Large Optics Suspension Final Design Review

1. **Significant Changes from PDR**
   (S. Kawamura, 10 min)
2. **Important Issues**
   (M. Barton, 20 min)
3. **Mechanical Design**
   (J. Hazel, 90 min)

Sep. 25, 97 at ECR

Significant Changes from PDR
(S. Kawamura)

- Actuator Range
- Magnetic Pitch Balance (M. Barton)
- Actuator Imbalance
- Thermal Noise Allocation
- LOS 3 (J. Hazel)

Required Actuator Range and Initial Pitch Imbalance

Mode		Range	Frequency Dependence
Displacement	Operation	20 μm_{pp}	1 Hz Pole 40 Hz zero
	Acquisition	20 μm_{pp}	Flat
Orientation		0.5 $mrad_{pp}$ (pitch) 0.5 $mrad_{pp}$ (yaw)	1 Hz Pole 40 Hz zero

- **Initial Pitch Imbalance: 0.1 mrad**
  - ››Magnetic pitch balance (-> M. Barton)
  - ››Fine reference (-> ASC)

Actuator Imbalance

- **Actuator Imbalance: 0.01**
  - ››No significant cross-coupling from the LSC and IOO signal to orientation of the optics.
  - ››No significant cross-coupling from the ASC signal to displacement of the optics.
- **Magnet Strength Variation : 0.05**
  - ››Good enough for ambient magnetic field fluctuations.
  - ››An adjustable output matrix will cancel the variation.

Required and Measured/ Estimated Thermal Noise

Damping Mode/ Mechanism	Noise Allocation		Loss at 100 Hz	Measured/ Estimated Loss at 100Hz
	@ 40 Hz	@ 100 Hz		
Internal mode	19%	75%	8.2×10^{-7}	8.2×10^{-7}
Pendulum	90%	58%	6.0×10^{-6}	3×10^{-6}
Pitch	10%	6%	5.4×10^{-4}	8×10^{-5}
Yaw	10%	6%	7.8×10^{-4}	$< 8 \times 10^{-5}$
Vertical	10%	6%	2.8×10^{-3}	2.5×10^{-4}
Eddy Current Damping	20%	20%	7.5×10^{-7}	4.2×10^{-7}
Total	96%	97%	N/A	N/A

Important Issues
by M. Barton

- This section is a grab-bag of miscellaneous issues:
  - Analytical checks on eddy current damping
  - Design of a system for extra control of pitch
  - Resonance testing of the LOS mockup

Eddy Current Damping Calculation

- Method of calculation
  - Divide conductor into independent conducting loops
    - for suspension wire, exactly one loop
    - in other cases, invoke axial symmetry
  - Calculate B-field perpendicular to axis
  - Calculate emf in loop from flux cut per time
  - Calculate current in loop from emf, resistivity
  - Calculate power loss from current, B-field
  - Integrate over all loops
- Validate against Miyoki's measurement
  - Factor of 3 uncertainty due to
    - uncertainty in magnet strength
    - uncertainty in distance (inverse sixth power!)

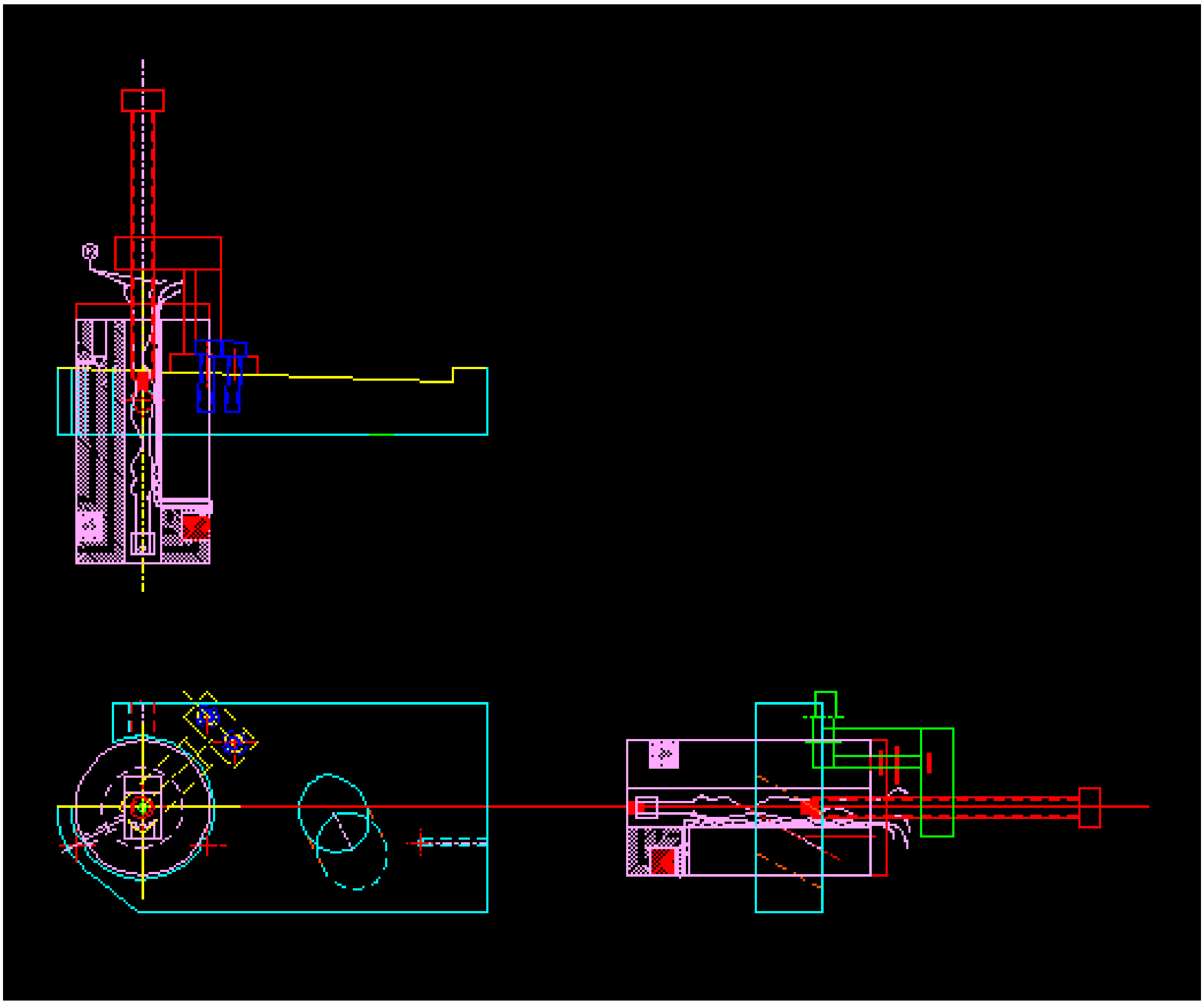
Magnetic Pitch Adjustment System for LOS

- Two-wire suspension means no control of pitch through wires.
- Balancing the optic is a delicate manual operation.
- Initial pitch should be comfortably in center of the dynamic range of the actuators, but this is difficult.
- We would like to apply (relatively) large extra torque from off the optic.
- Torque should be adjustable but thereafter static.
- Torque should be low noise.
- Solution: use permanent magnets.

Design Overview

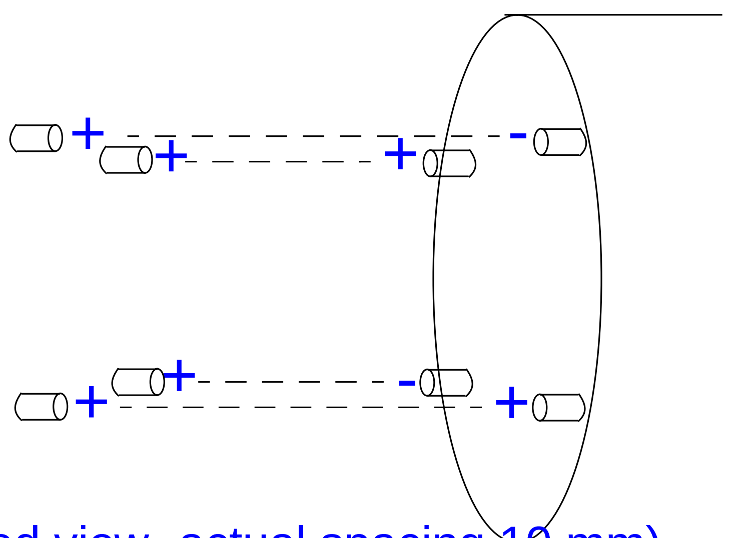
- A pitch adjustment magnet (PAM) is placed opposing each of the 4 magnets on the back face of the optic.
- The PAM is mounted on a non-conductive screw passing up the hollow center of the sensor actuator head.
- The position of the PAMs is adjusted by turning the screws with a tool from the rear.
- Equal and opposite numbers of turns on the top and bottom screws provide near-pure pitch adjustment. (Yaw also possible.)

Mechanical Design



Nulling of Net Force

- Pure pitch torque but no net force is desirable.
- Therefore the PAMs are *not* staggered in polarity, so that like-like and like-unlike pairs alternate:



(Exploded view- actual spacing 10 mm)

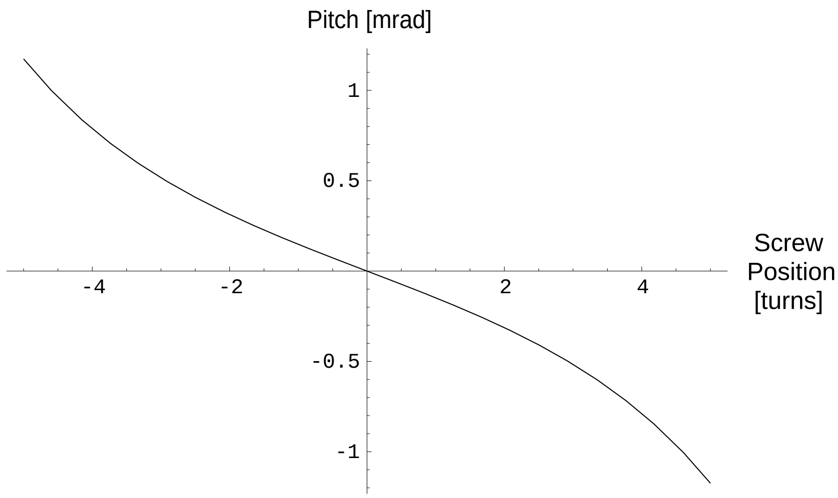
- Provided the PAMs are coplanar, there is no net force for small angles for any position.
- Restoring torque is also zero to first-order.

Eddy Current Damping Due To Pitch Adjustment Magnets

- Eddy current damping was calculated.
- Total budget for thermal noise
  - 1.6×10^{-20} $\mathrm{m} / (\sqrt{\mathrm{Hz}})$
- PAM to wire loop supporting optic:
  - 1.7×10^{-23} $\mathrm{m} / (\sqrt{\mathrm{Hz}})$
- PAM to optic magnet:
  - 2.6×10^{-22} $\mathrm{m} / (\sqrt{\mathrm{Hz}})$
- Optic magnet to PAM:
  - 2.6×10^{-22} $\mathrm{m} / (\sqrt{\mathrm{Hz}})$
- PAM to optic magnet standoff:
  - 5.9×10^{-22} $\mathrm{m} / (\sqrt{\mathrm{Hz}})$
- Conclusion: negligible

Dynamic Range and Precision of Adjustment

- With
  - ›› PAMs identical to optic magnets
  - ›› gap between pole faces of 10 mm
  - ›› thread pitch of 32 threads per inch
  - ›› thread range of 8 turns
- The dynamic range is 3 mrad(pp).
- Response is fairly linear.
- 0.25 turn gives around 0.07 mrad.



Resonances of Support Structure (i)

- Principal free/free modes are predicted to be
  - “Twist” - 424.6 Hz
  - “Leaning” - 448.7 Hz
  - “Bowing” - 728.1 Hz
  - “2nd Order Leaning” - 762.7 Hz
- Measured values are
  - “Twist” - 388.7 Hz
  - “Leaning” - 420 Hz
  - “Bowing” - 725 Hz
  - “2nd Order Leaning” - 762.7 Hz
- Qs are of order 750-1000 but this an upper bound and will fall when the structure is clamped.

Resonances of Support Structure (ii)

- Earlier attempts to measure resonances gave systematically low values.
- The discrepancy was traced to the use of optical table (the top surface is only loosely connected to the honeycomb body).
- Using a large milling machine as a test bed gave satisfactory results.
- Predicted resonances:
  - “Bowing” - 149.5 Hz
  - “Leaning” - 166.4 Hz
  - “Twist” - 321.6 Hz
- Measured resonances:
  - “Leaning” - 170 Hz
  - “Bowing” - 177 Hz
  - “Twist” - 311.2 Hz

LARGE OPTICS SUSPENSION FINAL MECHANICAL DESIGN
by J. Hazel

- **INTRODUCTION**
- **SUSPENSION DESIGN OVERVIEW**
- **SUSPENSION DESIGN CHANGES,IMPROVEMENTS AND VALIDATION**
- **FIXTURE OVERVIEW**
- **FIXTURE CHANGES AND IMPROVEMENTS**

DESIGN PHILOSOPHY

- Meet Requirements
- Reliability
- Simplicity - Modularity
- Safety - for the optic and the technician
- As little excess noise as possible

CORE OPTICS

Table 1: Core Optics Parameters

OPTIC	ETM	ITM 4k	RM 2k&4k	ITM 2k	BS 2k&4k	FM
diameter, mm	250	250	250	250	250	250
thickness, mm	100 thick side	100 thick side	97.5 thick side	100 thick side	40 thin side	100 thick side
wedge angle,deg	2.000 single sided	1.167 symm	2.406 symm	0.567 symm	1.000 symm	2.000 single sided
wedge orientation	up	up	down	up	up	up
incidence angle,deg nominal	90	90	90	90	45	45
height adapter,mm, nominal	150	150	43* 26*	150	64 107	150

*Recycling mirrors are mounted in HAM chambers. Height adapters are mounted to the bottom plate rather than the top plate.

From LIGO-T970091-00-D, “Determination of the Wedge Angles for the Core Optics Components”.

LOS TYPES

LOS1 STRUCTURE TYPE: 40cm wide x 22cm deep x 62cm high [15.5” x 22” x 24.25”]
LOS2 STRUCTURE TYPE: 52cm wide x 23cm deep x 62cm high [20.5” x 23” x 24.25”]

OPTIC	ETM	ITM 4k	RM 4k	ITM 2k	RM 2k	BS 4k	BS 2k	FM
suspension name	LOS1a	LOS1b	LOS1c	LOS1d	LOS1e	LOS2a	LOS2b	LOS3
structure type	LOS1	LOS1	LOS1	LOS1	LOS1	LOS2	LOS2	LOS1
differences	basic	A,B,D	A,B,D, E,F,G, H	A,B,D	A,B,D, E,F,G, H	A,B,C, D,E,I,J, K	A,B,C, D,E,I,J, K	I,L

Fixtures:
A = Guide Rod Fixture
B = Wire and Optics Fixture
C = Magnet/Standoff Fixture
D = Test Mass Fixture

E = Height Adapter
F = Side Standoff
G = Wire Standoff

H = Guide Rod
I = top plate
J = bottom plate
K = suspension block
L = side sensor/actuator plate

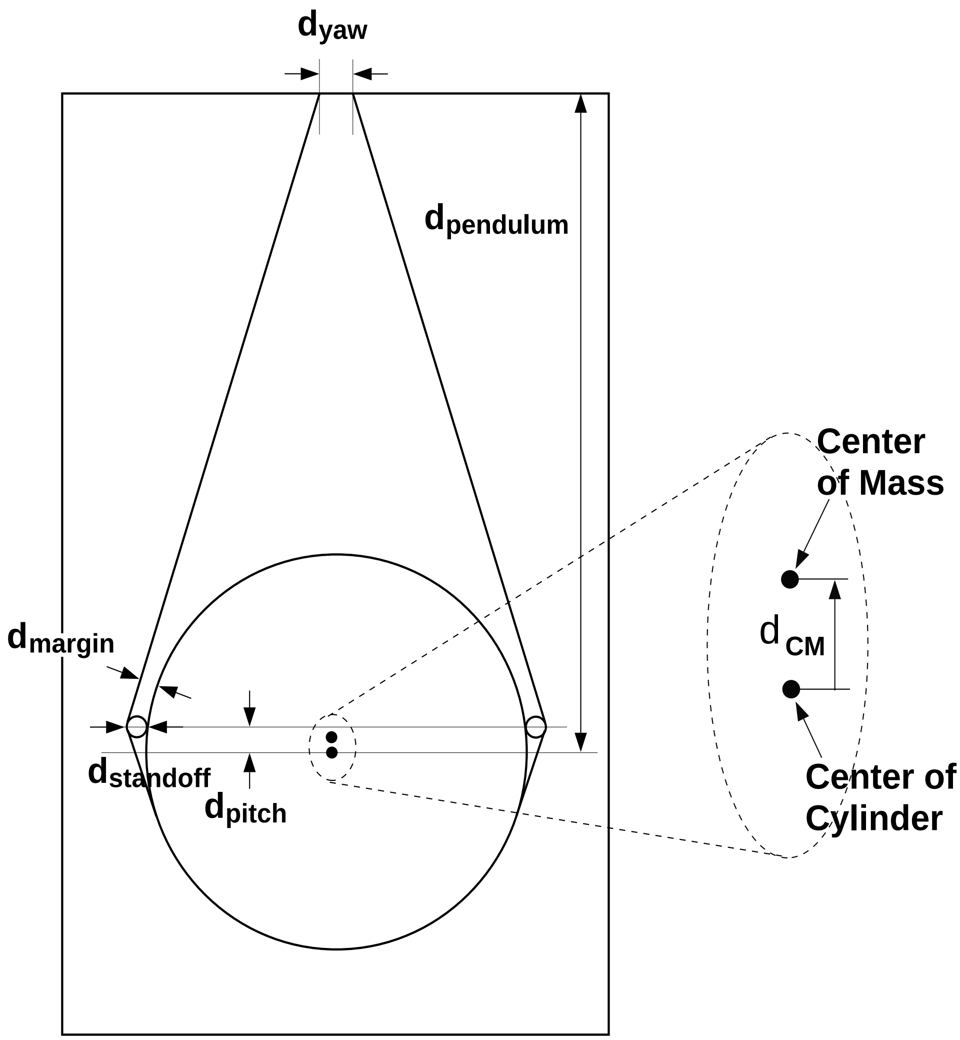
LOS PROTOTYPE

please view this at Caltech ftp site in /home/ligo/anonymo/sdrc/los1pict.pdf

DESIGN OVERVIEW

- The suspension assembly consists of a welded suspension support structure.
- The optical component is suspended by a single loop of wire from a suspension block with wire standoffs and guide rods between the suspension wire and the component.
- The optical component is damped and actuated by sensor/actuator heads and magnet/standoff assemblies.
- The optical component is protected during operation and held during transfer by a safety cage and safety stops/chamfer stops.
- The suspension support structure is strengthened by stiffening plates and gussets to increase its resonance frequencies.

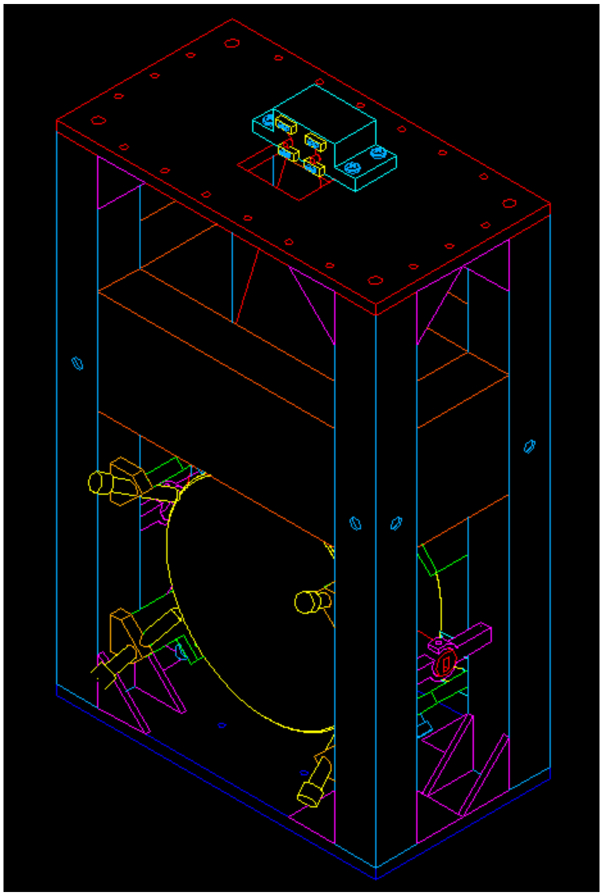
SUSPENSION CONFIGURATION



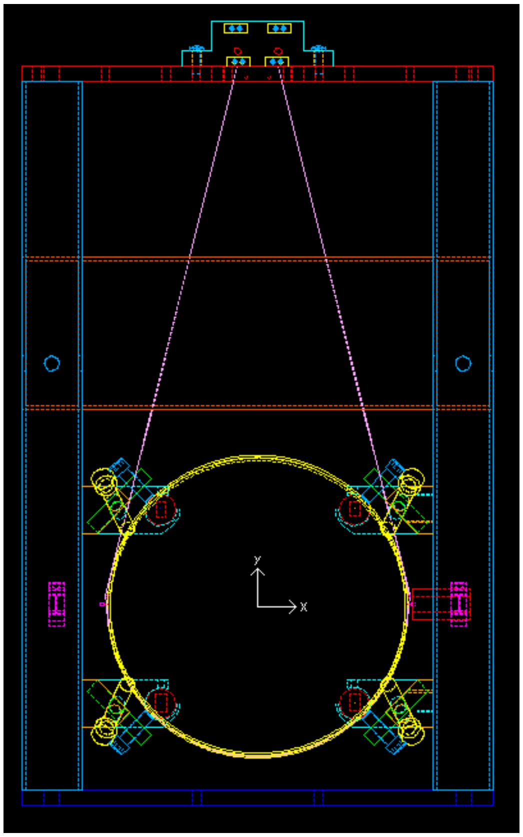
SUSPENSION CONFIGURATION

Parameters	*LOS 1*					*LOS 2 a, b*	*LOS 3*
	a	*b*	*c*	*d*	*e*		
Optic name	ETM	ITM, 4k	RM, 4k	ITM, 2k	RM, 2k	BS, 4k,2k	FM
Pendulum Frequency (Hz)	.744	.743	.741	.743	.741	.744	.744
Pitch Frequency (Hz)	0.600	0.600	0.600	0.600	0.600	0.600	0.600
Yaw Frequency (Hz)	0.500	0.499	0.501	0.497	0.501	0.500	0.500
Violin Frequency (Hz)	336	339	334	341	334	223	336
Vertical Frequency	12.85	12.72	12.86	12.63	12.86	19.36	12.85
$d_{pendulum}$ (mm)	450	450	450	450	450	450	450
d_{CM} (mm)	1.4	0.8	-1.8	0.4	-1.8	1.6	1.4
d_{pitch} (mm)	8.2	7.63	4.92	7.24	4.92	7.5	8.2
d_{yaw} (mm)	33.3	33.3	33.3	33.3	33.3	28.9	33.3
$d_{standoff}$ (mm)	ϕ2.8	ϕ2.8	ϕ3.5	ϕ2.8	ϕ3.5	ϕ2.8	ϕ2.8
d_{margin} (mm)	0.956	0.824	0.824	0.734	0.824	0.681	0.956

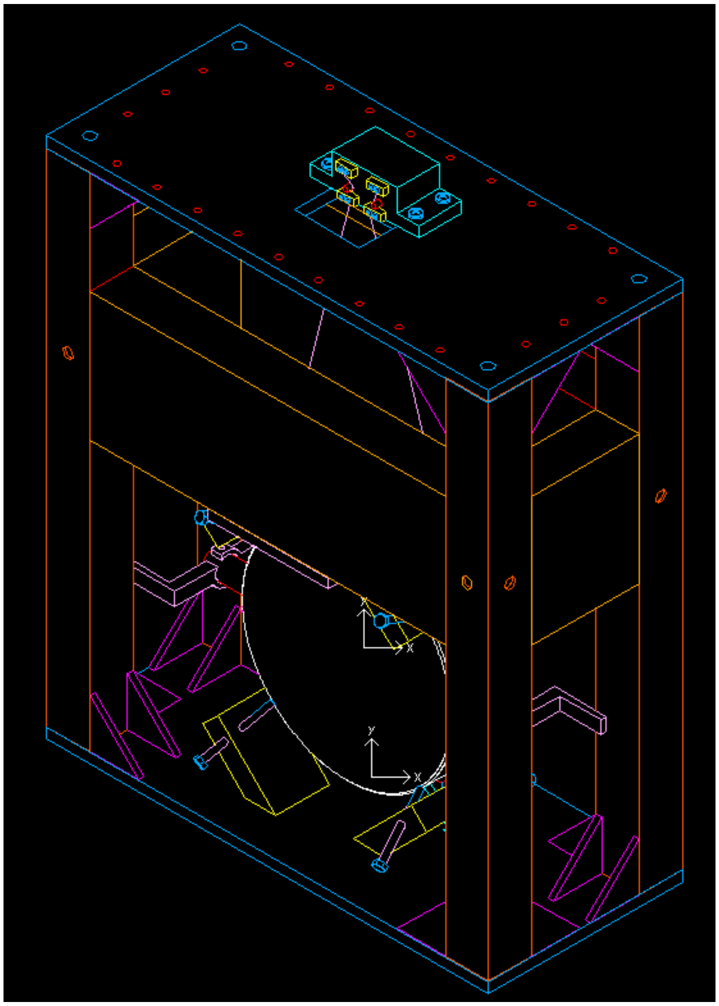
SUSPENSION CONFIGURATION - LOS1



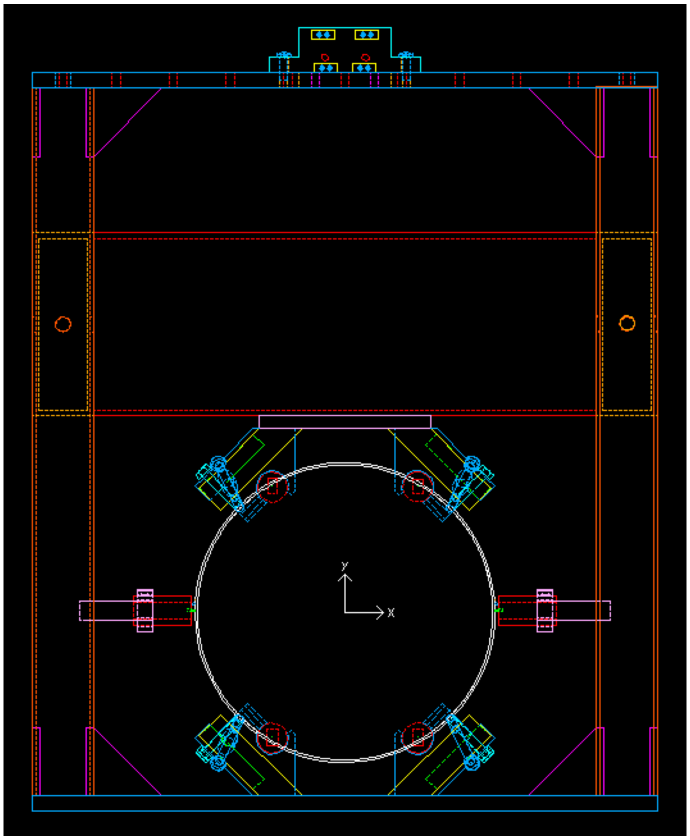
SUSPENSION CONFIGURATION - LOS1



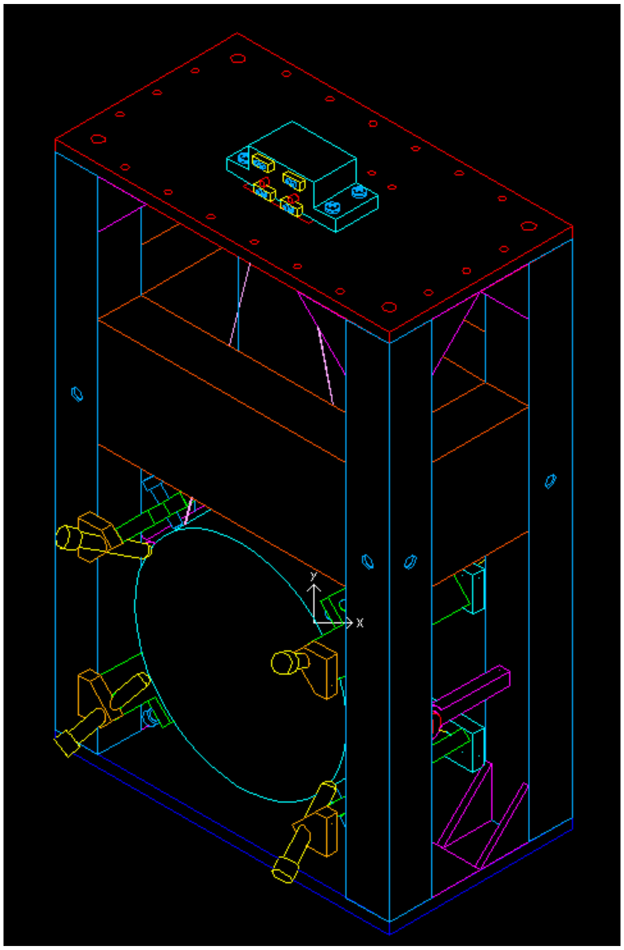
SUSPENSION CONFIGURATION - LOS2



SUSPENSION CONFIGURATION - LOS2



SUSPENSION CONFIGURATION - LOS3



CLEAR APERTURE REQUIREMENTS AND DESIGN

From LIGO-E950099-04-D, “Core Optics Components Requirements (1064)”,

Physical Quantity	*Test Mass* *ETM*	*ITM*	*Beam splitter*	*Recycling mirror*
Diameter of substrate, ϕ_s (cm)	25	25	25^{TBD}	25
Substrate Thickness, d_s (cm)	10	10	4 **TBD**	10
1 ppm intensity contour diameter (cm)[a]	24	19.1	30.2[b]	19.2

a. See Appendix A for exact definition.

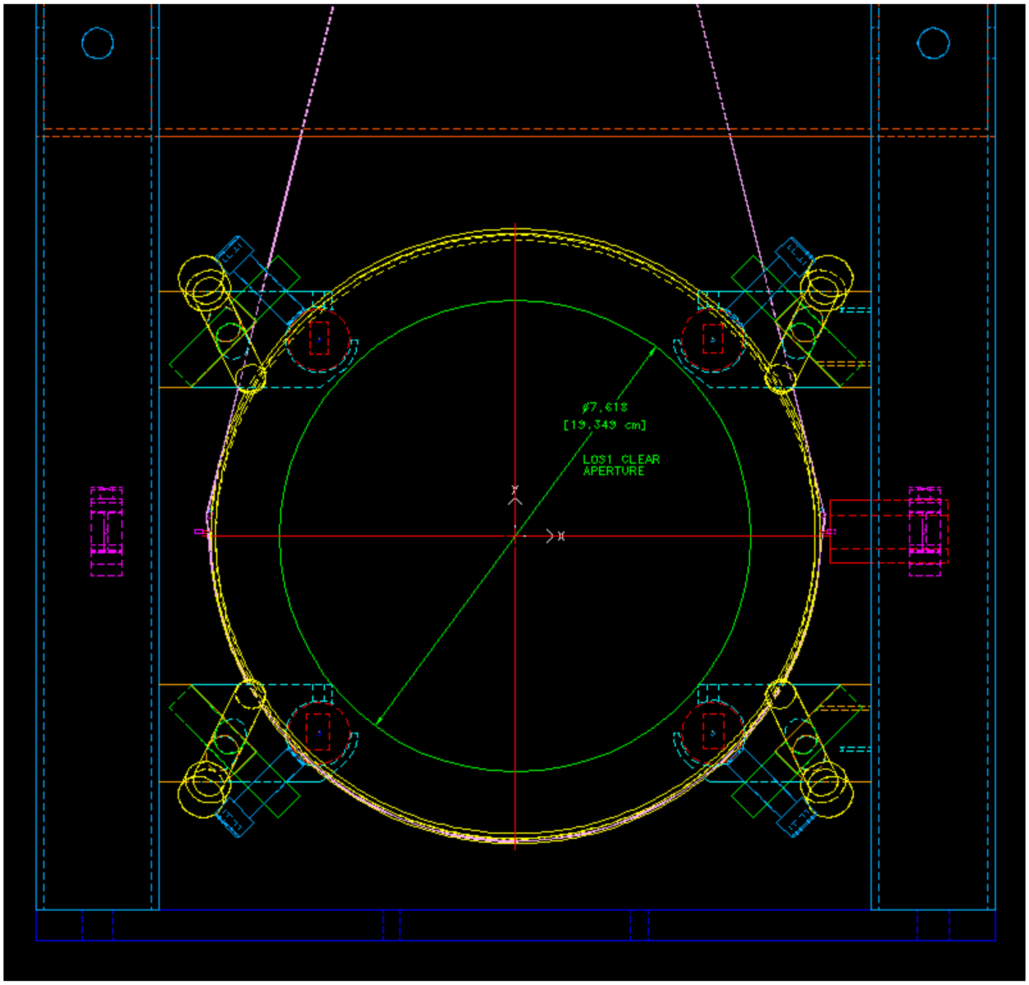
b. For these 45^o angle of incidence optics, this is the smallest diameter circle centered on the optic face which is everywhere outside of the 1 ppm intensity field.

Suspensions were designed to keep the faces of the optics as clear as possible at the angles of interest.

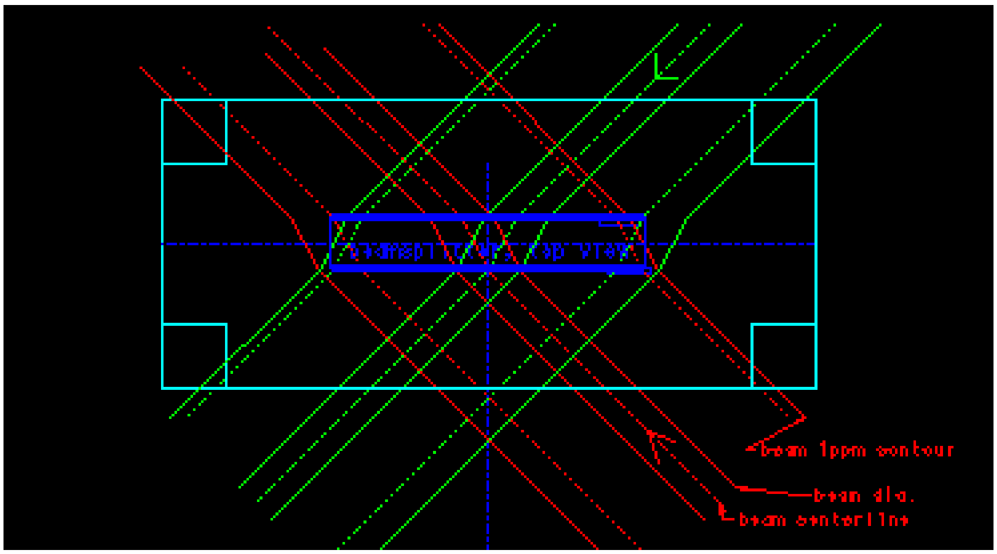
LOS1 clear aperture of 19.3cm dia [7.6”].

LOS2 and LOS3 constrained by optic size rather than suspension geometry.

CLEAR APERTURE DESIGN - LOS1



CLEAR APERTURE DESIGN - LOS2



SUSPENSION WIRE

- **Type: Steel music wire**
- **Density: 7.8 g/cm^3**
- **Diameter: 0.31 mm [.0122”]**
- **Ultimate Tensile Strength: 21.4 kg**
- **Yield Strength: 75% of Ultimate Tensile Strength**

GUIDE ROD AND WIRE STANDOFF

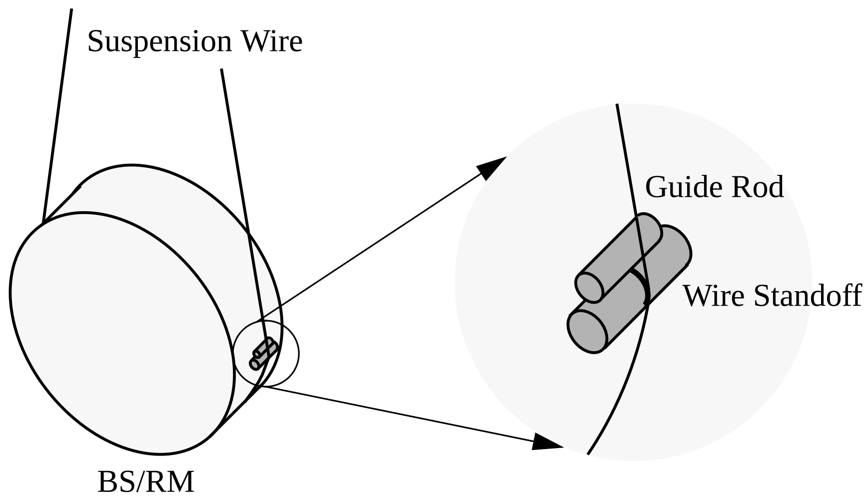


Fig. 1. Guide rod and wire standoff.

MAGNET AND DUMBBELL STANODFF

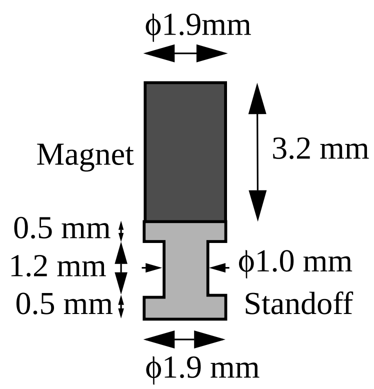


Fig. 2. Magnet standoff assembly.

Magnet: Material - Nd:Fe:B (NEO-35, Curie Temp 337 degrees C)
Standoff: Material - 6061-T6 Aluminum

DESIGN CHANGES, IMPROVEMENTS AND VALIDATION

in no particular order:

- DUMBBELL STANDOFFS
- CONDUCTIVE TEFLON SAFETY STOPS
- ADHESIVE TESTING/APPLICATION
- CONDUCTIVE COATING ON SENSOR/ACTUATOR HEADS
- MAXIMUM COIL CURRENT TEST
- RGA SCAN OF SENSOR/ACTUATORS AND KAPTON CABLES
- PROTOTYPE TEST
- SPECIFICATION
- QUALITY CONFORMANCE WORKSHEET

DUMBBELL STANDOFFS

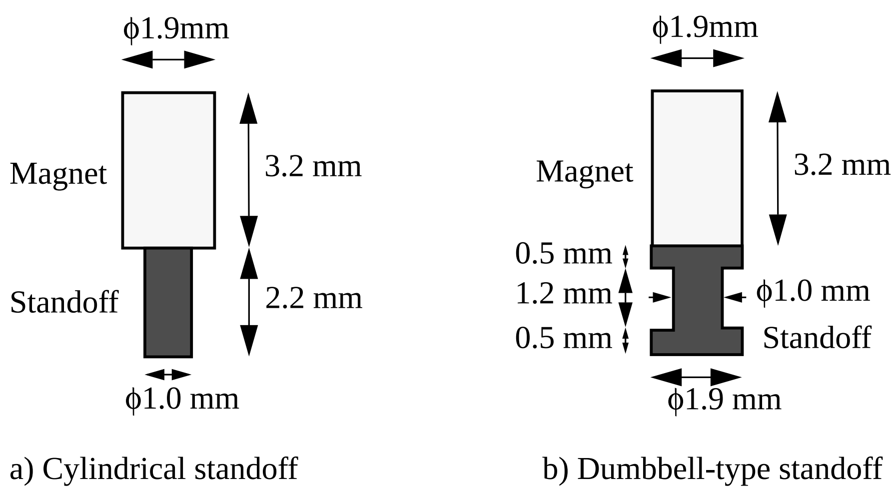


Figure 3: Dimensions of magnet/standoff assemblies using a) a conventional cylindrical standoff and b) a dumbbell-type standoff.

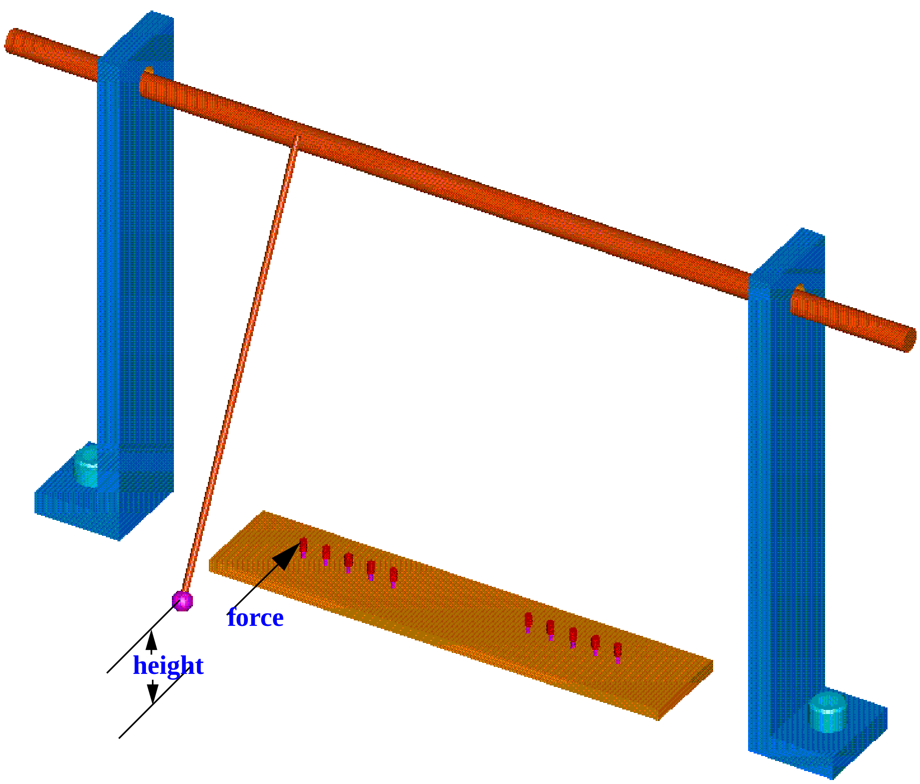
- **MORE ROBUST AND MUCH EASIER TO HANDLE THAN THE UNSTABLE CYLINDRICAL STANDOFF**
- **3.5X MORE SURFACE AREA FOR ADHESIVE**
- **MECHANICAL LOSSES WERE NOT DEGRADED WHEN TESTED ON A LIGO LARGE TEST MASS AROUND 100 Hz.**
- **REPORTED IN “DUMBBELL-TYPE STANDOFF FOR MAGNET/STANDOFF ASSEMBLY” LIGO-T970096-00-D.**

CONDUCTIVE TEFLON SAFETY STOPS

- GRAPHITE FILLED TEFLON
- COMPARED TO TEFLON, PASSED ELECTROSTATIC TEST WITH THE 40 METER RECYCLING MIRROR SUSPENSION
- PASSED RGA SCAN AFTER BAKING AT 120 DEGREES C
- FOUR CONDUCTIVE TEFLON SAFETY STOPS INSTALLED IN THE RECYCLING MIRROR SUSPENSION IN THE 40 METER INTERFEROMETER.
- MANUFACTURED BY FURON DIXON, BRISTOL, RHODE ISLAND
- RESEARCHING POSSIBLE GRAPHITE COMPOUND WITH TEFLON PFA 440HP (LOW EXTRACTABLE FLUORINE)

ADHESIVE TESTING/ APPLICATION

- ONGOING TESTING OF VAC-SEAL, TORR SEAL AND OTHER ADHESIVES TO INCREASE RELIABILITY AND REPEATABILITY OF GLUING OPERATIONS.
- OPTIMIZE PREPARATION AND CLEANING OF STANDOFFS AND MAGNETS TO ENSURE GLUE JOINT INTEGRITY ----> FINE ABRASION
- CURRENTLY TESTING CERAMIC ADHESIVES INCLUDING GRADED JOINTS WITH AREMCO'S CERAMABOND 571
- OVERVIEW OF TESTS IN "ADHESIVE TESTING" LIGO-T970006-00-D



CONDUCTIVE COATING ON SENSOR/ACTUATOR HEADS

- **GOLD COATING ON SENSOR/ACTUATOR HEADS BEFORE LED AND PHOTODIODE HAVE BEEN INSTALLED.**
- **PROTOTYPE COATED, FIRED, BAKED AND RGA SCANNED.**
- **PROTOTYPE PASSED RGA SCAN AFTER BAKING AT 120 DEGREES C.**
- **COATING THICKNESS CALCULATED TO WEIGH REDUCTION OF ELECTROSTATIC CHARGE AGAINST EDDY CURRENT DAMPING EFFECT.**

MAXIMUM COIL CURRENT TEST

- EXAMINED MAXIMUM DC CURRENT OF THE COIL OF A SENSOR/ACTUATOR HEAD.
- 150mA DC CURRENT HEATED THE COIL HEAD TO 33 DEG. C ON THE SURFACE AND 42 DEG. C INSIDE WHEN ROOM TEMPERATURE WAS 19 DEG. C.
- NO DAMAGE TO LED AND PHOTODIODE.
- PASSED RGA SCAN
- RESULTS REPORTED IN “MAXIMUM CURRENT OF THE SUSPENSION ACTUATOR COIL” LIGO-T960148-01-D.

RGA SCAN OF SENSOR/ACTUATORS AND KAPTON CABLES

- BAKING AND RGA SCANNING OF THE SENSOR/ACTUATOR HEAD ASSEMBLIES AND THEIR KAPTON CABLES WERE UNDERTAKEN AND REPORTED AFTER GROSS RGA FAILURES OF THESE COMPONENTS
- TESTS CONCLUDED THAT NON-VACUUM COMPATIBLE GLUE WAS USED TO ATTACH STIFFENERS TO THE KAPTON CABLES AND FAULTY CLEANING PROCEDURES WERE USED ON THE VAC SEAL EPOXY.
- KAPTON CABLE MANUFACTURER HAS BEEN INSTRUCTED TO USE VACUUM COMPATIBLE ADHESIVE.
- ACETONE SHOULD NOT BE USED NEAR CURED VAC SEAL
- RESULTS REPORTED IN “RGA SCANNING TEST OF SENSOR/ACTUATOR HEAD AND KAPTON CABLE” LIGO-T970094-02-R.

PROTOTYPE TEST

- ALUMINUM DUMMY MASS WAS SUSPENDED IN A LARGE OPTICS SUSPENSION PROTOTYPE.
- MECHANICAL RESONANCES OF THE SUSPENSION STRUCTURE WERE MEASURED. ANALYSIS PERFORMED AND ASSEMBLY REDESIGNED. MOCK-UP OF UPDATED DESIGN FABRICATED AND TESTED.
- THESE MEASUREMENTS MET THE DESIGN REQUIREMENTS.
- TEST RESULTS REPORTED IN “LARGE OPTICS SUSPENSION PROTOTYPE TEST RESULTS” LIGO-T970161-00-D. (WORK IN PROGRESS)

SPECIFICATION

- LARGE OPTICS SUSPENSION ASSEMBLY SPECIFICATION, LIGO-E970038-00-D, CREATED TO PROVIDE FABRICATION REQUIREMENTS AND ASSEMBLY AND OPTIC HANGING INSTRUCTIONS.
- DETAILS THE USE OF THE FIXTURES, CLEANING AND BAKING PROCEDURES, QUALITY ASSURANCE REQUIREMENTS AND IDENTIFICATION REQUIREMENTS.
- LESSONS LEARNED FROM TWO SOS PROTOTYPE OPTICS' SUSPENDING AND BALANCING FOLDED INTO DOCUMENT.

QUALITY CONFORMANCE WORKSHEET

- LARGE OPTICS SUSPENSION ASSEMBLY QUALITY CONFORMANCE WORKSHEET, LIGO-E970132-00-D, CREATED TO PROVIDE A DIMENSIONAL CHECK OF SUSPENSION AND FIXTURE MECHANICAL PARTS, AND A COLLECTION OF COMPONENT AND SUSPENSION DATA FOR EACH SUSPENSION.
- COMPLETED WORKSHEETS WILL BE USED TO STREAMLINE SUSPENSION PREPARATION AND ASSEMBLY PROCESSES AND TO INCREASE SUSPENSION RELIABILITY AND REPEATABILITY.

FIXTURE OVERVIEW (I)

- **Set Screw Tool** Used to ease in the installation of the set screws in the Sensor/Actuator Plates.
- **Magnet-to-Dumbbell Standoff Fixture** Used to configure and bond the magnets to the dumbbell shaped aluminum standoffs.
- **Magnet/Standoff Assembly Fixture** Used to position and epoxy the magnet/standoff assemblies to the face of the optic.
- **Guide Rod Fixture** Used to position and bond a guide rod, a wire standoff and side magnet/standoff assemblies to the side of the optic.
- **Test Mass Fixture** Aluminum “optic” has the same size, wedge, chamfer and approximate mass as the fused silica optic.
- **Measuring Microscope** Used to align the sensor/actuator plates to the magnet/standoff assemblies glued on the optic or dummy mass.

FIXTURE OVERVIEW (II)

- **Microscope Bushing** Bushing/adapter used to align the centerline of the microscope (crosshairs) to the centerline of the outside diameter of the bushing.
- **PZT Buzzer** Used for sliding the wire standoff along the side of the optic to change the pitch balance of the optic.
- **LED Fixture** Used to position and mount the LED relative to the photodiode in the sensor/actuator head.
- **Winch Fixture** Used to microposition the suspension wire vertically.
- **Height Adapter** Used to adapt suspension to its correct vertical position relative to the laser beam.
- **Fixture, Wire and Optics** Used to position the wire and to protect and move the optic into position in the suspension support structure.

FIXTURE CHANGES AND IMPROVEMENT

- **MAGNET-TO-DUMBBELL FIXTURE**
  - **Larger for “mass production”**
  - **Accommodate dumbbell**
- **GUIDE ROD FIXTURE**
  - **Completely redesigned from PDR to increase user-friendliness and decrease failure rate.**
  - **Installs one wire standoff and one guide rod**
- **MAGNET/STANDOFF ASSEMBLY FIXTURE**
  - **Completely redesigned from PDR to increase user-friendliness and decrease failure rate.**
- **WINCH FIXTURE**
  - **Easier and more reliable than manually pulling on wire**
- **SPECIFICATION**
  - **Covers fixture usage**