(size(M));    % lightly damped
F = [1 0 0 0 0 0;
   0 1 0 0 0 0;
   0 0 1 0 0 0;
   0 h 0 1 0 0;
   h 0 0 0 1 0;
   0 0 0 0 0 1];

A = [zeros(num_DOF)                                  eye(num_DOF);
                       -inv(M)*K                                           -inv(M)*damp];
B = [zeros(num_DOF,num_inputs); inv(M)*F];
C = eye(num_DOF, num_states);                        % returns the first 2 states (x and ry);
D = zeros(num_DOF, num_inputs);

sys = ss(A, B, C, D);
freq = logspace(-1,1,1000);
w = 2*pi*freq;
sys_resp = freqresp(sys, w);
in.Fx = 1; in.Fy = 2; in.Fz = 3; in.Trx = 4; in.Try = 5; in.Trz = 6;
out.x = 1; out.y = 2; out.z = 3; out.rx = 4; out.ry = 5; out.rz = 6;

figure
pp=loglog(freq,3*Kxx*abs(squeeze(sys_resp(out.x,in.Fx,:))),'b',...
   freq,3*Kzz*abs(squeeze(sys_resp(out.z,in.Fz,:))),'g',...
   freq,Kryry*abs(squeeze(sys_resp(out.ry,in.Try,:))),'m',...
   freq,Krzrz*abs(squeeze(sys_resp(out.rz,in.Trz,:))),'k',...
   freq,Kryry/h*abs(squeeze(sys_resp(out.ry,in.Fx,:))),'c');

grid on
set(pp(1),'LineWidth',2);
set(pp(2),'LineWidth',2);
set(pp(3),'LineWidth',2);
set(pp(4),'LineWidth',2);
set(pp(5),'LineWidth',2);

xlabel('freq (Hz)')
ylabel('normalized response magnitude (m/N or rad/N-m)')
title('System response, normalized by diagonal stiffness')
legend('Fx->x','Fz->z','Try->ry','Trz->rz', 'Fx->ry')

%%%%%%%%%%
% Calculate the tilt-horizontal coupling zero (Brian Lantz)

act_offset = 1e-3;           % m offset of horz acts and LZMP
tilt_horz_coupling_zero = 1/(2*pi) * ...
                             sqrt(act_offset * g * 3*Kxx/Kryry)
% this is the frequency at which the horz seismometers
% see as much signal from the tilt (theta) of the stage as from
% the translation (x) of the stage.
% x = F / (3*Kxx)      (total horz stiffness is 3*Kxx)
% theta = (F*act_offset) / Kryry
% set (g/w^2) * theta = x, and solve for w
% we can also set f = 2*pi*w = 50 mHz, and solve for
% the ratio of the total horizontal stiffness over the rotational stiffness
% (.05*2*pi)^2/(1e-3*9.81) = 10.061 m^-2
```

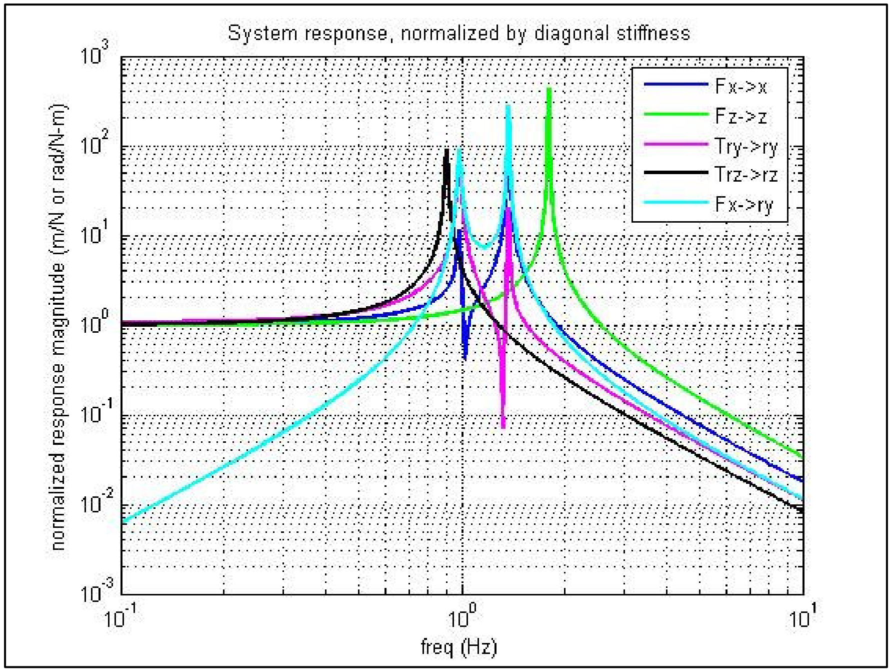
System Frequency Response – Body Modes

CG – LZMP offset: h = .027m (Payload scenario 1)



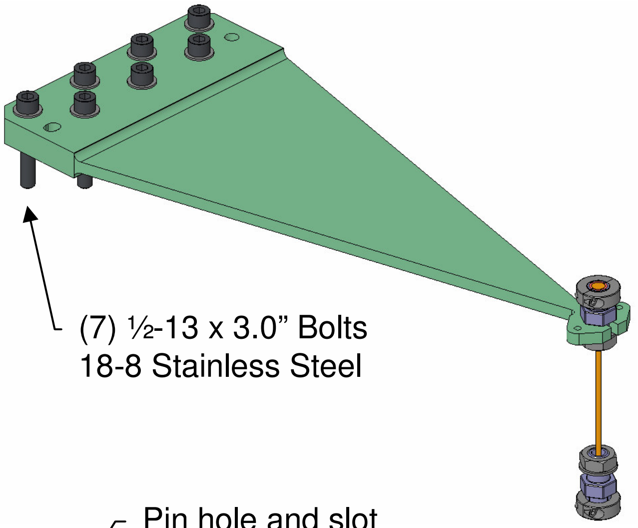
	Natural Frequencies (Hz)					
	1.3249	0	0	0	0	0
	0	1.0495	0	0	0	0
	0	0	1.325	0	0	0
	0	0	0	1.0554	0	0
	0	0	0	0	1.8000	0
	0	0	0	0	0	0.9026
	Mode Shapes					
X	0.9675	0.0732	0	0	0	0
Y	0	0	-0.9656	-0.0746	0	0
Z	0	0	0	0	1	0
RX	0	0	-0.2601	0.9972	0	0
RY	0.2528	-0.9973	0	0	0	0
RZ	0	0	0	0	0	1

h = .1m (max allowable offset)



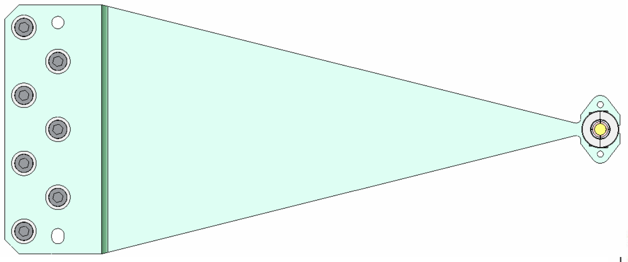
	Natural Frequencies (Hz)					
	1.3720	0	0	0	0	0
	0	0.9835	0	0	0	0
	0	0	1.3732	0	0	0
	0	0	0	0.9882	0	0
	0	0	0	0	1.8000	0
	0	0	0	0	0	0.9026
	Mode Shapes					
X	0.7808	0.2192	0	0	0	0
Y	0	0	-0.7736	-0.2218	0	0
Z	0	0	0	0	1	0
RX	0	0	-0.6337	0.9751	0	0
RY	0.6248	-0.9757	0	0	0	0
RZ	0	0	0	0	0	1

Spring and Flexure Assembly

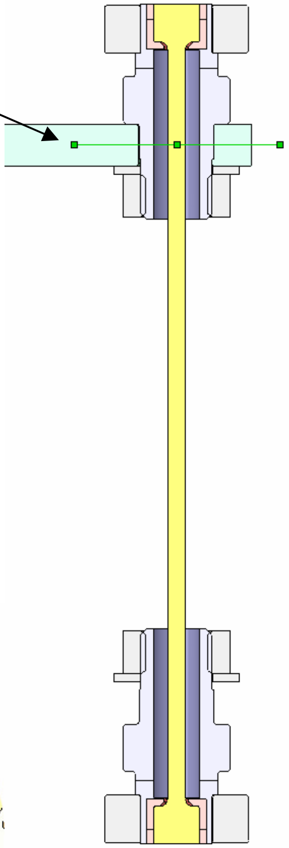


(7) ½-13 x 3.0” Bolts
18-8 Stainless Steel

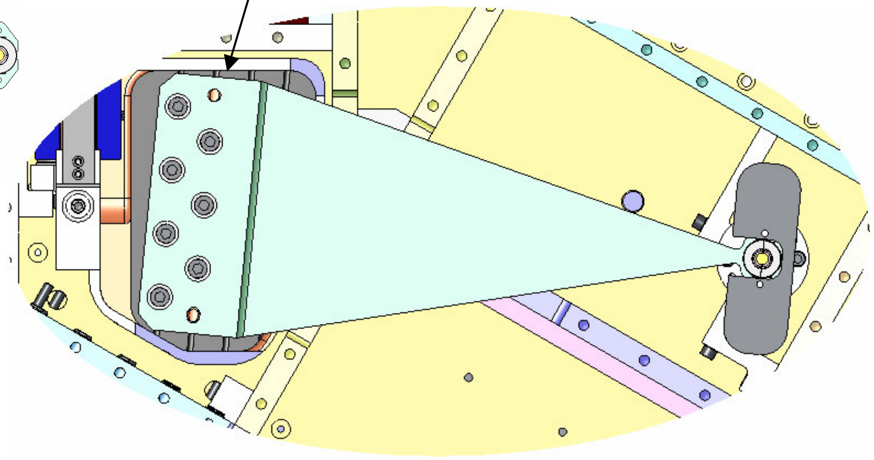
Pin hole and slot
for positioning



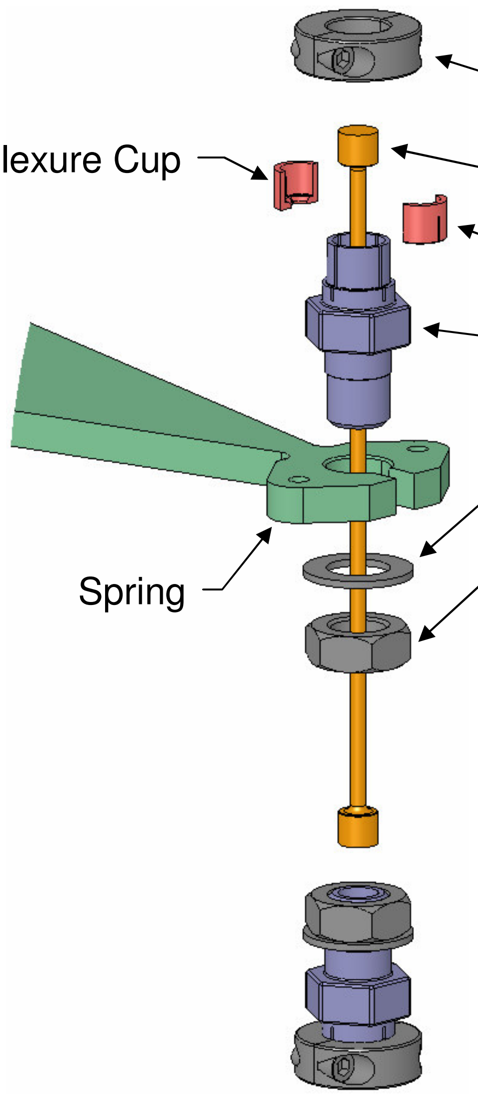
UZMP aligned with
Spring neutral plane



Spring and mounting design have
flexibility for accommodating future
Spring design changes if necessary



Flexure Termination



Lock Collar

Flexure Cup

Flexure

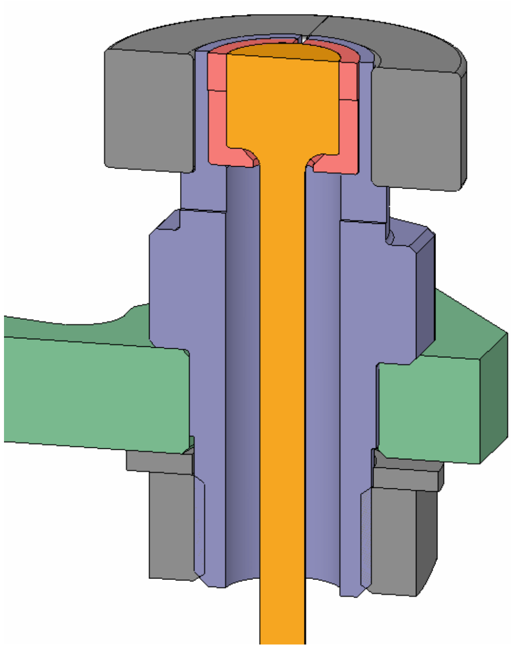
Flexure Cup

Flexure Mount

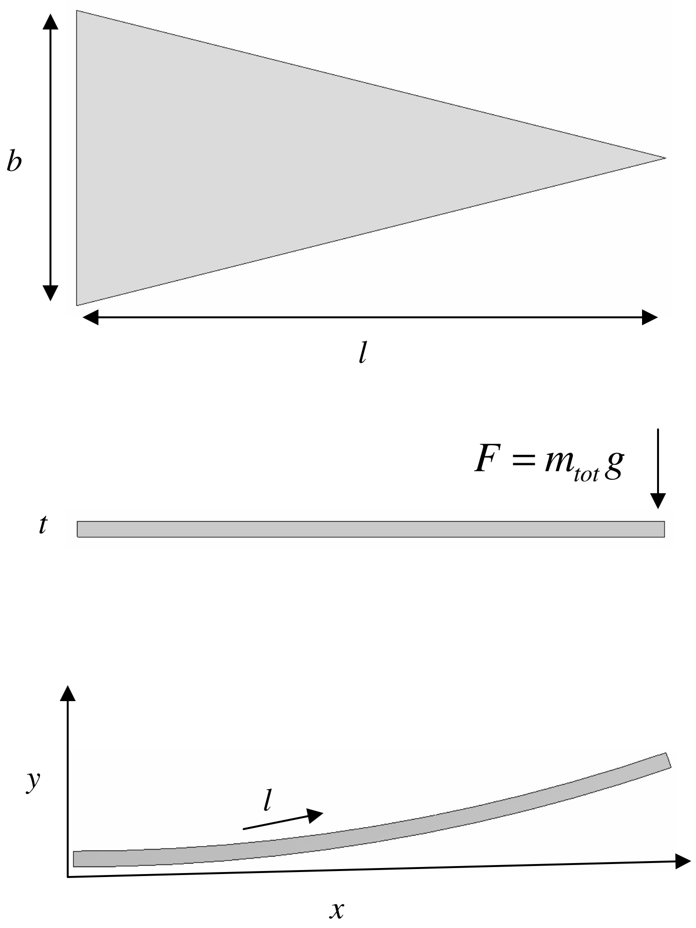
Flat Washer

Jam Nut

Spring



Spring Design



Triangular cantilever spring

- Uniform stress distribution – desirable design
- From simplified bending:

$$y = \alpha x^2 \qquad \alpha = \frac{6Fl}{Ebt^3} \qquad k_{zz} = \frac{Ebt^3}{6l^3} \qquad \sigma = \frac{6FlK_b}{bt^2}$$

$K_b \equiv$ bending stress concentration factor at base fillet

Design Approach

- Choose $\frac{b}{l} = \frac{1}{2}$ then $\alpha = \frac{12F}{Et^3}$

- Choose *t* such that maximum stress is satisfied

$$t = \sqrt{\frac{12FK_b}{\sigma_{\max}}}$$

- Calculate *l* for required k_{zz}

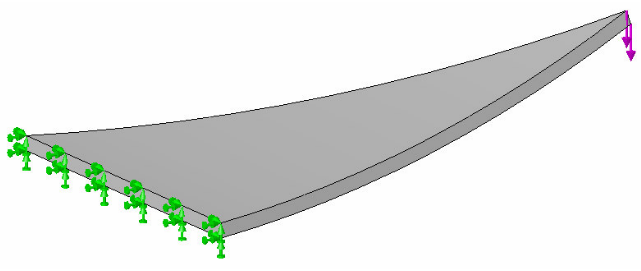
$$k_{zz} = \frac{Et^3}{12l^2} \qquad l = \sqrt{\frac{Et^3}{12k_{zz}}}$$

Spring Design

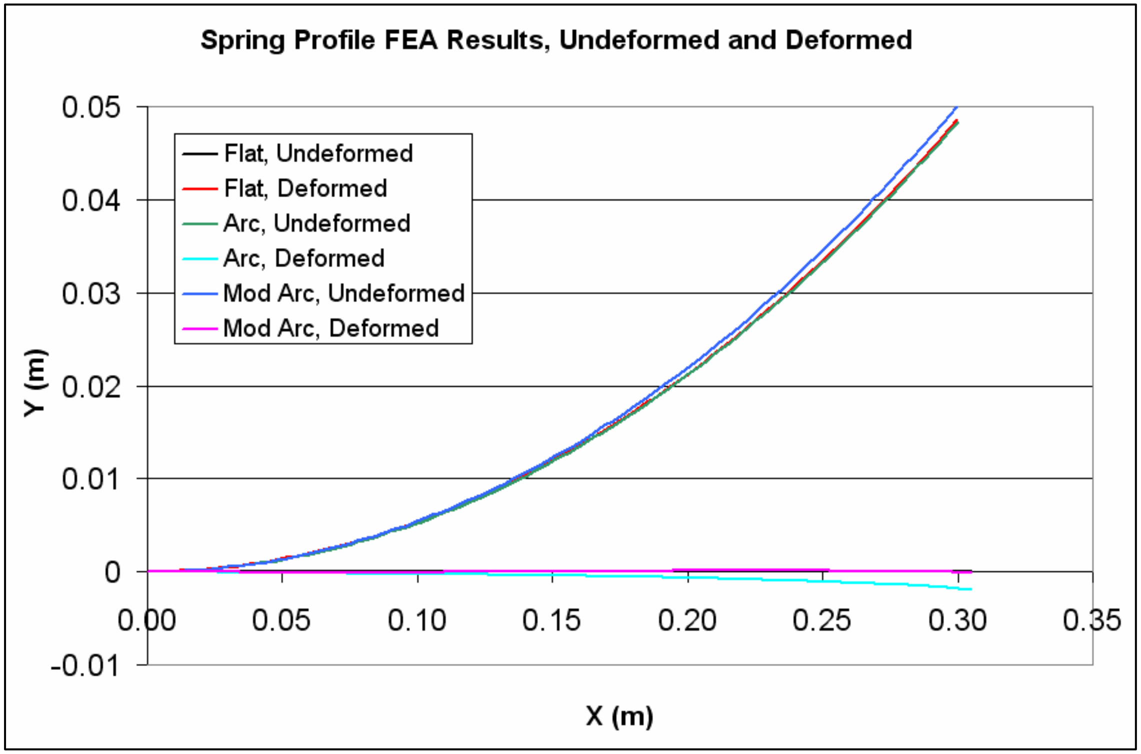
Issue: The deformed profile of an initially flat spring is not the ideal profile for the undeformed HAM spring

- This is due to the horizontal displacement of the spring tip (which changes the moment arm of the force)

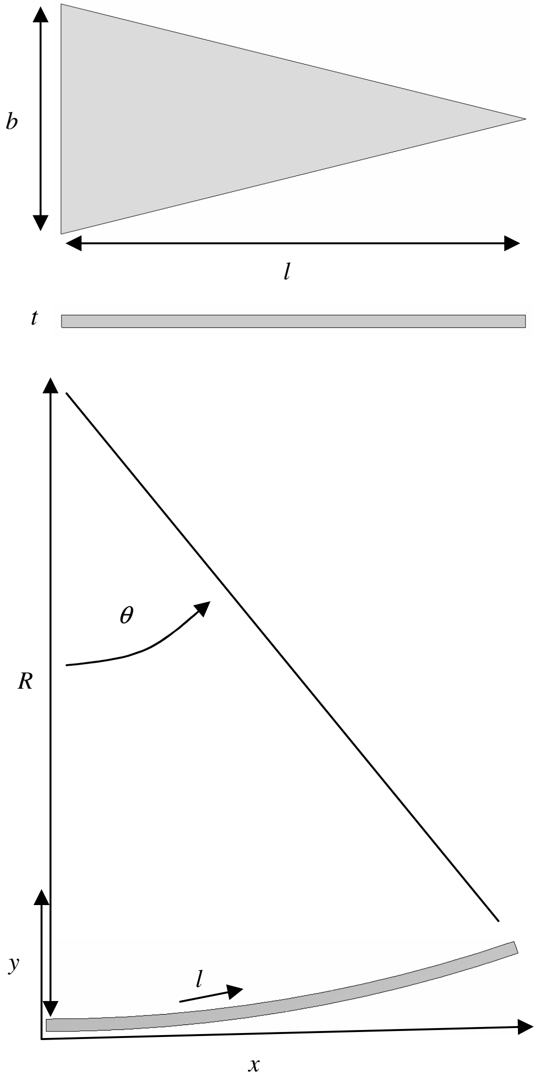
Solution: Modify the undeformed spring profile: $y = \alpha l^2$, not $y = \alpha x^2$, where l is the length along the spring



Idealized geometry



Spring Design



Determine spring profile

- Ideal profile – solve for *x* at tip:

$$y = \alpha l^2$$

$$l = \sqrt{\frac{Et^3}{12k_{zz}}} = \int \sqrt{1+\left(\tfrac{dy}{dx}\right)^2}\,dx = \frac{x\sqrt{(2\alpha x)^2+1}}{2} + \frac{\ln\left(\sqrt{(2\alpha x)^2+1}+2\alpha x\right)}{4\alpha}$$

- Arc approximation – fit arc to ideal profile end points – solve for *R, θ*

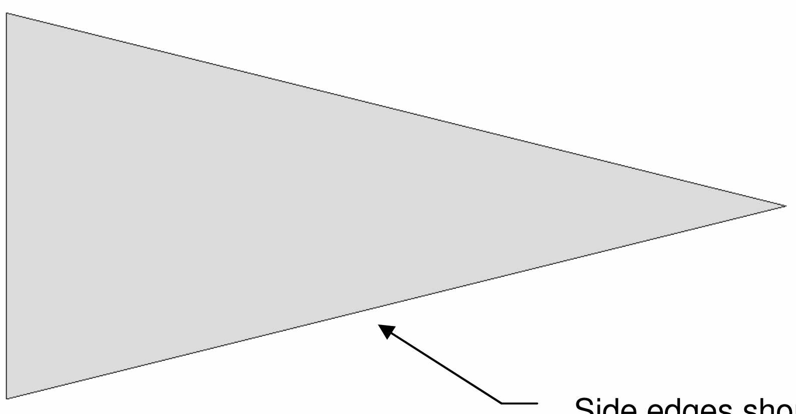
$$\theta = \sin^{-1}\left(\frac{x}{R}\right) \qquad y = \frac{F}{k_{zz}} = R(1-\cos\theta) \qquad R = \frac{F}{k_{zz}(1-\cos\theta)}$$

Spring Design

Issue: Spring must be triangular in shape when flat

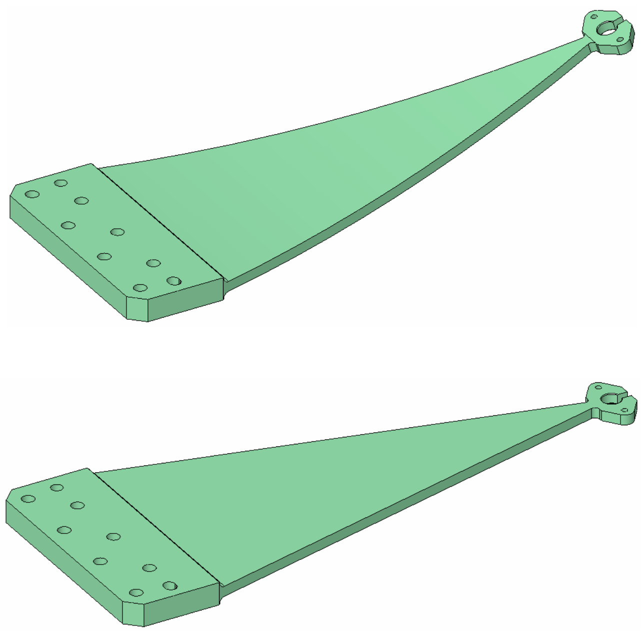
Solution: Proper CAD modeling

Improper modeling could result in a spring with curved edges in the loaded state



Side edges should be straight
when spring is flat

Spring Design



Deviations from idealized model

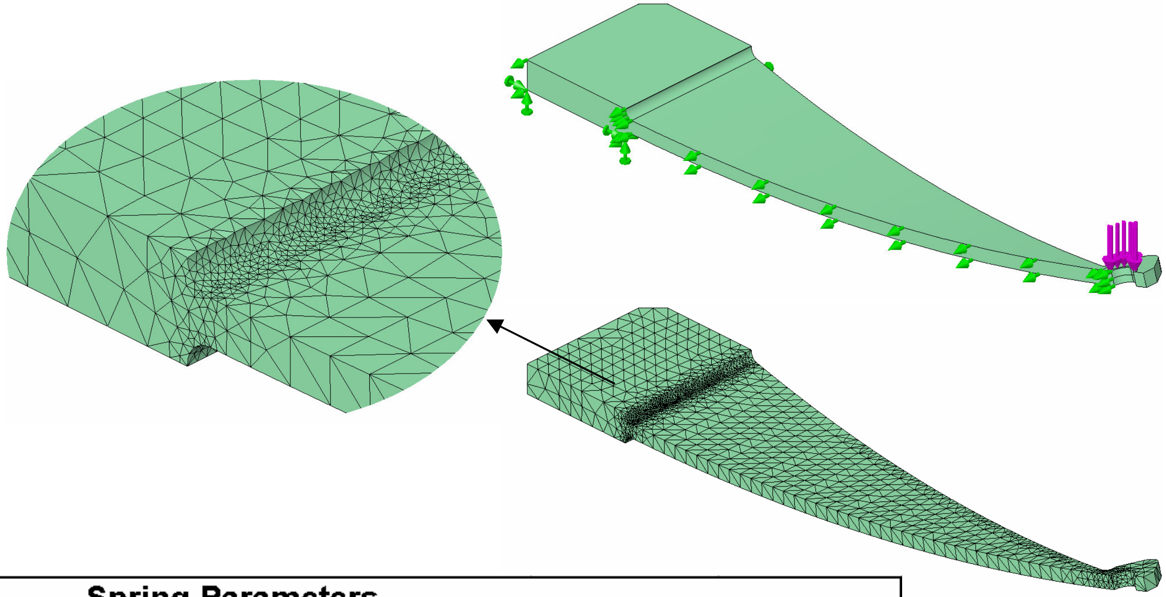
- Transverse bending (Poisson effect)
    - Causes uneven stress distribution
    - Reduces spring stiffness
- Base and base fillet
    - Stress concentration
    - Increases spring stiffness
- Base termination
    - Not rigidly constrained
    - Reduces effective spring stiffness
- Tip geometry
    - Stress concentration
    - Increases spring stiffness

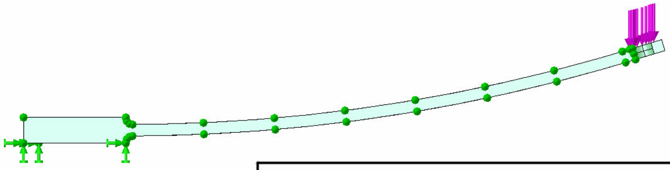
FEA results will be used for the final design iteration and verification

Spring Design – FEA

FEA static analysis model

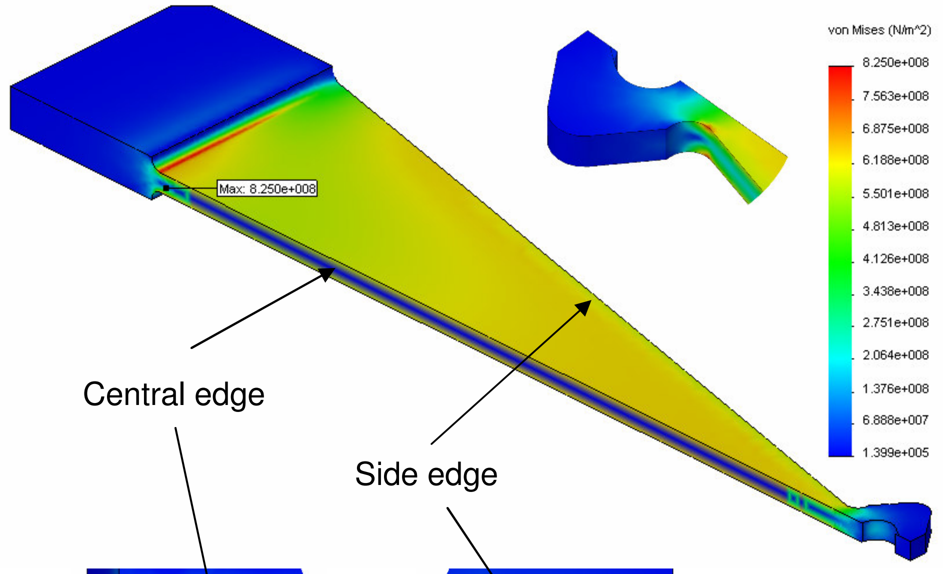
- Material properties
    - Maraging 300 steel
- Solid mesh
    - h-adaptive refinement
- Analyze ½ of model based on symmetry
- Bottom of base is fixed
- Force is applied to tip in vertical direction
- Iterative solution for large displacements

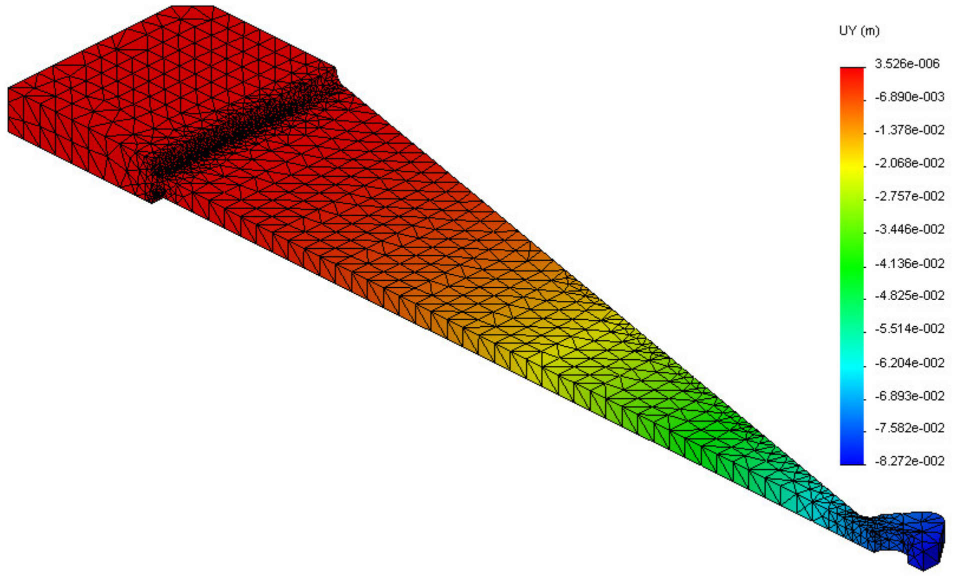




Spring Parameters		
Increased stiffness design value	add_Kzz	3.00%
Stiffness (N/m)	Kzz	83352
Thickness (m)	t	0.0112
Base Width (m)	b	0.2567
Length (m)	l	0.5134
Equilibrium Load (N)	F	6451.71
Equilibrium Deflection (m)	d	0.0774
Global max fiber stress, theoretical (N/m^2)	sigma	6.17E+08
Global max fiber stress % of yield	%yield	30.65%
Worst Case max fiber stress % of yield - from uncertainty analysis	worst %yield	32.27%
Max % of yield	%yield	40.98%

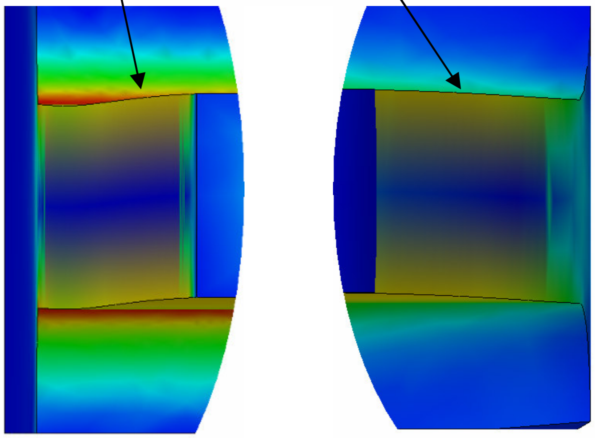
Spring Design – FEA





Central edge

Side edge

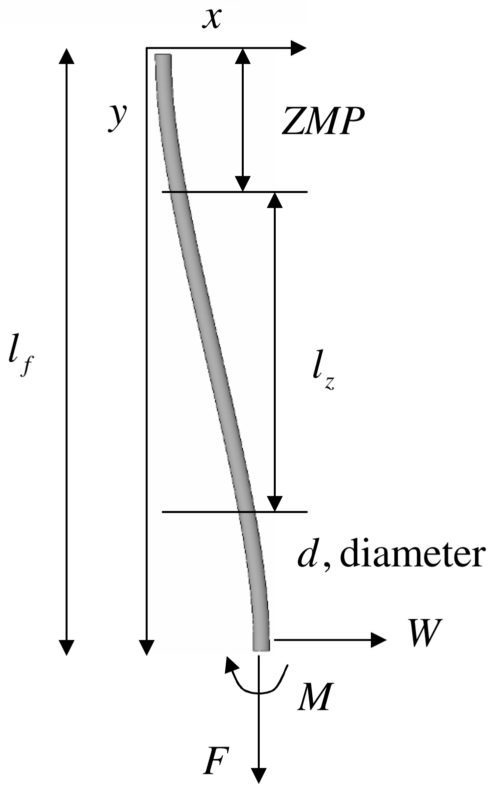


Edges have small curvature
(views from tip - 1 ° from normal)

FEA results

- Nominal fiber stress (calculated): 6.17E8 N/m^2
  - 30.7% of yield strength
- Maximum stress at base fillet (from FEA): 8.25E8 N/m^2
  - 41.0% of yield strength
- FEA vertical stiffness K_{zz} is 0.9% greater than theory predicts
  (but the FEA model restraints are better than actual)

Flexure Design – Analytical Model



$$M = \frac{W}{k}\tanh\left(\frac{kl_f}{2}\right)$$

$$k = \sqrt{\frac{F}{EI}} \qquad I = \frac{\pi d^4}{64}$$

$$ZMP = \frac{1}{k}\tanh\left(\frac{kl_f}{2}\right)$$

$$l_z = l_f - 2ZMP$$

Design Approach

- Horizontal natural frequency determines k_{xx}, W, and l_z

$$W = k_{xx}x_{\max}$$

- Choose d such that maximum stress at $x_{max} = 2\ mm$ is satisfied
  - Consider max stresses at outer surface

$$\sigma_{axial} = \frac{F}{A} \qquad A = \frac{\pi d^2}{4} \qquad \sigma_{bending} = \frac{Md}{2I} \qquad \tau_{torsion} = \frac{Gdx_{\max}}{2l_f r_s}$$

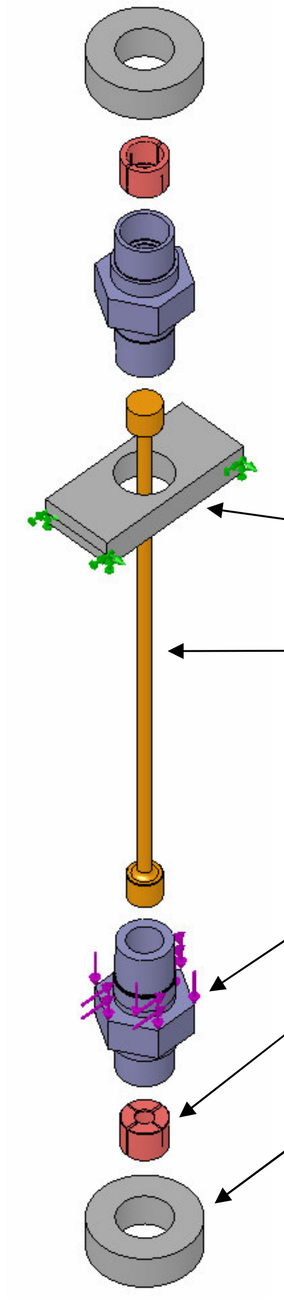
$$\sigma_{\max} = \sqrt{\left(\sigma_{axial} + K_f\sigma_{bending}\right)^2 + 3\tau_{torsion}^2}$$

$$K_f \equiv \text{bending stress concentration factor at fillet}$$

- Solve for l_f (iterate d for σ_{max} if necessary)

$$x = \frac{1}{F}\left[Wy - \frac{M + M\cosh kl_f}{\sinh kl_f}\sinh kx + M\cosh kx - M\right]\Bigg|_{x=x_{\max}=1mm}$$

Flexure Design – FEA



FEA Fixture
Unobtainium

Flexure
Maraging 300

Flexure Mount
17-4 PH H1150

Flexure Cup
Maraging 300

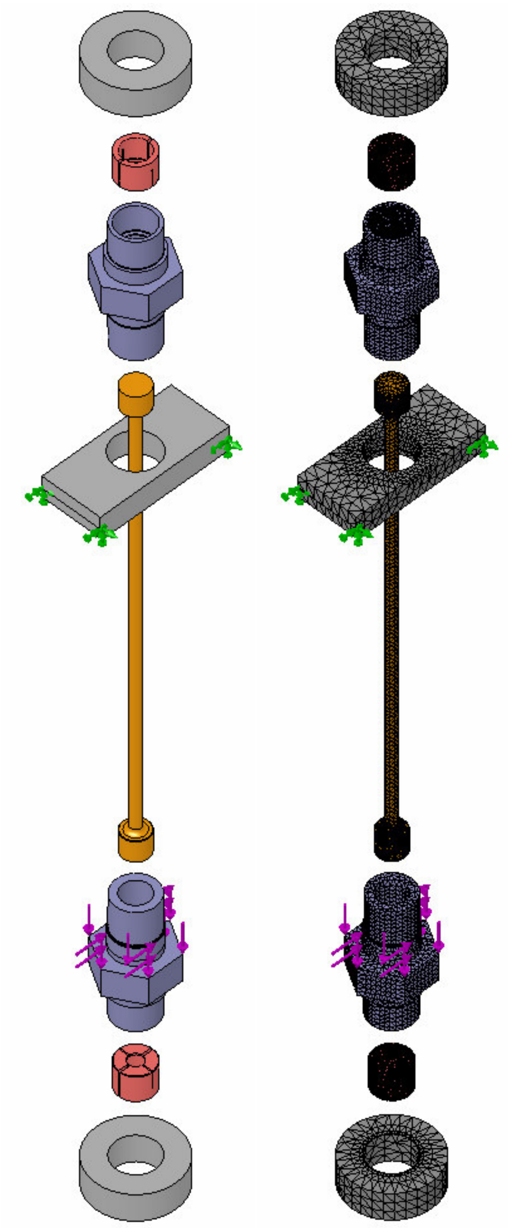
Shaft Collar
303 Stainless Steel

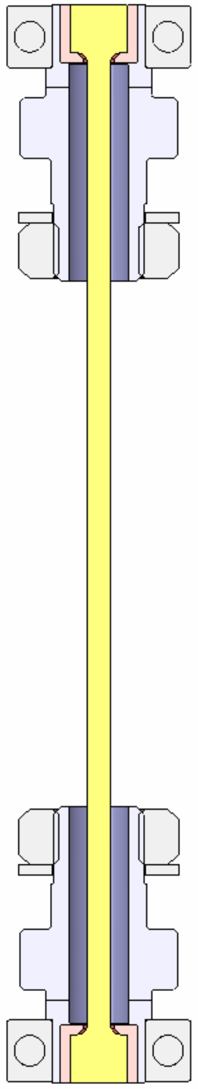
FEA ZMP and Flexure stress analysis model

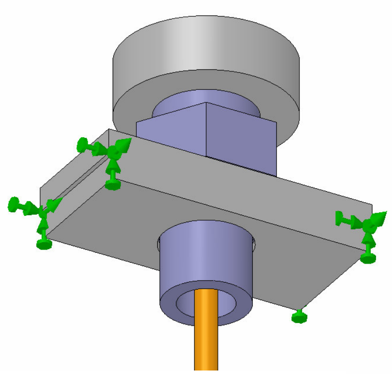
- Complete Flexure Assembly
- Solid mesh - refined at stress concentrations
- All parts are globally bonded
- Loads are calculated from analytical model
    - Axial and Horizontal forces are applied to Flexure Mount
- Reaction moment at FEA Fixture is measured (should be zero!)
- Iterative solution for large displacements

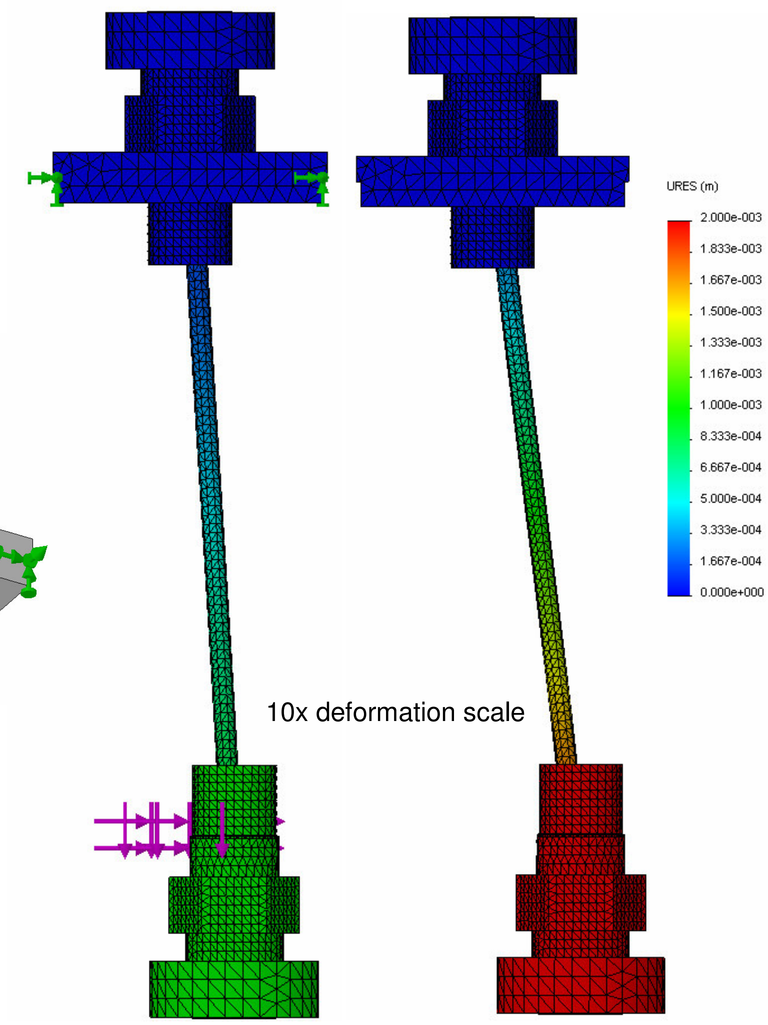
Flexure Parameters		
Horizontal Stiffness (N*m/rad)	Kxx	43519
Length, including fillets (m)	lf	0.20324
Diameter (m)	df	0.0048
Fillet Radius (m)	rf	0.002
Axial Load (N)	F	6451.71
Horizontal range of motion (one direction) (m)	xmax	0.002
Horizontal Load (N)	W	87.0387
Moment at ends (N*m)	Mmax	2.3931
Axial Moment (N*m)	Maxial	0.0822
Zero Moment Point, distance from end (m)	ZMP	0.02749
Effective Length (distance between ZMPs) (m)	lz	0.1482
Axial Displacement, Tip (m)	dl	0.00039
Global max fiber stress, theoretical (N/m^2)	sigma	5.87E+08
Global max fiber stress % of yield	%yield	29.13%
Max % of yield	%yield	34.42%

Flexure FEA – ZMP Determination





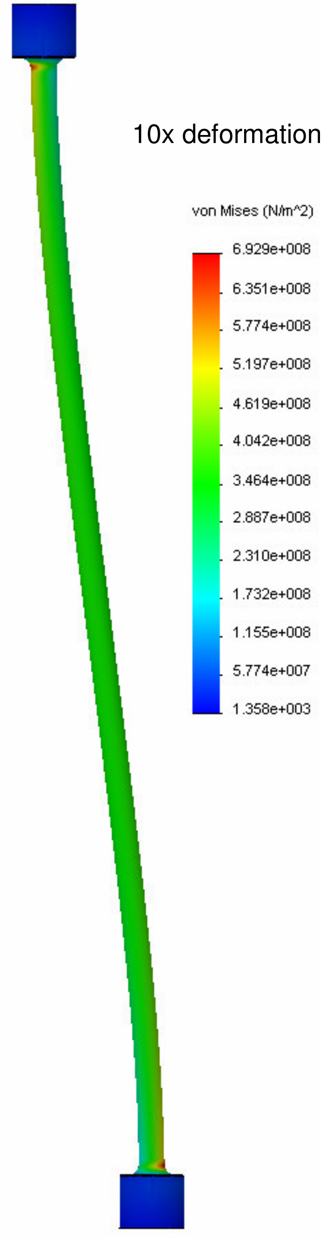


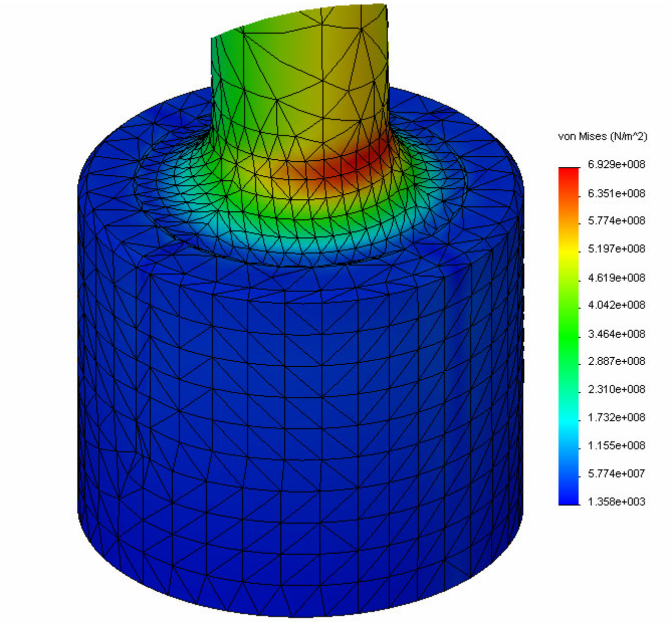


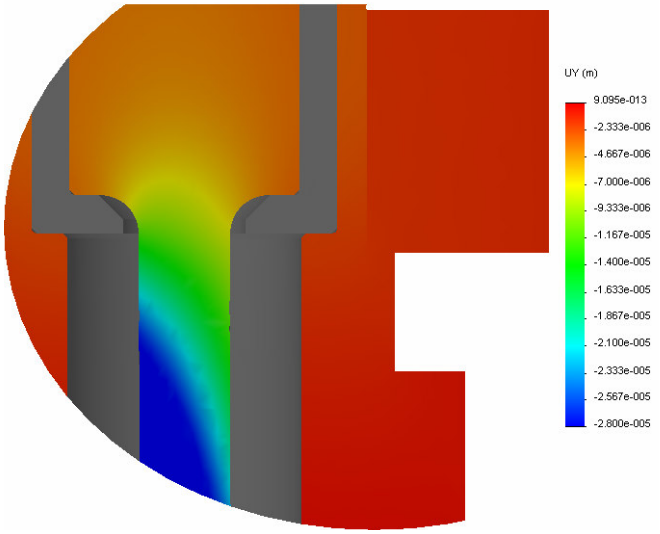
Xmax = 1 mm

Xmax = 2 mm

Flexure FEA – Stress

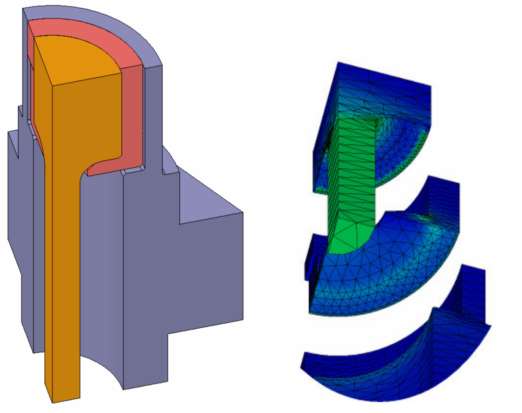






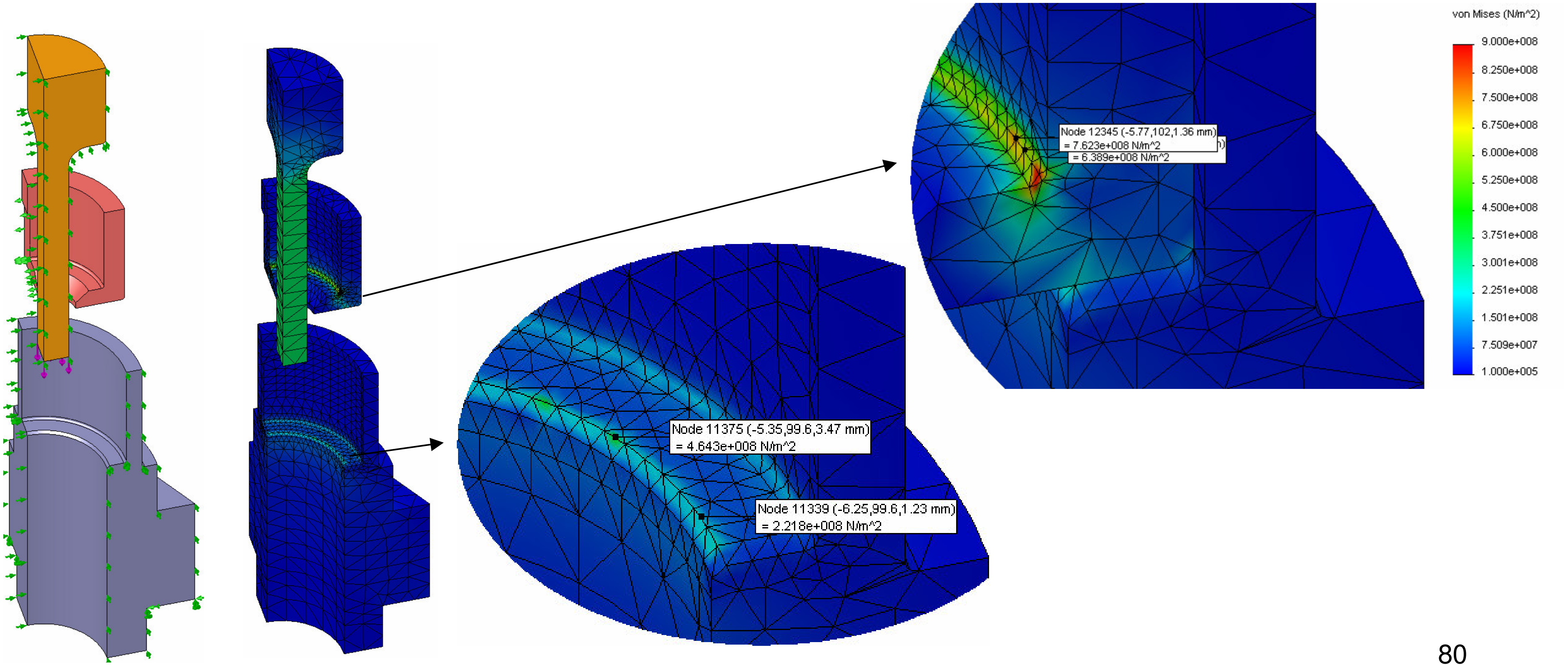
Flexure Assembly FEA		
FEA-Determined ZMP (m)	ZMP FEA	0.02745
Difference from analytical model (m)	ZMP Error	-0.00005
Flexure max stress - at fillet		6.93E+08
Maraging 300	%yield	34.42%
Flexure Cup max stress - at fillet		7.00E+08
Maraging 300	%yield	34.77%
Flexure Mount max stress - at contact surface		4.00E+08
17-4 PH H1150 yield strength (N/m^2)	Sy	8.69E+08
	%yield	46.05%

Flexure Assembly FEA – Stress



FEA contact analysis model

- Solid mesh
    - Refined mesh controls at stress concentrations
- Analyze ¼ of model based on symmetry
- Contact constraint: no penetration (parts can slide, not bonded)
- Flexure Mount flange surface is fixed
- Axial force is applied to bottom surface of Flexure (neglect horizontal force and moment)



Uncertainty & Sensitivity Analysis

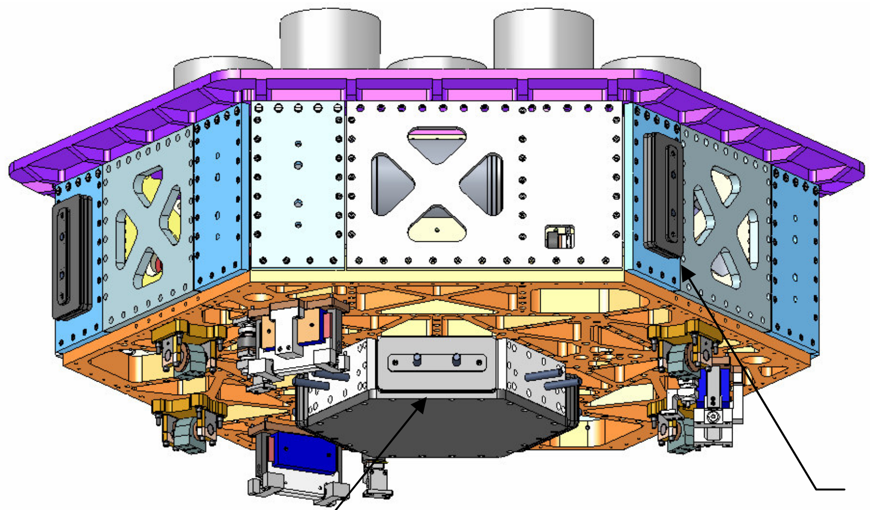
Determine the spring stiffness uncertainty (U_Kzz) in order to design adjustment mass quantities and increments

- Sources of uncertainty in Kzz
  - Material properties – ~2%
  - Fabrication tolerances – small effect
  - Spring FEA vs. reality – up to a few %
- LIGO/HPD decisions from meeting 2/13/2007
  - Use U_modulus = 3.0%, U_yield = 2.0% for design
    - These values account for random errors (materials + fabrication tolerances)
  - Design spring such that Kzz is 3.0% high
    - This is intended to account for systematic error in the design methodology – FEA restraints are too ideal, FEA converges from stiff side
- It is not necessary to make all springs from the same material lot
  - The material property uncertainties across all lots and within a single lot are very similar
  - Adjustment mass plan can accommodate stated uncertainties
  - HOWEVER, this method could result in the spring neutral axis being less straight and level at equilibrium (probably OK)

Spring and Flexure Sensitivity to Material Properties

		Sensitivity Analysis							
Spring and Flexure Material Properties		Nominal Value	%Uncert. (+/-)	Uncert. (+/-)	%Uncert. (+/-)	Uncert. (+/-)	%Uncert. (+/-)	Uncert. (+/-)	
Elastic Modulus (pa)	E	1.876E+11	1.93%	3.63E+09	1.93%	3.63E+09	**3.00%**	5.63E+09	
Yield Strength (pa)	Sy	2.014E+09	1.48%	2.98E+07	1.48%	2.98E+07	**2.00%**	4.03E+07	
Design values in bold Chosen by HPD/LIGO 2-13-2007									
Spring			**Case 1: Change L based on material testing**		**Case 2: Change t based on material testing**		**TOTAL uncertainties**		
Stiffness (N/m)	Kzz, U_Kzz	80924	Below: required change in l, b to maintain Kzz with different material properties				**3.72%**	**3012**	**(in) for reference**
Length (m)	l	0.5134	0.97%	0.0050			0.05%	0.0003	0.0098
Base Width (m)	b	0.2567	0.97%	0.0025			0.06%	0.0002	0.0059
Thickness (m)	t	0.0112	stress (would need to change t to compensate if necessary)		3.38%	0.0004	0.67%	0.000075	0.0030
Global max fiber stress % of yield	avg %yield	30.65%	1.48%	0.45%	6.92%	2.12%	2.41%	0.74%	
Ballast Mass required to adjust table height as a result of U_Kzz (kg)	mballast	73.4					Increase F to level spring if too stiff by U_Kzz		
Min. Height adjustment increment (m)	dh	0.0003							
Min. Incremental Ballast Mass to adjust table height by dh (kg)	mballastmin	6.4					F_increased	6692	
Optics table tilt due to stiffness variation (rad)	tilt	0.0085					Worst case Max fiber stress		
Trim Mass mounting radius (m)	r_mtrim	0.942					worst %yield	32.53%	
Trim Mass required to level table as a result of U_Kzz (kg) (3X)	mtrim_level	11.7							
Table leveling angular adjustment requirement (rad)	dtheta	0.0002							
Min. Incremental Trim Mass to adjust table angle by dtheta (kg)	mtrimmin	0.3							
Flexure			**Case 1: Change lf based on material testing**		**Case 2: Change df based on material testing**		**TOTAL uncertainties**		
Horizontal Stiffness (N*m/rad)	Kxx	43519	Below: required change in lf, ZMP to maintain Kxx with different material properties				0.56%	244	
Length (m)	lf	0.2032	0.26%	0.0005			0.05%	0.0001	0.0039
Zero Moment Point, distance from end (m)	ZMP	0.02749	0.96%	0.0003	0.00%	0.0000	1.68%	0.0005	
Diameter (m)	df	0.0048	Below: resultant change in stress (would need to change df to compensate if necessary)		199.52%	0.009577	0.10%	0.000005	0.0002
Global max fiber stress % of yield - Ignore torsion here	%yield	28.65%	1.10%	0.31%	-77.07%	-22.08%	1.46%	0.42%	

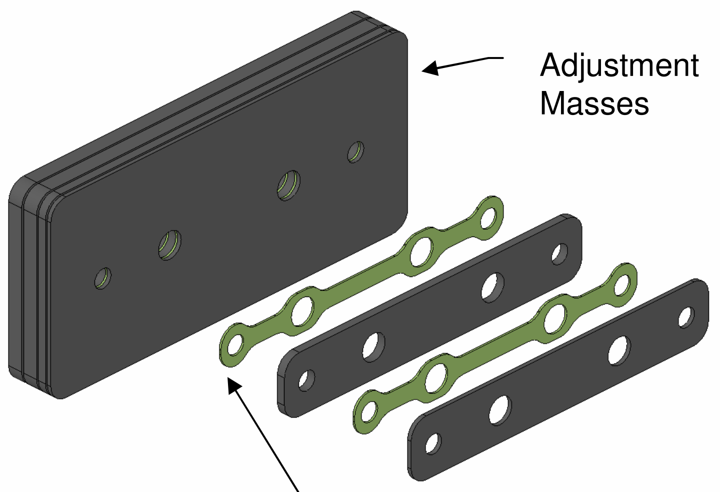
Adjustment Masses



Payload Masses
- 285 – 435 Kg
- + 75 Kg suspended

Ballast Masses
- Adjust table height
- Up to 150 Kg of payload goes here

Trim Masses
- Adjust tip/tilt



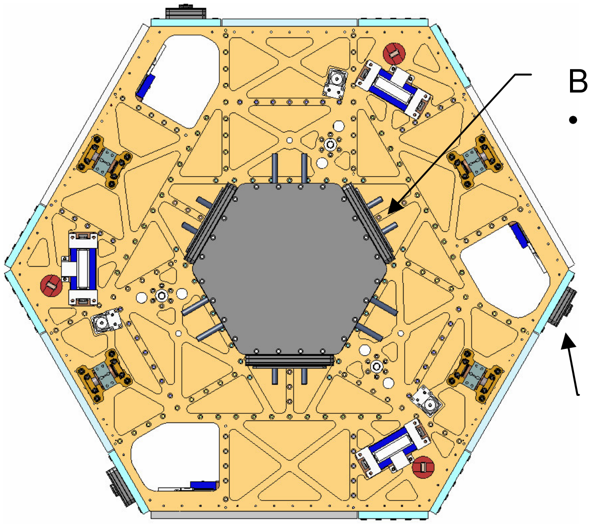
Adjustment Masses

Mass Spacers for venting

Adjustment Mass Requirements - for U_Kzz = 3.2%		
	Total (nominal)	**Min. Increment**
Trim Mass	35.1	0.32
Ballast Mass	38.4	2.12

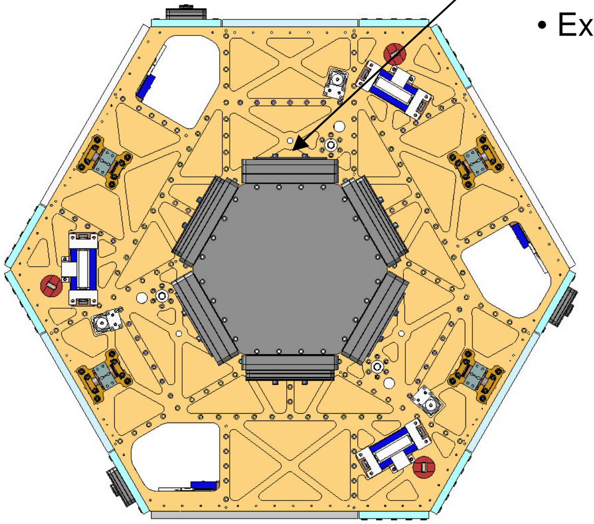
Single Stage HAM Isolator - Mass Adjustments		
	Adjustment Method	
Scenario	**Trim Mass**	**Ballast Mass**
1. All springs too soft	Remove (use as ballast mass)	Remove
2. All springs too stiff		Add
3. Some springs soft, some stiff (table tilts)	Rearrange as necessary	

Adjustment Masses



Ballast Masses
- Nominal

Trim Masses

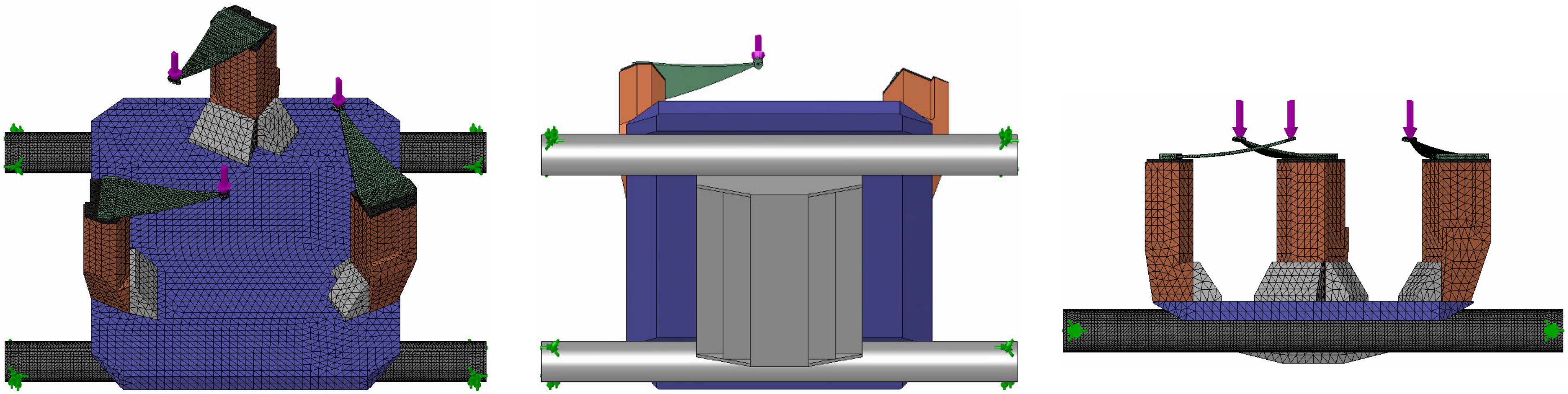


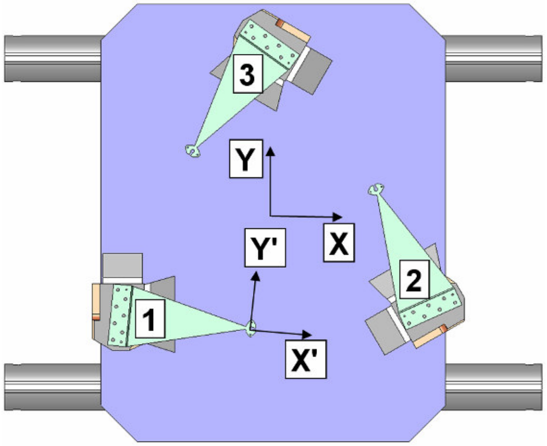
Ballast Masses
- Extra 150 kg

Adjustment Masses				
		Thickness (in)	Mass each (kg)	
Mass Spacer		0.060	0.044	
Fine Trim Mass		0.120	0.250	
Adjustment Mass		0.120	1.013	
Payload Extra Mass		0.690	7.204	
Trim Masses	**Qty**	**Thickness (in)**	**Each w/ spacer (kg)**	
Fine Trim	6	0.120	0.294	
	3	0.240	0.544	
Adjustment Mass	3	0.120	1.057	
	3	0.240	2.070	
	6	0.440	3.758	
Min. Increment (kg)	**0.29**	**Total**	**35.32**	
Ballast Masses	**Qty**		**Each w/ spacer (kg)**	
Fine Trim	0	0.120	0.294	**Fraction**
	3	0.240	0.544	1.85
Adjustment Mass	3	0.120	1.057	1.94
	6	0.240	2.070	1.96
	6	0.440	3.758	1.82
Payload Extra Mass	0	0.690	7.248	1.93
	0	1.190	12.468	1.72
Min. Increment (kg)	**1.63**	**Total**	**39.76**	

Ballast Masses	**Qty**		**Each w/ spacer (kg)**
Fine Trim	0	0.120	0.294
	3	0.240	0.544
Adjustment Mass	3	0.120	1.057
	6	0.240	2.070
	6	0.440	3.758
Payload Extra Mass	6	0.690	7.248
	9	1.190	12.468
Min. Increment (kg)	**1.63**	**Total**	**195.46**

Stage 0 – Static Deflection FEA Model

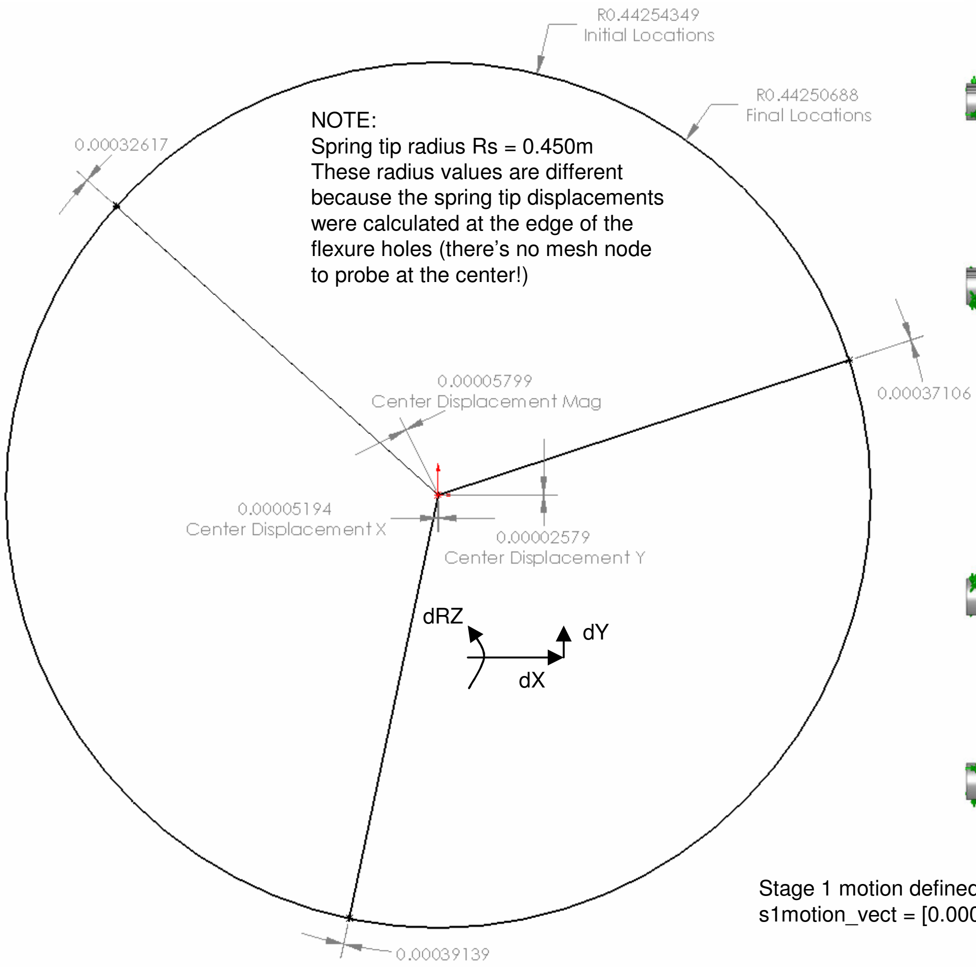




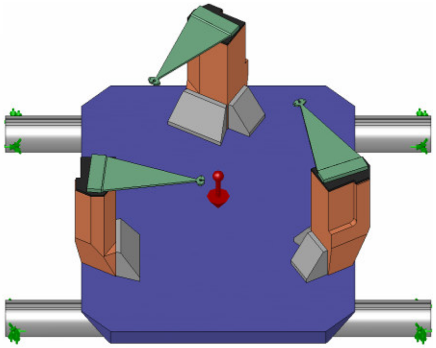
Tip disp. relative to local coordinate system			
	X' (in)	Y' (in)	Z' (in)
Spring 1	0.0071	0.0020	0.0051
Spring 2	0.0063	-0.0016	0.0039
Spring 3	0.0059	0.0016	0.0055
	Magnitude (in)	Angle from X' (deg)	
Spring 1	0.0074	15.67	
Spring 2	0.0065	-14.26	
Spring 3	0.0061	14.86	

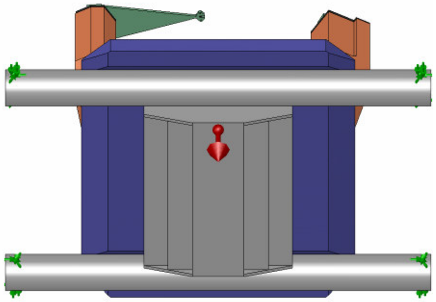
Stage 0 – Static Deflection FEA Results

Stage 1 Motion results for Stage 0 with revised box stiffener



NOTE:
Spring tip radius Rs = 0.450m
These radius values are different because the spring tip displacements were calculated at the edge of the flexure holes (there's no mesh node to probe at the center!)





Stage 1 motion defined in Matlab code:
s1motion_vect = [0.000052, 0.000026, 0, 0, 0, 0.00037]

Motion at important locations as a result of Stage 0 static deflection

running simple_limiters2_jonas_03_13_07 on 13-Mar-2007

Displacement sensor and actuator gap displacements due to Stage 0 static deflection ONLY

vertical displacement sensor #1
0.00 mm

vertical displacement sensor #2
0.00 mm

vertical displacement sensor #3
0.00 mm

horizontal displacement sensor #1
0.32 mm

horizontal displacement sensor #2
0.35 mm

horizontal displacement sensor #3
0.35 mm

vertical actuator #1
0.06 mm

vertical actuator #2
0.03 mm

vertical actuator #3
0.06 mm

horizontal actuator #1
0.16 mm

horizontal actuator #2
0.16 mm

horizontal actuator #3
0.16 mm

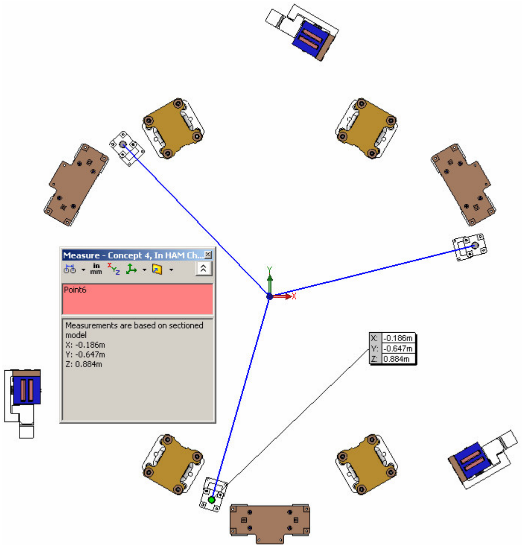
Kinematic Analysis – Locker/Locator/Limiters

Calculate displacements at the critical gaps of the actuators and displacement sensors

Gap displacements allowed by lockers:
- 0.62 mm max at displacement sensors
- 0.63 mm max at actuators

Gap displacements due to S0 static deflection:
- 0.35mm max at displacement sensors
- 0.16 mm max at actuators

If S0 deformation is problematic, it may be necessary to realign components after installation



Point6

Measurements are based on sectioned model
X: -0.186m
Y: -0.647m
Z: 0.884m

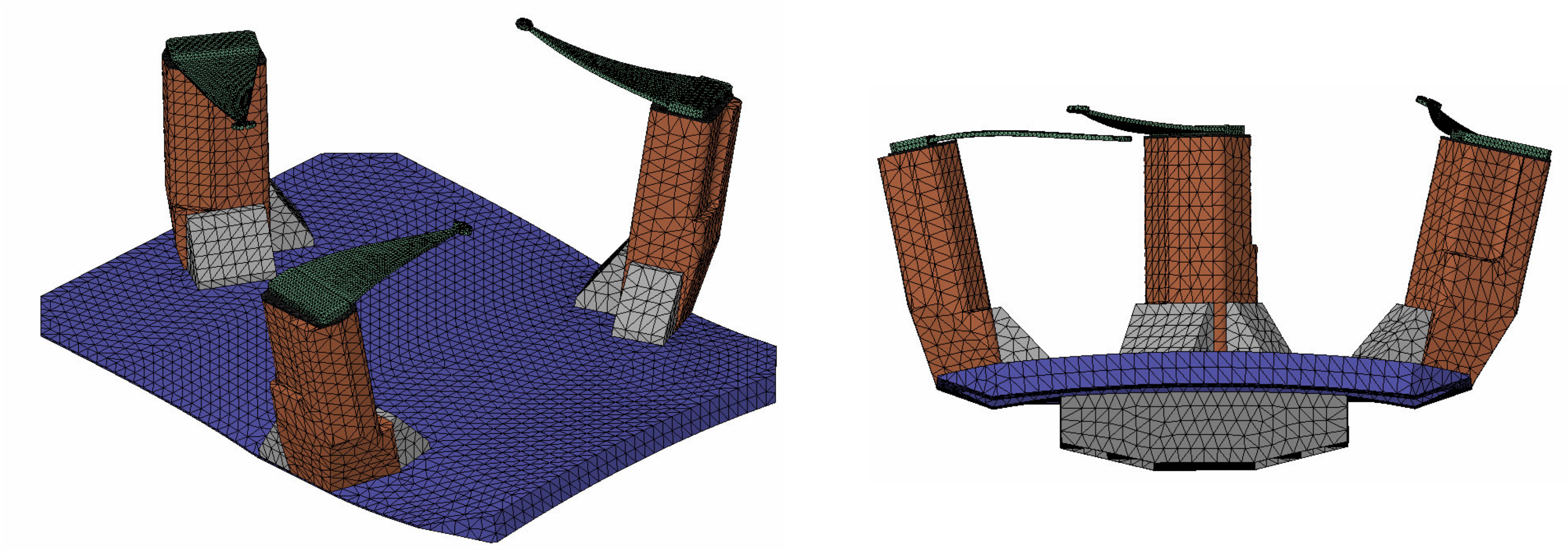
X:	-0.186m
Y:	-0.647m
Z:	0.884m

Brian Lantz's Matlab code results

```
running simple_limiters2_jonas_03_13_07 on
22-Mar-2007

vertical displacement sensor #1
  0.00 mm, due to S0 static deformation ONLY
Allowed motion due to lockers ONLY
  0.92 mm, simple calc
  0.38 mm, ASI min

vertical displacement sensor #2
  0.00 mm, due to S0 static deformation ONLY
Allowed motion due to lockers ONLY
  0.76 mm, simple calc
  0.31 mm, ASI min

vertical displacement sensor #3
  0.00 mm, due to S0 static deformation ONLY
Allowed motion due to lockers ONLY
  0.92 mm, simple calc
  0.53 mm, ASI min

horizontal displacement sensor #1
  0.32 mm, due to S0 static deformation ONLY
Allowed motion due to lockers ONLY
  1.03 mm, simple calc
  0.62 mm, ASI min

horizontal displacement sensor #2
  0.35 mm, due to S0 static deformation ONLY
Allowed motion due to lockers ONLY
  0.81 mm, simple calc
  0.40 mm, ASI min

horizontal displacement sensor #3
  0.35 mm, due to S0 static deformation ONLY
Allowed motion due to lockers ONLY
  0.81 mm, simple calc
  0.40 mm, ASI min
```

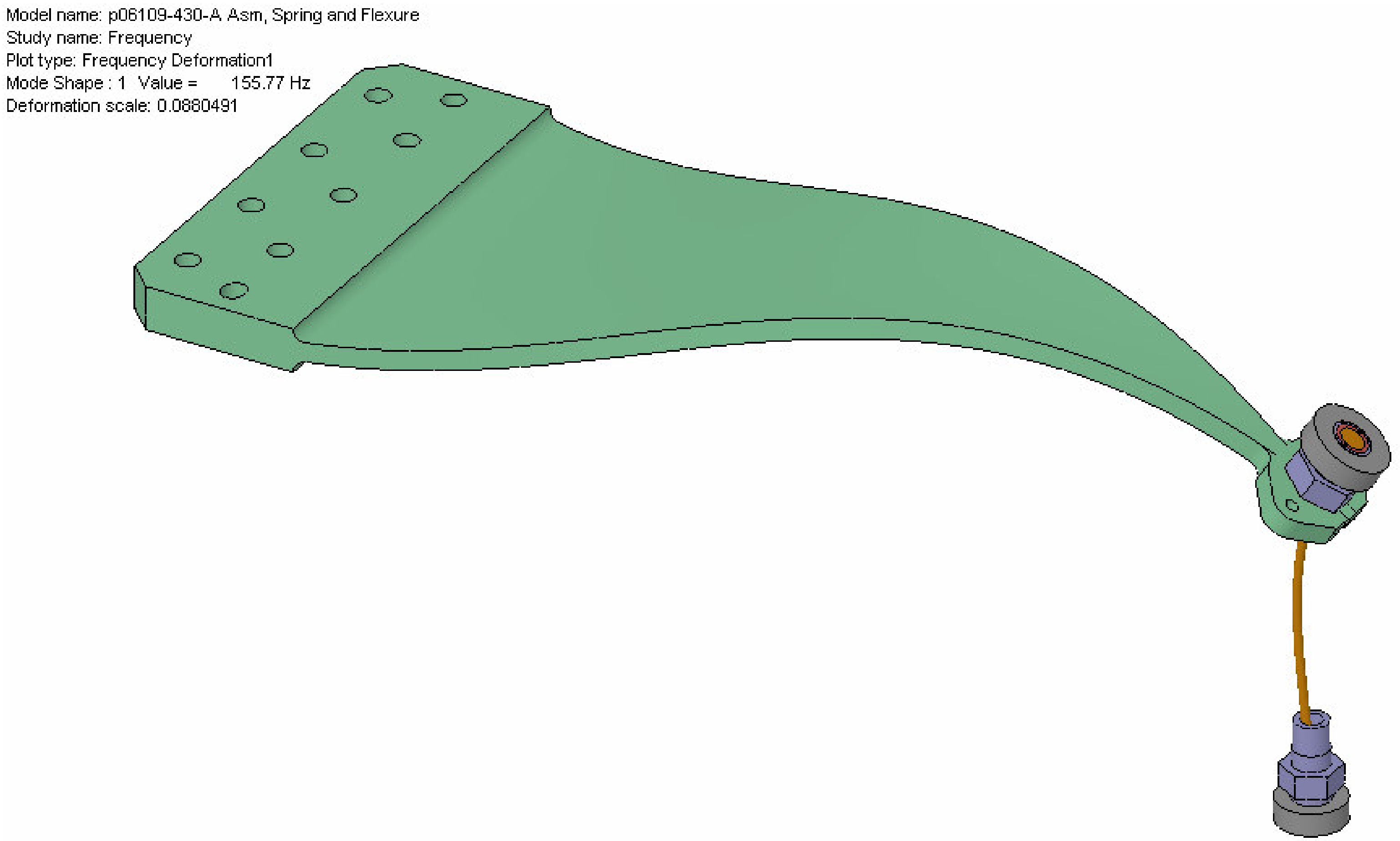
```
vertical actuator #1
  0.06 mm, due to S0 static deformation ONLY
Allowed motion due to lockers ONLY
  0.31 mm, simple calc
  0.31 mm, ASI min

vertical actuator #2
  0.03 mm, due to S0 static deformation ONLY
Allowed motion due to lockers ONLY
  0.61 mm, simple calc
  0.61 mm, ASI min

vertical actuator #3
  0.06 mm, due to S0 static deformation ONLY
Allowed motion due to lockers ONLY
  0.31 mm, simple calc
  0.31 mm, ASI min

horizontal actuator #1
  0.16 mm, due to S0 static deformation ONLY
Allowed motion due to lockers ONLY
  0.80 mm, simple calc
  0.53 mm, ASI min

horizontal actuator #2
  0.16 mm, due to S0 static deformation ONLY
Allowed motion due to lockers ONLY
  0.97 mm, simple calc
  0.63 mm, ASI min

horizontal actuator #3
  0.16 mm, due to S0 static deformation ONLY
Allowed motion due to lockers ONLY
  0.97 mm, simple calc
  0.63 mm, ASI min
```

Stage 0 FEA – Bending Modes



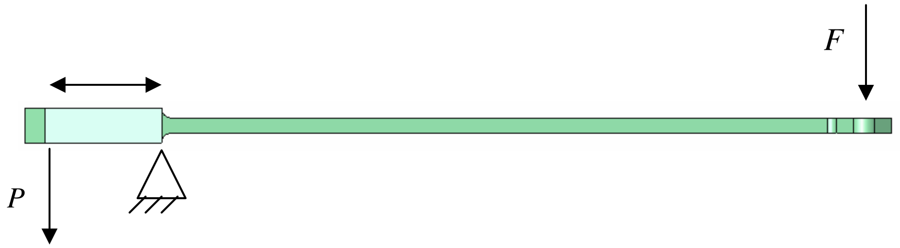
Natural Frequency: 107 Hz
(Unconstrained)

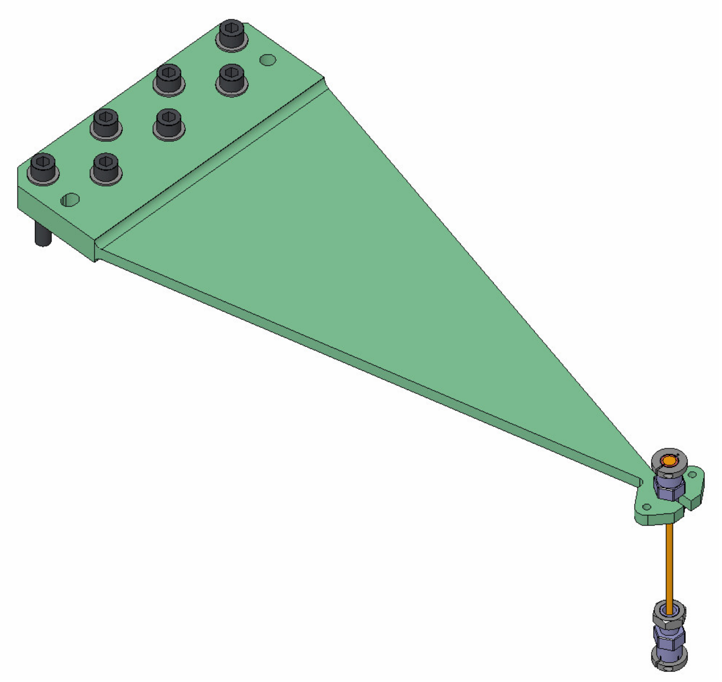
Spring and Flexure Parasitic Modes



Model name: p06109-430-A Asm, Spring and Flexure
Study name: Frequency
Plot type: Frequency Deformation1
Mode Shape : 1 Value = 155.77 Hz
Deformation scale: 0.0880491

Bolted Connection Analyses





Spring Bolts

½-13 x 3.0” 18-8 SHCS

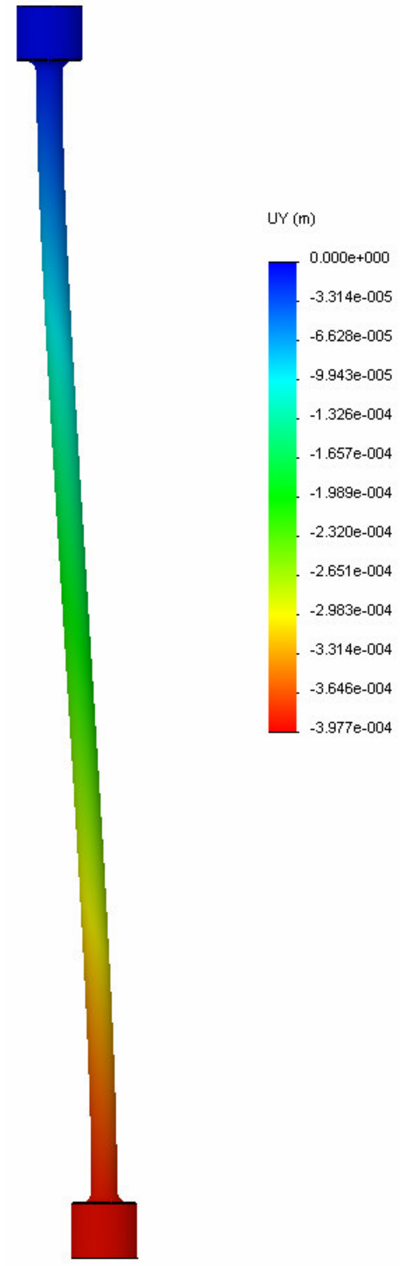
- Neglect front row of bolts
- Preload to 75% of proof strength
- Safety Factor with external load P: 7.5

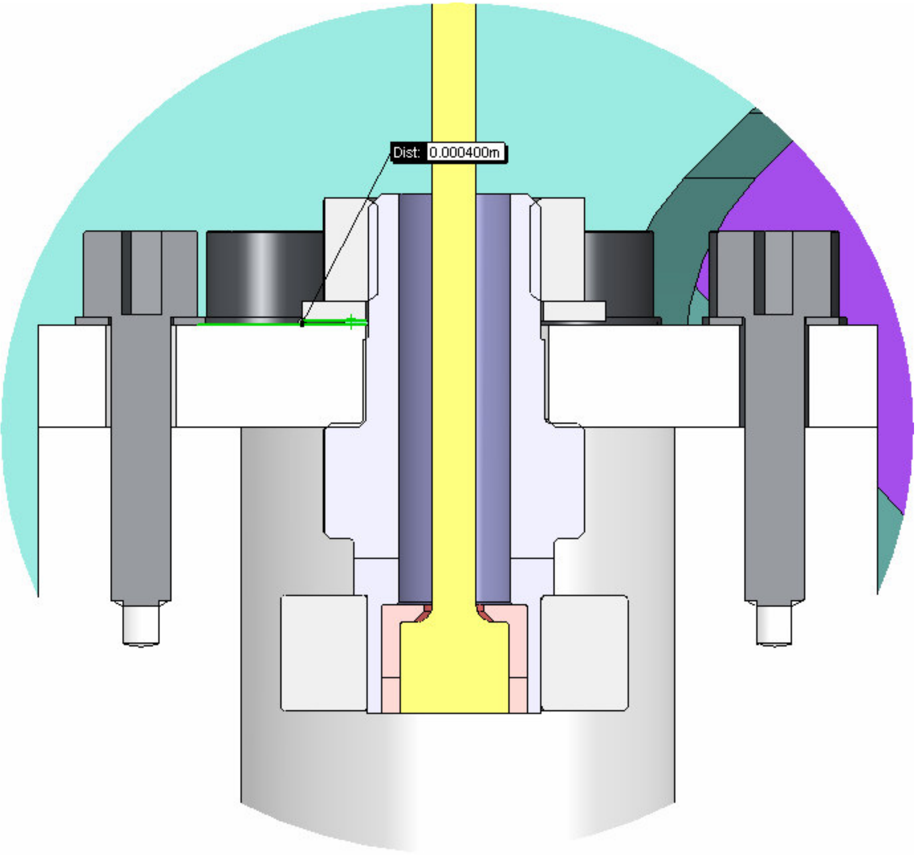
ISSUE: What to use for Lubrication Factor Kl?

- For Kl = 0.2, Tightening Torque T = 1440 (in*lbf)

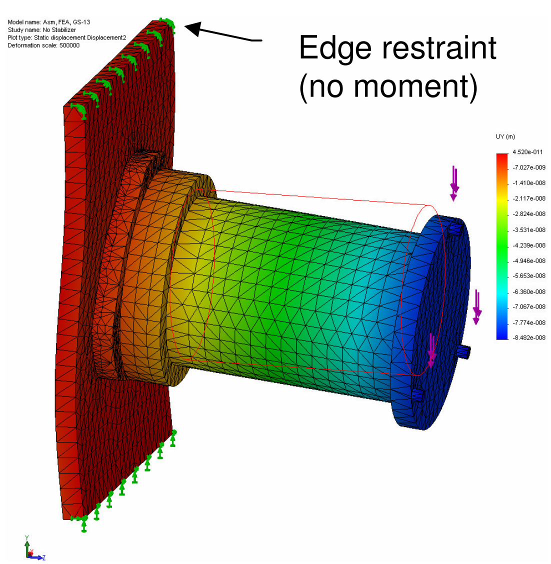
Horizontal Actuator Position

Account for flexure axial deformation in system design

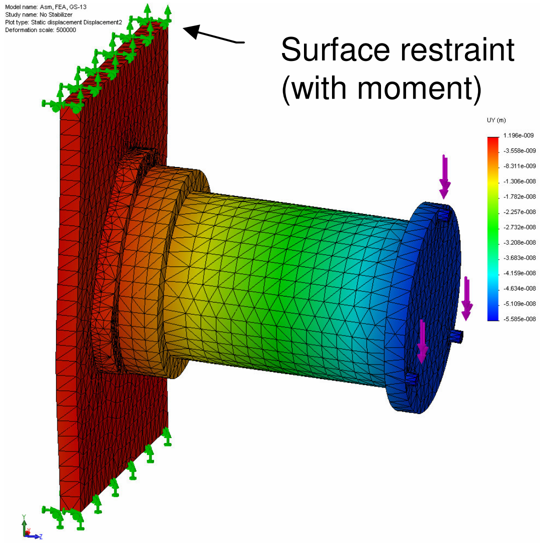




GS-13 End Stabilizer FEA



Edge restraint
(no moment)



Surface restraint
(with moment)

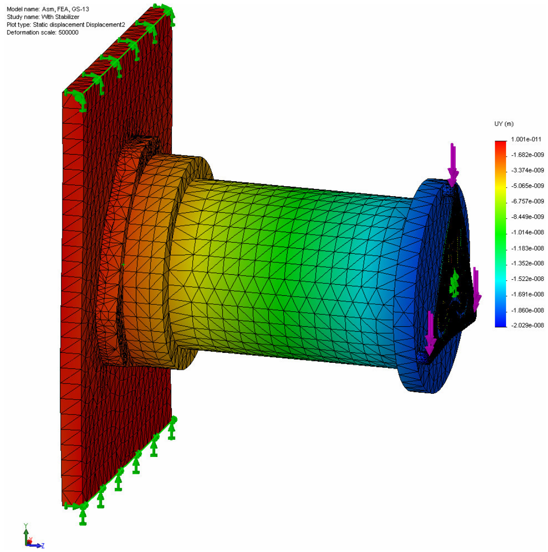
Stiffness determination from FEA model

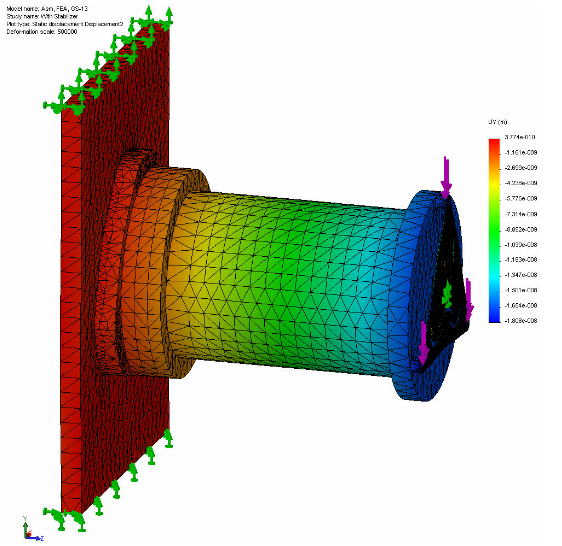
Restrain vertical plate on edges (optimistic)

- Lateral stiffness increase with Stabilizer: 4.3x

Restrain vertical plate on surfaces (conservative)

- Lateral stiffness increase with Stabilizer: 3.2x





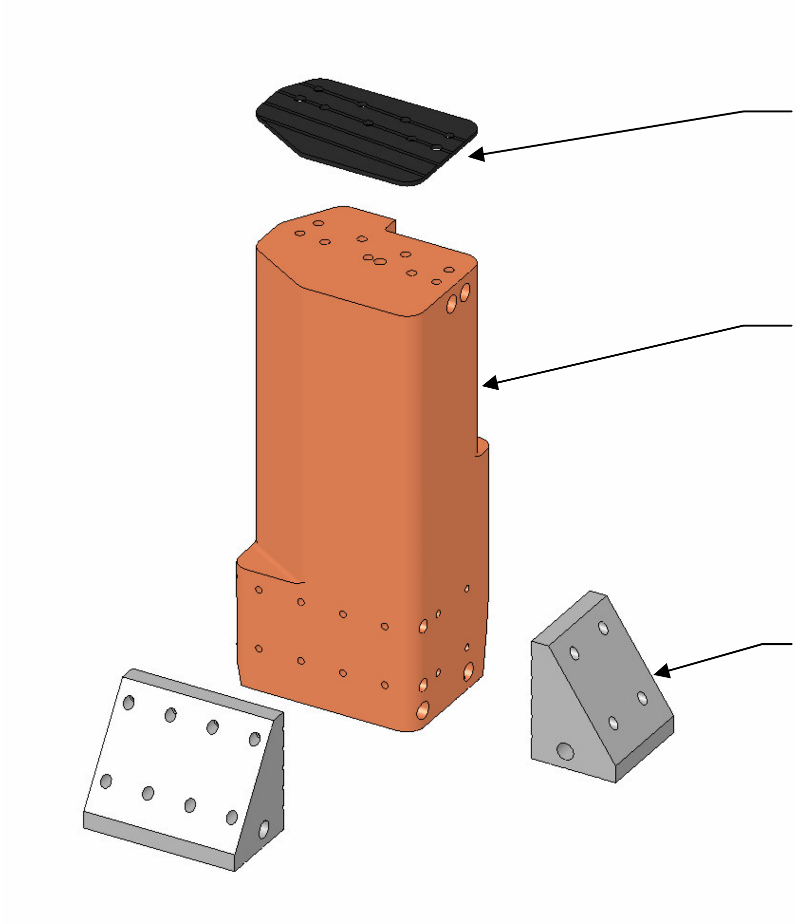
Agenda

1. **System Design**
   1. Layout and Section Views
      1. System in HAM Chamber
      2. System Overview
      3. Components and Sub-Assemblies
   2. Critical Component Locations
   3. Fastener Plan
2. **Technical Review**
   1. Overall Approach
   2. Stage 1 FEA
   3. System Dynamics
   4. Spring & Flexure Assembly
      1. Spring Design & FEA
      2. Flexure Design & FEA
      3. Uncertainty & Sensitivity Analysis
      4. Adjustment Masses
   5. Payload Scenarios
   6. Stage 0 FEA
   7. Kinematic Analysis
   8. Bolted Connection Analyses
3. **Assembly Sequence**
   1. Dirty Assembly Plan
   2. Framework Assembly
   3. Spring Compression
   4. Flexure Assembly
   5. Component Adjustment & Alignment
4. **Design Requirement Compliance**
5. **Risk Analysis & Mitigation**
6. **Fabrication Cost Estimate**
7. **Project Schedule**

Dirty Assembly Plan

1. Dirty Assembly Strategy
    1. Lubrication/anti seize will be used in bare aluminum threads
    2. Helicoils will only be installed in optical grid where required to attach masses
    3. Low priority items (cover plates, etc.) will be omitted for initial testing
2. After Dirty Assembly & Test Are Complete
    1. All fasteners, barrel nuts and Helicoils will be removed for cleaning
    2. Any parts intended to be Helicoiled but tapped with straight threads in Dirty Assembly will re-tapped and cleaned

Support Post Assembly

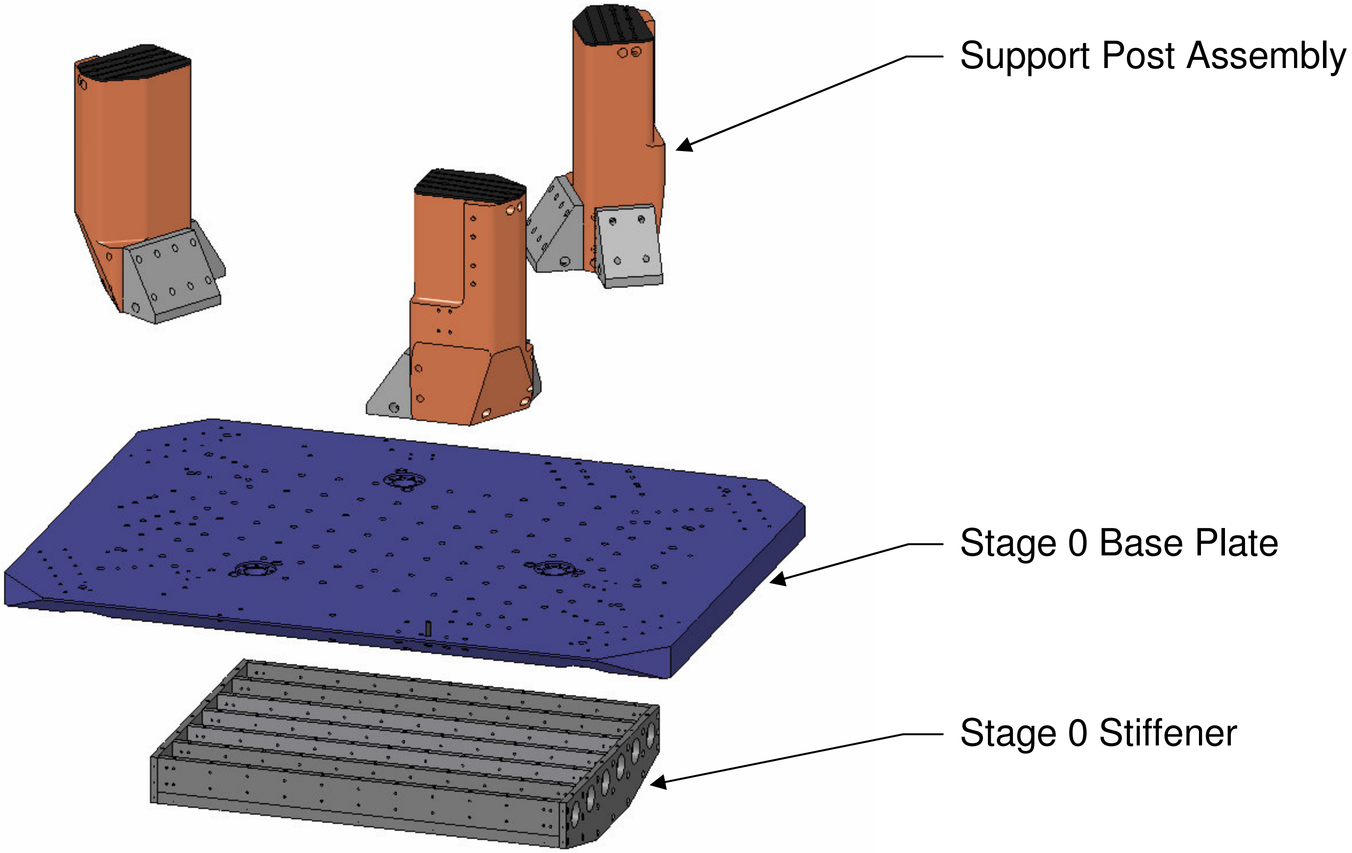


Support Post Cap

Support Post

Support Post Gusset

Stage 0 Assembly

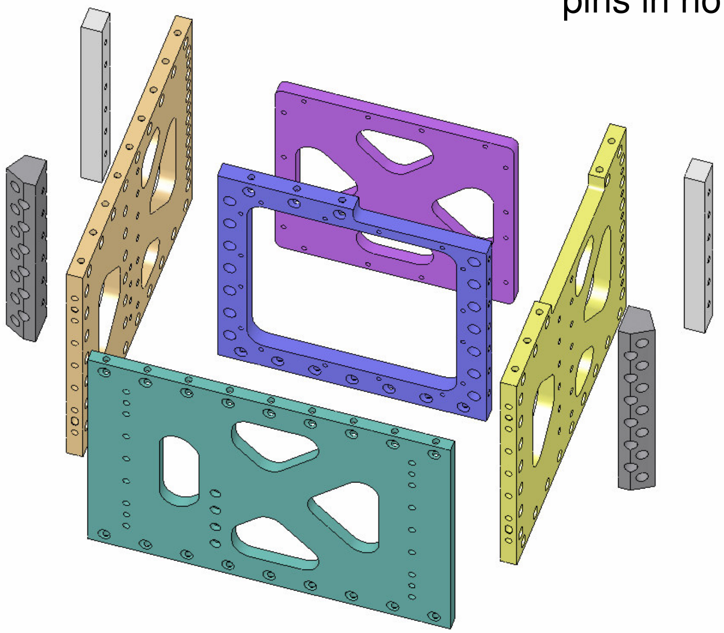


Support Post Assembly

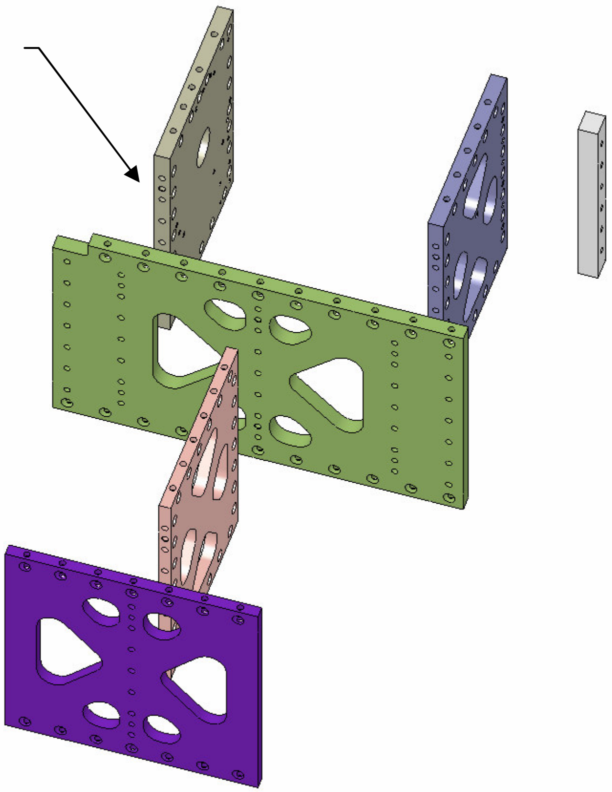
Stage 0 Base Plate

Stage 0 Stiffener

Internal Wall Sub-Assemblies



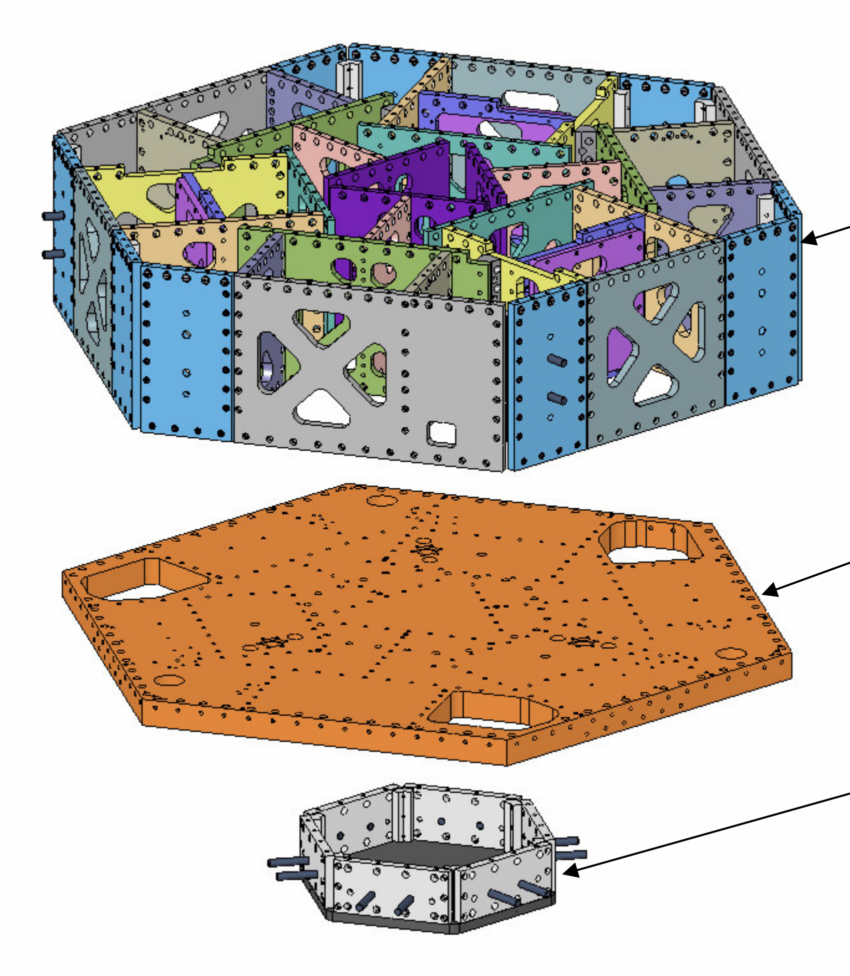
Boxwork Assembly



All plates located with pins in holes and slots

Pitchfork Assembly

Stage 1 Initial Assembly

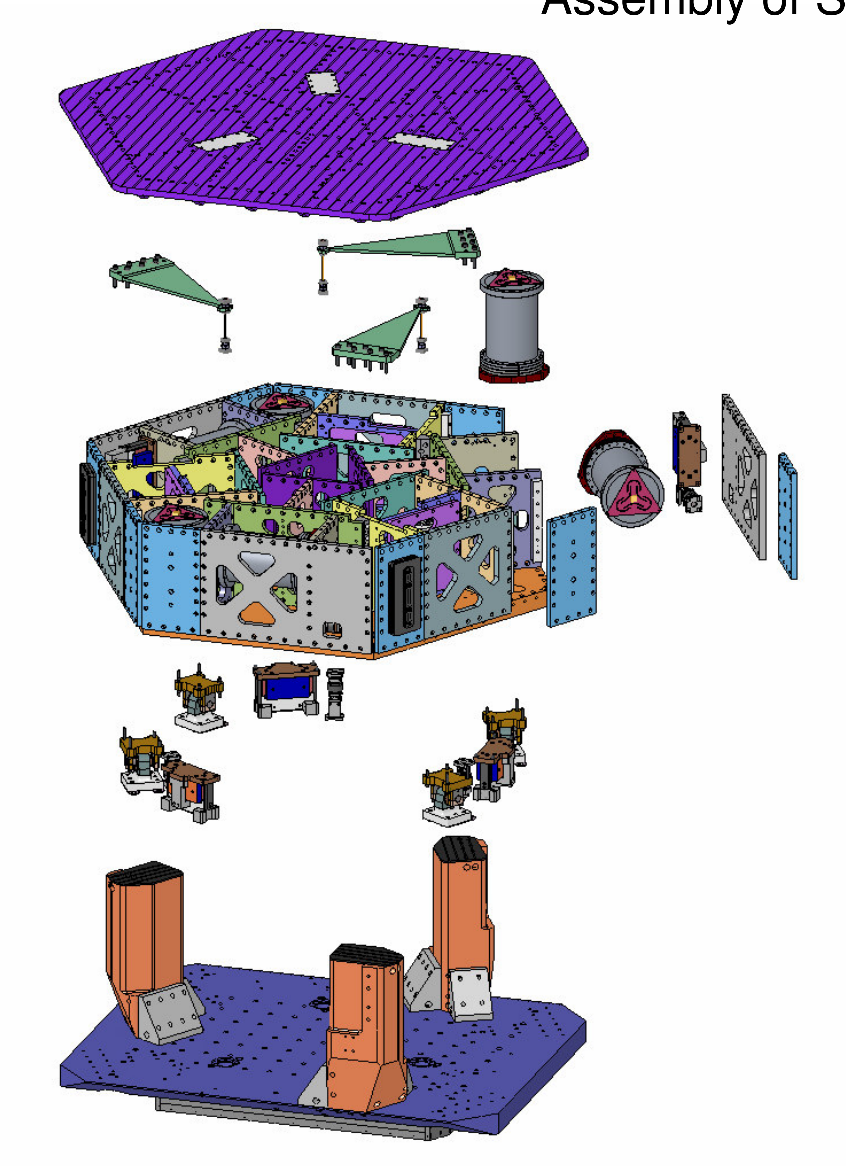


Wall Sub-Assemblies

Stage 1 Base Plate

Keel

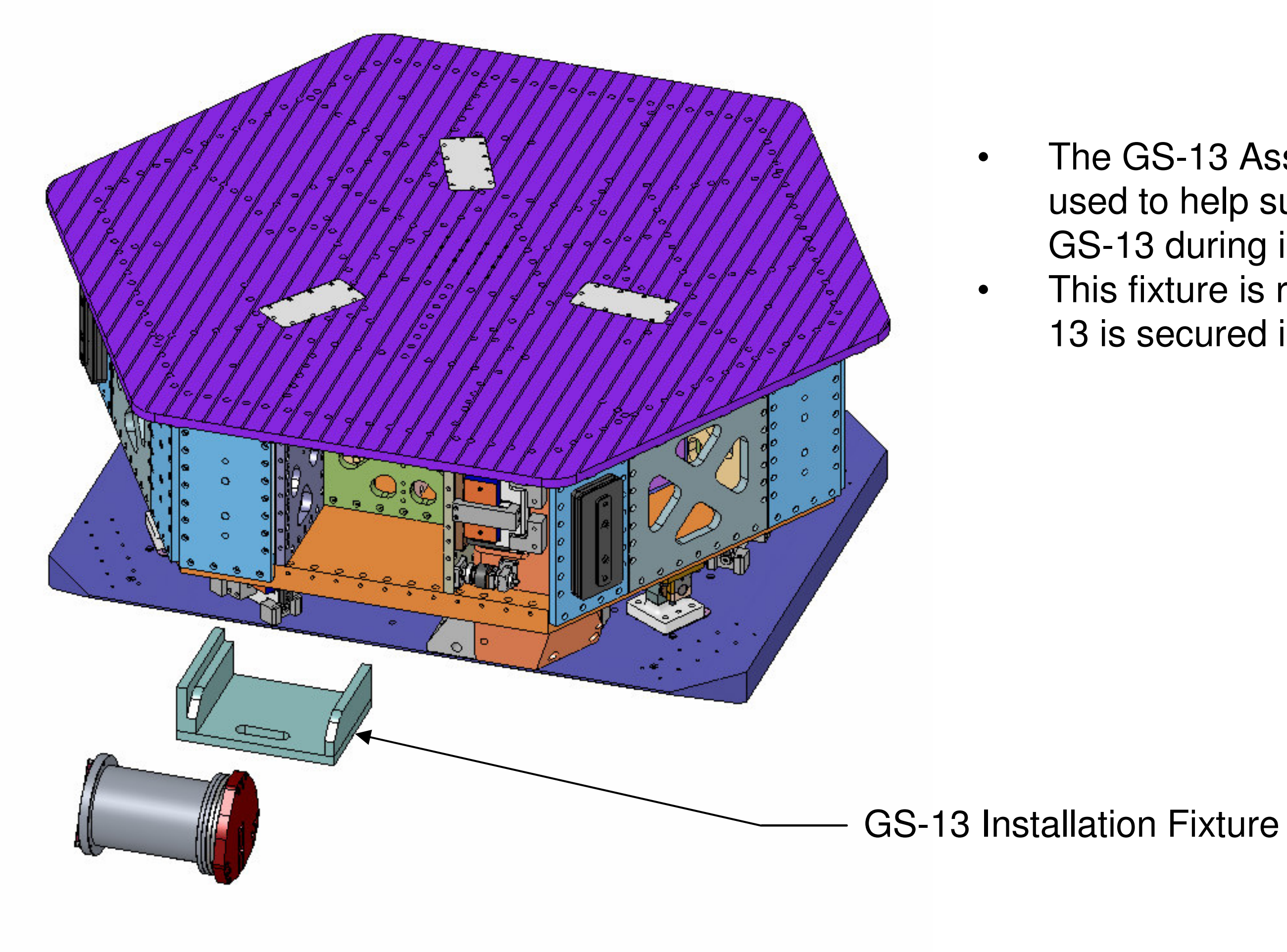
Assembly of Stage 1 to Stage 0



Assembly Sequence

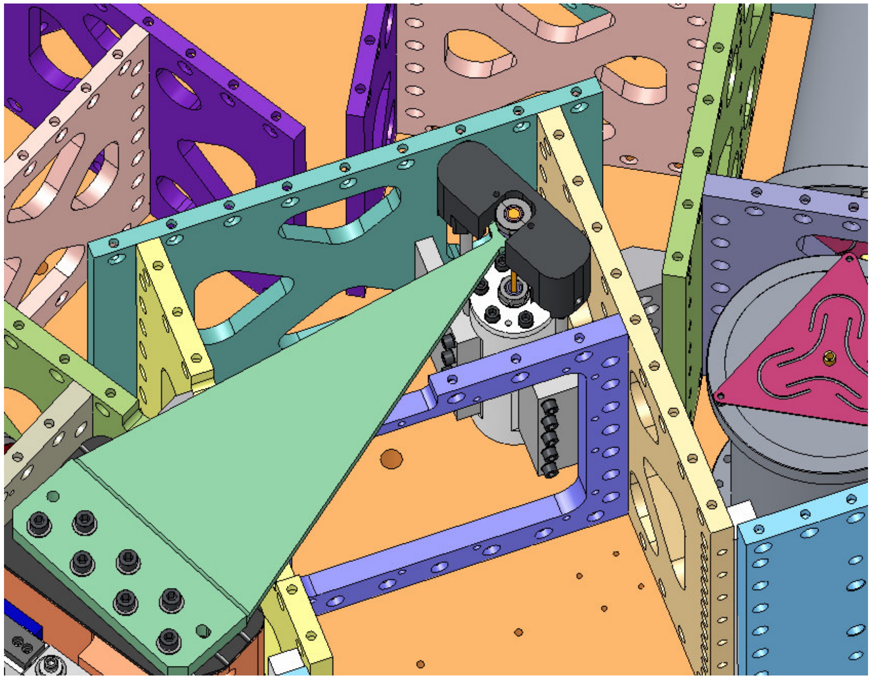
1. Lower Stage 1, with Lockers attached and locked, onto Stage 0
2. Pin and bolt Lockers to Stage 0 with nominal shims
3. Secure GS-13s in place
4. Attach Actuators (with fixturing) and Sensor Targets to Stage 1
5. Attach Position Sensor Targets to Stage 1 and place in retracted position
6. Attach Position Sensor Detectors to Stage 0
7. Mount Springs to top of Support Posts
8. Compress Springs and connect Flexures to Stage 1
9. Attach Optics Table
10. Remove Spring compressors
11. Mount Optics Table access covers
12. Alternatively, steps 3, 4, 5 & 6 can be performed after step 10, if perimeter plates are not included in Stage 1, per step 1

Horizontal GS-13 Installation

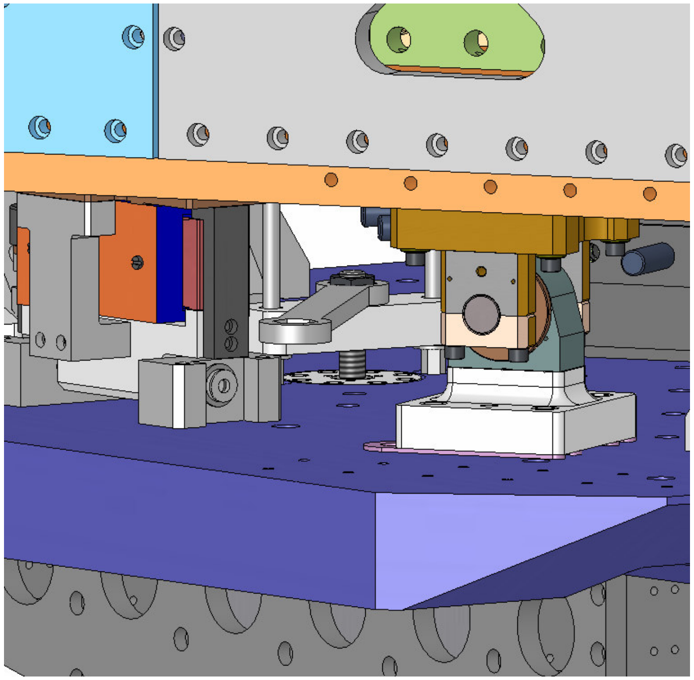

GS-13 Installation Fixture

- The GS-13 Assembly Fixture can be used to help support the horizontal GS-13 during installation
- This fixture is removed once the GS-13 is secured in place

Spring Compression Detail

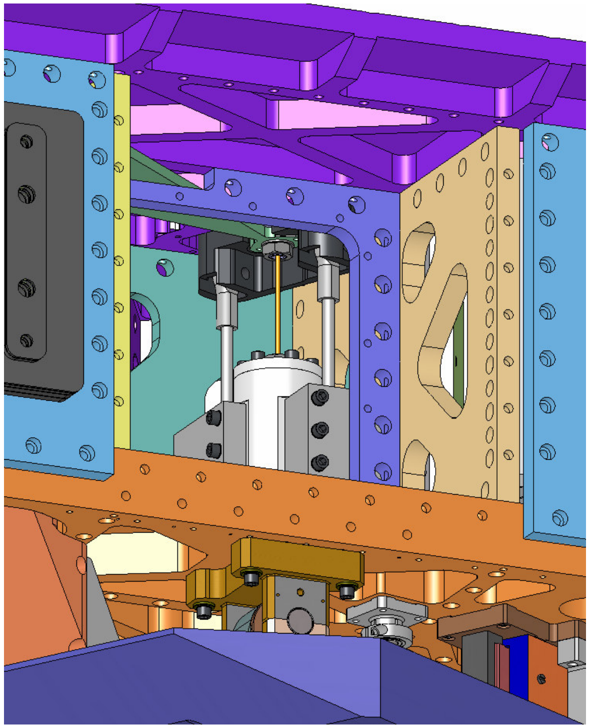


Access with Optics Table removed

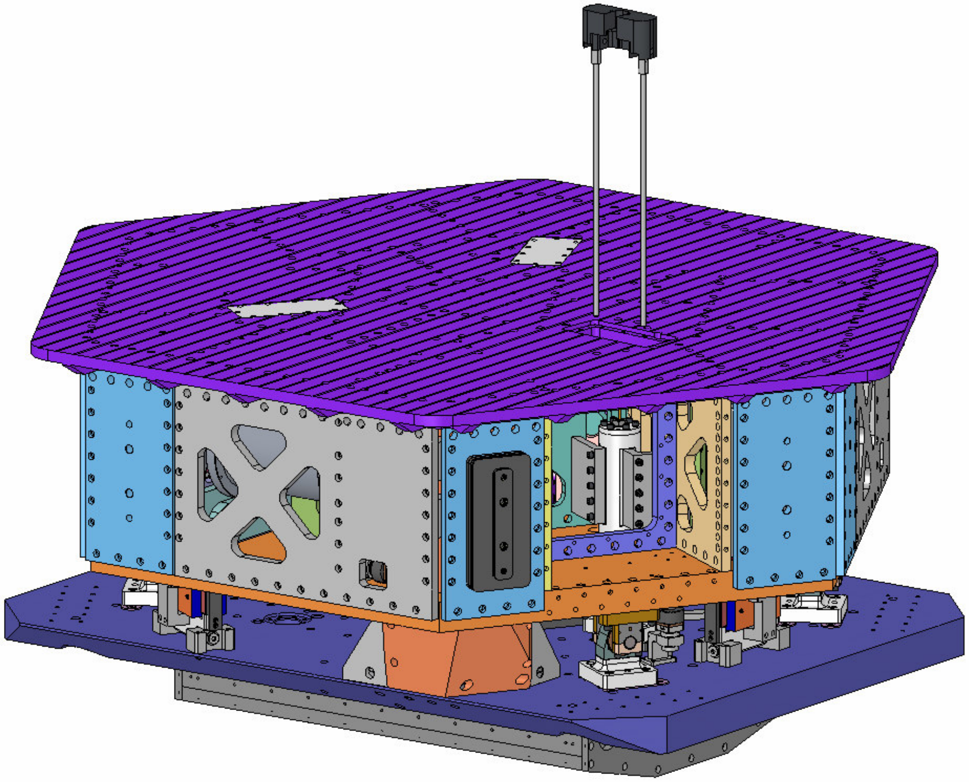


Wrench access from under Stage 1

Spring Compression Detail

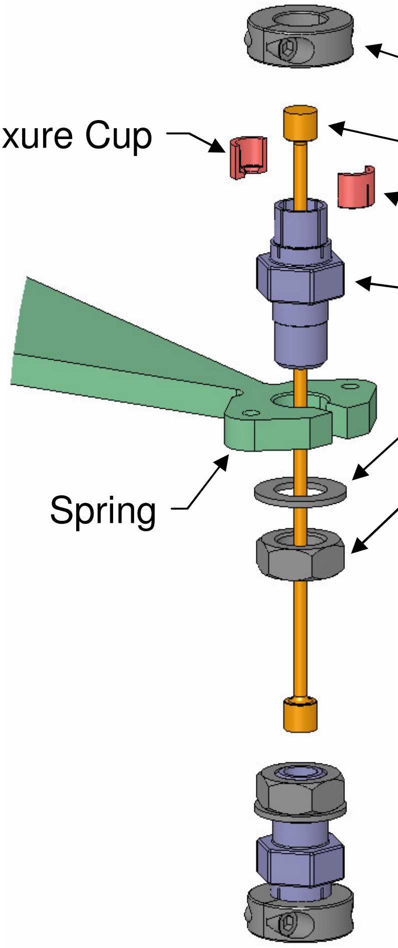


Access with Optics Table mounted



Removal of Spring Compressor with Optics Table in place

Flexure Assembly



Lock Collar

Flexure Cup

Flexure

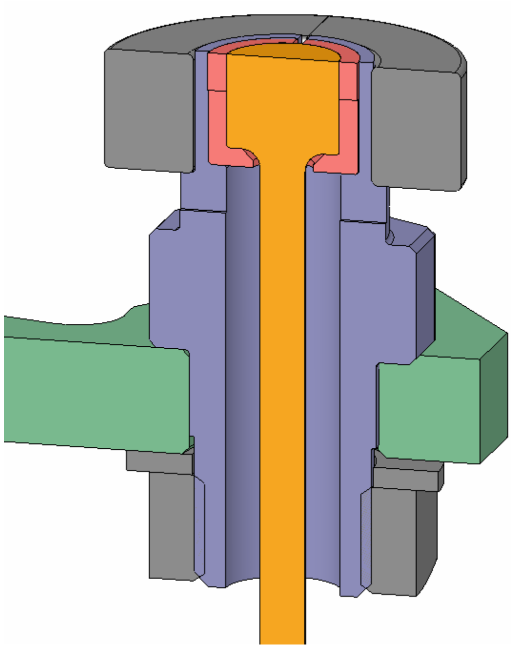
Flexure Cup

Flexure
Mount

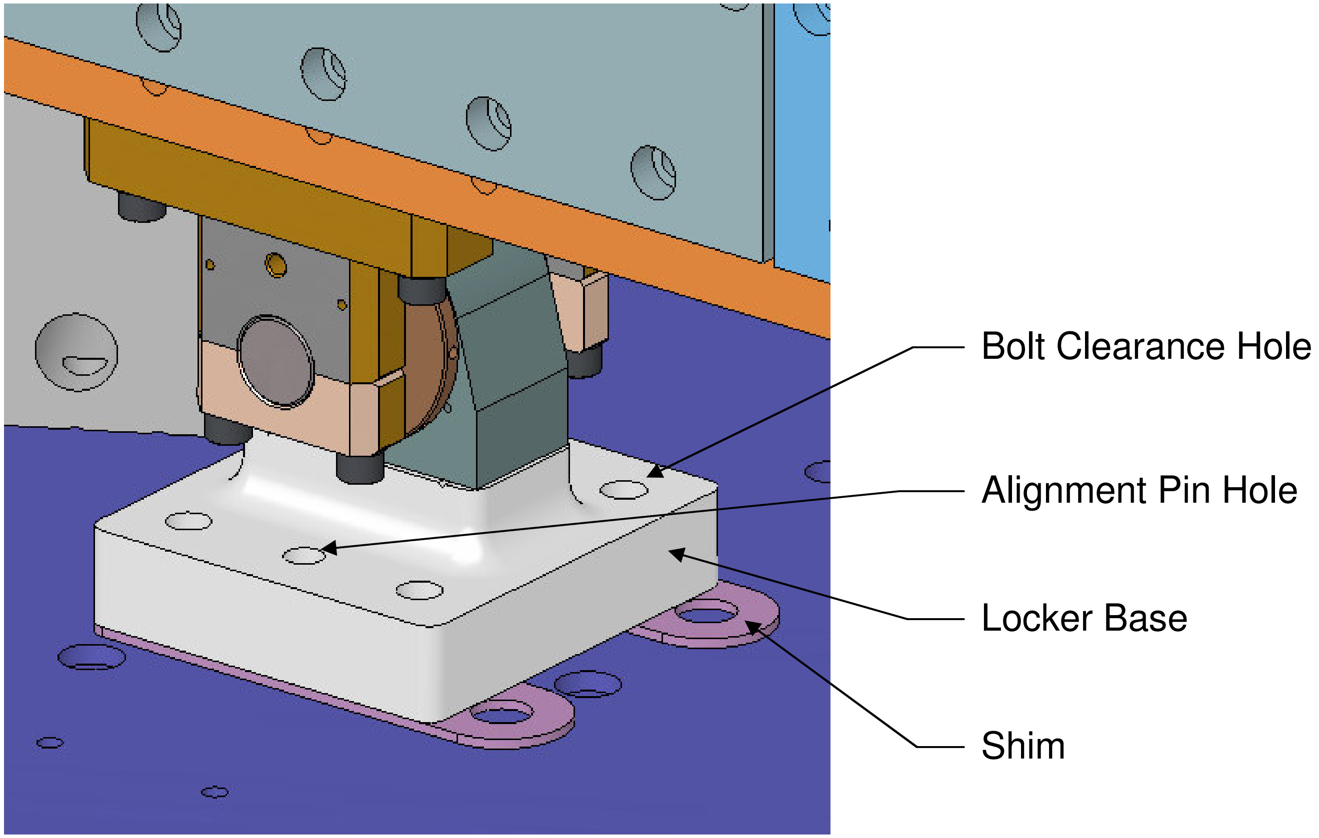
Flat Washer

Jam Nut

Spring



Locker Detail



Bolt Clearance Hole

Alignment Pin Hole

Locker Base

Shim

Locker Adjustment Sequence

1. After Lockers are attached to Stage 0 with locating pins and nominal shims
2. Install Payload and Adjustment Masses to assembled system
3. Release Lockers
4. Add or remove Adjustment Masses to achieve initial height and orientation of Optics Table
5. Engage Lockers
6. Loosen bolts, then remove pins from Locker Bases and allow Stage 1 to float
7. Add or remove Adjustment Masses to achieve correct height and orientation of Optics Table
8. Adjust shims under Locker Bases, and tighten bolts to Stage 0
9. Release Lockers and measure movement of Stage 1 relative to Stage 0
10. Add or remove masses as necessary or change shims (steps 4 through 8) until hang requirement is met
11. Close Lockers
12. Attach free half of Actuators and adjust to nominal
13. Remove Actuator fixturing
14. Adjust Sensor Detectors relative to Sensor Targets
15. Remove Adjustment Masses approximating Actuator halves now attached to Stage 0
16. Confirm that system meets hang requirement

Agenda

Design Requirements

Req.	Description	Value	Compliance
A	References		
B	General		
C	Stage Structures		
C.1	Major structure elements aluminum	Aluminum	Yes
C.2	Stage 0 mount on eleven bosses of Support Tubes – **Changed: 9 is acceptable**	Stage 0 mounts on 9 of 11 bosses	Yes
C.3	Lower surface of structure extend 9.9” max from interface, 16” from center line – **Changed: minimum clearance to chamber limits SO structure size**	As specified	Yes
C.4	2-point lift on optical table **– Changed: lift points designed for elevator at MIT**	(4) ¾-10 Helicoils at 48” x 48”	Yes
C.5	Clearance of 0.5” from chamber, 0.2” between stages	As specified	Yes
C.6	Shall survive 1g Vertical 0.5g Horizontal shipping loads	Analysis not yet performed	Not yet
C.7	Structure to be suitably stiff between GS-13s and actuators	No frequency response analysis necessary.	Yes
C.8	Minimum natural frequency to be 250 Hz **– Changed: simplified FEA model 338 Hz**	Simplified model result 339 Hz	Yes
C.9	Stage 0 to be moderately stiff **– Changed: Spring tips displace < .008” in XY plane under static loading**	Static deflection FEA results meet requirement	Yes
C.10	Incorporation of Lock/Locator from BSC	BSC design is incorporated	Yes
C.11	Heavy structures to have lifting provisions	¾-10 Helicoils	Yes
C.12	Radius of gyration to meet natural frequencies	All natural frequencies met, see D,1,a,ii	Yes

Design Requirements

Req.	Description	Value	Compliance
D	Springs & Flexures		
D.1.a.i.	Spring & Flexure at 3 corners	Yes	Yes
D.1.a.ii	Horizontal translation 1.0-1.4 Hz	1.32 Hz	Yes
D.1.a.ii	Vertical translation: 1.3-1.9 Hz	1.8 Hz	Yes
D.1.a.ii	Tip & tilt: 0.8-1.1 Hz	1.07 Hz	Yes
D.1.a.ii	Yaw: 0.8-1.2 Hz	0.90 Hz	Yes
D.1.a.iii	Spring & flexure stresses to be 30%, max 35% of yield at 1mm excursion, in max fiber, 55% in local risers	Spring: 30.7% except for local stress risers, 41.0% in risers Flexure: 29.1% except for local stress risers, 34.4% in risers (at 2mm deflection)	Yes
D.1.a.iv	Made from single billet of Maraging 300	Sensitivity analysis shows this is not necessary	Yes, but not necessary
D.1.a.v	Springs to be flat & horizontal when loaded	As specified	Yes
D.1.a.vi	Max length 55cm	51.34cm	Yes
D.1.a.vii	UZMP within 1mm of spring centerline	As specified	Yes
D.1.a.viii	Springs & flexures lie at corners of equilateral triangle	As specified	Yes
D.1.a.ix	Zero Moment point definition	Design per definition, verified with FEA	Yes

Design Requirements

Req	Description	Value	Compliance
D.1.b	Magnetic Actuators		
D.1.b.i	Actuators to be per PSI# 0487-LIGO-D110- **050904-SCS – Changed: New design not yet available**	Incomplete	Not yet
D.1.b.ii	6ea, 2 at each corner, with axes perpendicular to line connecting center of structure with instrument axis	As specified	Yes
D.1.b.iii	H. actuator centerline plane to be within 1mm of LZMP plane	Tolerance analysis not performed	Probably
D.1.b.iv	H. actuators plane to be parallel to LZMP plane to within 1 mrad	Tolerance analysis not performed	Probably
D.1.b.v	Each H. actuator axis to be parallel to LZMP plane to within 1 mrad	Tolerance analysis not performed	Probably
D.1.b.vi	Permanent magnet to be attached to Stage 1, bobbin side to Stage 0	As specified	Yes
D.1.c	Capacitive Sensors		
D.1.c.i	Design per ADE Technologies, 20mm probe	As specified	Yes
D.1.c.ii	6 ea, 2 at each corner, I vertical, 1 tangential	As specified	Yes
D.1.c.iii	Probe mounted on Stage 0, target on Stage 1	As specified	Yes
D.1.c.iv	Each pair at least 39” from other pairs	Vertical 45.9”; Horizontal 58.2”	Yes
D.1.c.v	Targets made of 1100 Al, >40mm dia, 0.1 micron flat	As specified	Yes

Design Requirements

Req	Description	Value	Compliance
D.1.c.vi	Target to be within 2 mrad of nominal design direction	As specified	Yes
D.1.c.vii	Sensor head to be parallel to target within 2 mrad	As specified	Yes
D.1.c.Viii	Sensor to be near companion actuator, at outer edge of structure	As specified	Yes
D.1.d	Seismometers		
D.1.d.i	Use existing design	As specified	Yes
D.1.d.ii	Add holes to far end of pod for stabilizing pod	Incomplete	Yes
D.1.d.iii	1.0 diameter mounting pads, bracket at far end	Mounting pads will move to perimeter of flange, bracket is included	Yes
D.1.d.iv	Pods per LIGO D047810-A	As specified	Yes
D.1.d.v	6 ea, 2 at each corner, at far edge to measure tilt	As specified	Yes
D.1.d.vi	Pods to be within 1 mm of nominal location, aligned within 5 mrad of nominal orientation	As specified	Yes
D.1.d.vii	Pods to be removable, repositionable to 1 mrad, 1mm	As specified	Yes

Design Requirements

Req	Description	Value	Compliance
D.1.d.viii	Stage 1 pods to be located near accompanying actuators	Pods are within 2.3" of actuators,	Yes
D.2	Access to be provided for installation, adjustment & removal of pods, actuators, sensors, springs & flexures	All components are removable while in the chamber. Removal of spring would require removal of optical table.	Yes
E	Additional alignment		
E.1	Maximum offset between LZMP & CG of platform to be 10 cm	27 mm offset for payload scenario 1, -32mm for payload scenario 2	Yes
E.2	Actuator alignment jigs	Incomplete – actuator design not yet finalized	Not Yet
E.3	Maximum movement between Stage 0 & Stage 1, when removed from Locks, to 0.1mm.	Same lockers are to be used with same shimming and adjustment scheme as in BSC. Alignment precision must meet requirement.	Yes
E.4	Procedure and fixturing to be provided for installing springs & flexures without damage	As specified	Yes

Design Requirements

Req	Description	Value	Compliance
F	Optical Table		
F.1	To be nine-sided circumscribed around circle of 76.77” with one side parallel to HAM support tubes, or circular, or other three way symmetrical shape with at least a 76.77” circular surface. **Changed**	Table design is 6 sided circumscribed around a 76.0” circle	Yes
F.2	Optical table to be centered in Ham chamber	As specified	Yes
F.3	Matrix of ¼-20 tapped holes, one axis of grid to be parallel with axes of support tubes.	As specified	Yes
F.4	Table to be flat within 0.01”, surface finish of 64rms or better	As specified, in unloaded state	Yes
F.5	Table top to be 78.0 cm above structure interface. No part of structure extending above table surface	As specified	Yes
F.6	Local stiffness to be sufficient to support suspension frame without large deformations.	As specified	Yes

Design Requirements

Req	Description	Value	Compliance
G	Masses		
G.1	Total mass to be less than 4026 kg	Current mass ~ 3000 kg	Yes
G.1.i	Structural Elements	As specified	Yes
G.1.ii	Trim masses to be bolted to Stage 1 in increments to make table level within 0.2 mrad	As specified	Yes
G.1.iii	Balance masses to be bolted to Stage 1 to adjust table height	As specified	Yes
G.1.iv	Mass of Stage 1 to be less than 1500 kg	Currently 1463 kg	Yes
G.2.i	Aggregate of non-suspended optical masses to be 435 kg	As specified	Yes
G.2.ii	Aggregate of suspended optical masses to be 75 kg	As specified	Yes

Design Requirements

Req	Description	Value	Compliance
H	Cabling		
H.1	Cable clamping and routing provisions to be made that prevent cables from touching.	Design not yet detailed	Not yet
I	Vacuum Compatibility		
I.1	Structures designed for high vacuum	As specified	Yes
I.2	Approved materials	As specified	Yes
I.3	Welds to be full penetration to avoid trapped volumes	As specified, no welds	Yes
I.4	Trapped volumes to have venting holes	Incomplete	Not yet
I.5	Tapped holes to be made 0.005” over to minimize galling	As specified	Yes
I.6	Nuts used in vacuum locations to be tapped .005” over	As specified	Yes
I.7	SST screws to be used in Al, silver plated SST screws used in SST. Proper sizing shall be used for plated screws	As specified	Yes
I.8	Lubricants are not allowed	As specified	Yes
I.9	Processing (cleaning, sampling, baking, assembly, packaging & labeling)	To be addressed in Fabrication Phase	Yes
J	Drawing Notes		
J.1-13	Various drawing requirements and callouts	To be addressed in Detail Design Phase	Yes

Project Risks

Risk	Mitigation
Mass estimate is significantly inaccurate	Add or remove mass from payload (not ideal), or redesign the Spring and Flexure for correct mass
Spring and Flexure performance are different than designed	Redesign the Spring and Flexure
Zero Moment points are displaced from theoretical locations	Redesign and replace Flexure Lower Mount Plate, Support Post Cap, or Flexure Mount as necessary
Stage 1 bending mode is below 250 Hz	None
Stage 0 deforms more than predicted under static loading, due to support tube compliance	Readjust sensors and actuators in situ

Prototype Initial Cost Estimate

Discussion

Project Schedule

Discussion