A renewal proposal

The Stanford Advanced Gravitational Wave Detector Research Program

Vacuum System in Stanford Engineering Test Facility

LIGO PAC 11
Meeting

LIGO-G010416-00-

Robert Byer

Faculty

Robert Byer	-	Lasers, Optics and Interferometry
Daniel DeBra	-	Seismic Isolation and Alignment
Martin Fejer	-	Materials, Lasers and Interferometry
James Harris	-	High power photodiode development
Robert Wagoner	-	Gravitational wave sources and analysis

History

• 10 Watt Laser development	1991 - 1995
• GALILEO Program	1996 - 1999
• MRI Funding ETF Vacuum System	1998
• Renewal of Stanford Advanced Gravitational Wave Detector Program	1999 - 2002
• Currently proposed Stanford Program	2002 - 2005

Presentation Outline

- Robert Byer
  - Project summary
  - Prior work from the Stanford Group
    - Lasers, optics and interferometry
    - Thermal loading
    - Advanced configurations
    - Active laser spatial mode control
    - High power photodiode development
    - Core optics development
- Sheila Rowan
  - Materials for test masses and suspensions
- Brian Lantz
  - Seismic isolation and alignment

Stanford Gravitational Waves Group

Faculty
Robert Byer, Daniel DeBra, Martin Fejer, James Harris, Robert Wagoner

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Undergraduate Students
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Stanford Research coupled with LIGO and LSC collaborators

Advanced LIGO should exceed LIGO performance through improvements in: **(2/3 effort)**

High power lasers, optics and interferometry

- New laser designs, effective thermal management and modelling, photodiode detection systems, lower loss substrate materials, lower loss optical coatings

Materials for test masses and suspensions (thermal noise)

- Changes in suspension fibers, new test mass materials, improved dielectric mirror coatings, bonding techniques

Seismic isolation

- Improved seismic isolation and alignment systems

Future improvements in performance (at various frequencies) may require: **(1/3 effort)**

Higher laser powers

- > 500W for improved shot noise performance

Management of thermal effects

- high thermal conductivity materials (silicon) to minimize thermal distortions
- well understood thermal models (MELODY)
- development of diffractive optics
- adaptive optic systems to correct thermal wavefront distortions

Alternative topologies to take advantage of the above

- all- reflective interferometers (silicon optics)
- delay lines

Improvements in thermal noise

- alternative test mass and suspension materials (silicon), cooling, delay-lines

Project Summary

Goals

- **Advanced LIGO**
  - the development of a prototype 200-W laser with the spectral, temporal, and spatial mode qualities required by Advanced LIGO
  - the design and demonstration of a pre-mode cleaner which will support the 200 W power and demonstrate filtered output power at the 160 W power level, that meets the Advanced LIGO specifications.
  - the study of laser beam induced thermal distortions and the means for minimizing thermal effects in interferometers
  - the development of a photo-detection system, capable of detecting 1 W of laser power with high quantum efficiency and operating at RF frequencies, required to meet the Advanced LIGO specifications.
  - the development of a multiple-stage stiff, active isolation and alignment system
  - the investigation of data analysis and data reduction

Project Summary

Goals

- **Future detectors**
  - the design and demonstration of an all-reflective Fabry-Perot interferometer capable of handling very high powers and incorporating a low-loss diffractive silicon input coupler.
  - the investigation of silicon as a material for test masses and suspensions that will enable cryogenic operation as well as operation at high circulating power levels
  - the study of flat-topped super-Gaussian beams in tabletop interferometers for both thermal distortion and thermal noise reduction

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Lasers, Optics and Interferometry

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Materials for Test Masses and Suspensions (Thermal Noise)

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Seismic Isolation and Alignment

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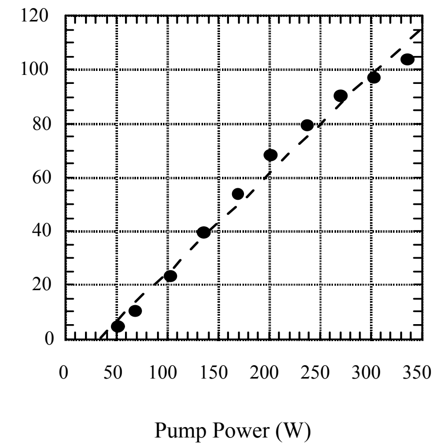
Lasers, Optics and Interferometry

Research in collaboration with wide variety of people and institutions both inside and outside LIGO and the LSC

Caltech, Univ. Florida, MIT, GEO 600 Group, Univ. of Adelaide, Sandia Labs, LLNL, Lightwave Technology, Crystal Systems Inc, and others

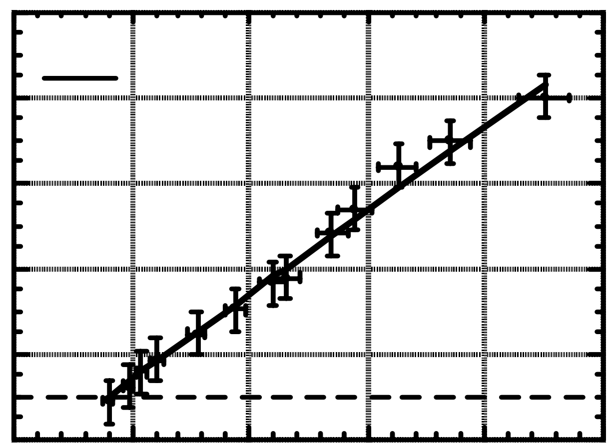
Prior Work - Lasers, optics and interferometry

- ## High power laser development
  - Invention of Nd:YAG Non-planar ring oscillator (NPRO), demonstration of high power injection locking, demonstration of high power Master Oscillator Power Amplifier (MOPA) systems
  - Research forms basis for laser designs for GEO 600, TAMA, VIRGO and LIGO
  - Adv. LIGO requires ~200 W for improved shot noise limited sensitivity
  - Edge-pumped slab design invented at Stanford >100W multi-mode operation demonstrated
  - Currently developing 2-slab MOPA system - 100 W single frequency target
  - **Aim to demonstrate MOPA system capable of meeting Adv. LIGO requirements by end of current grant**



Multi-mode power vs pump power or edge pumped Nd:YAG slab

- ## Laser noise
  - Studied MOPA laser quantum noise at RF frequencies - first measurement in this type of laser.
  - Good agreement with theory
  - **Essential for design of LIGO modecleaners to provide suitable filtering at modulation frequency**
  - Also developed novel above threshold OPO technique for amplitude noise suppression



Intensity noise for unsaturated triple-pass amplifier compared to theory

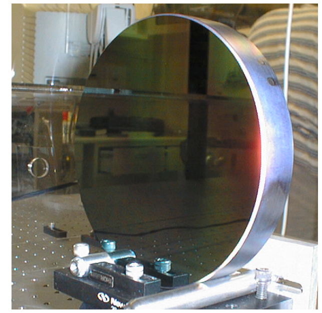
Prior Work - Lasers, optics and interferometry

- **Modelling of thermal loading effects**
  - Adv. LIGO powers ~ 10 X higher than LIGO - sets shot noise limited sensitivity
  - Depending on level of absorption in core optics - **thermal loading will stress stability limits of cavities**
  - Important to model, predict and understand thermal effects: "MELODY" computer model developed by Ray Beausoleil
  - Framework to simulate thermal lensing and aperture diffraction due to interferometer mirrors and beamsplitter
  - Used to study different optical schemes in thermally loaded regimes and specific thermal loading issues :
    - effectiveness of thermal compensation schemes,
    - expected behavior of optics in Adv. LIGO high power test bed in Gingin,
    - Australia, diffraction losses/thermal lensing at high laser powers in Adv. LIGO
  - In addition, being used to study significance of thermal lensing effects in current LIGO interferometers

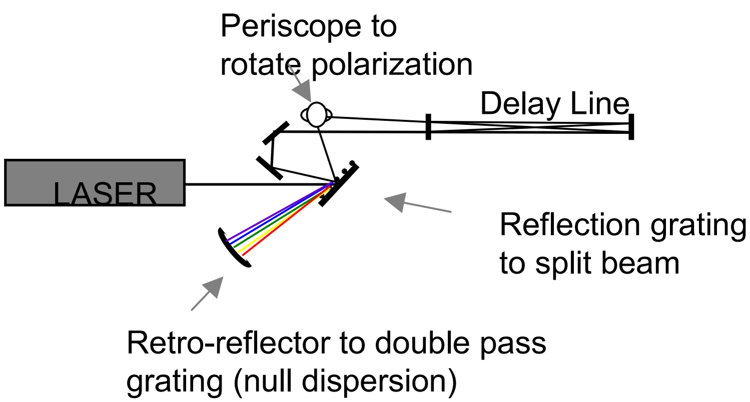
- **Thermal loading effects caused by high optical powers of importance for LIGO, Adv. LIGO and future detectors**

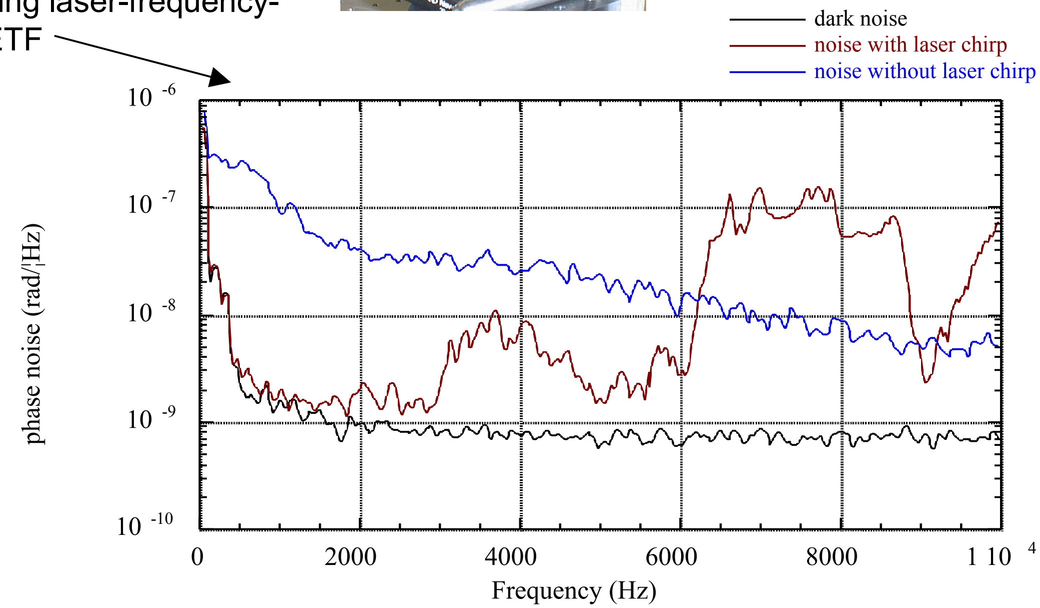
Prior Work - Lasers, optics and interferometry

- **Advanced interferometers**
  - In anticipation of the need for interferometer topologies **robust in thermally loaded** conditions, described and demonstrated all reflective interferometers using a grating beamsplitter
  - In particular studied the all-reflective delay-line Sagnac - greatly reduces control effort
  - demonstrated elimination of scattered light using laser-frequency-sweep technique in 10m system in Stanford ETF



6" dielectric coated silicon mirror

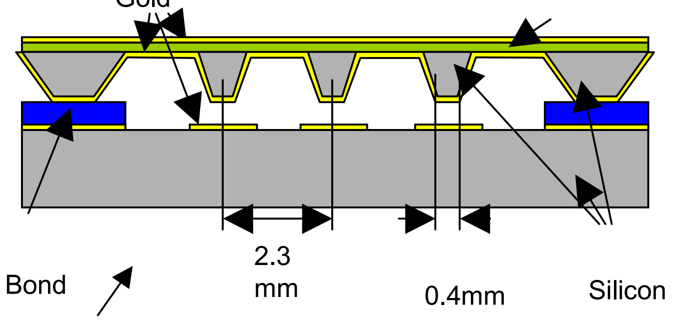




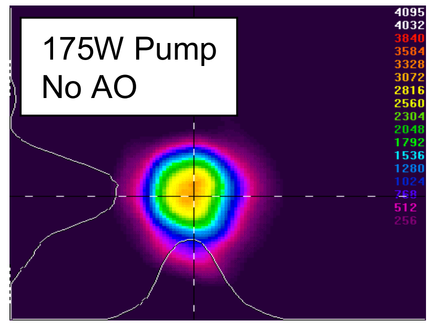
- **Thermal loading of a grating beamsplitter**
  - Diffraction grating thermally loaded with a Gaussian beam
  - Resulting distortion from non-uniform grating expansion results in phasefront distortion of beam
  - Measured using Shack-Hartmann wavefront sensor - data fits well with MELODY model
  - Results generalized to describe expected wavefront distortions in any substrate illuminated by a Gaussian

Prior Work - Lasers, optics and interferometry

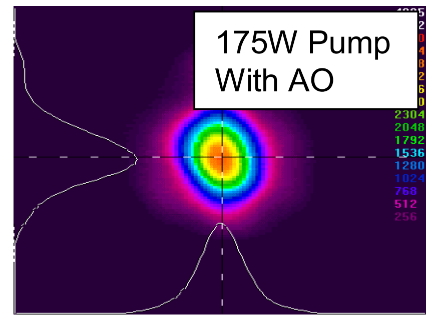
- **Active optic (AO) control of laser spatial modes**
  - Thermal distortions in laser (amplifier)/input optics chain limit TEM_{00} power available
  - Developed Shack-Hartmann wavefront sensors and silicon deformable mirrors - active mode control system
  - **actively correct thermal distortions** - eg from input optics, or final stage of amplifier system
  - Allows active modematching to modecleaner cavities



Gold coated deformable mirrors

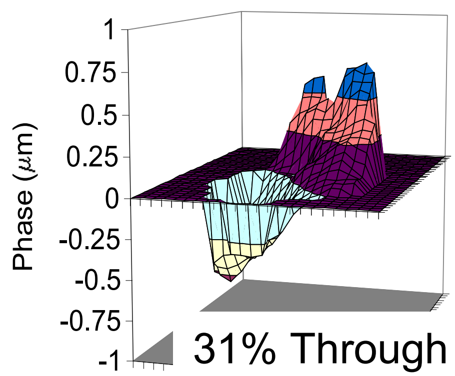


Distorted wavefront

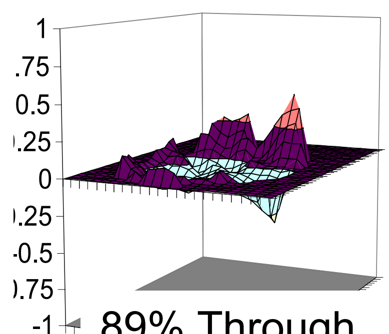


Corrected wavefront

Wavefront correction of beam passing through slab laser head pumped with 175W of diode power



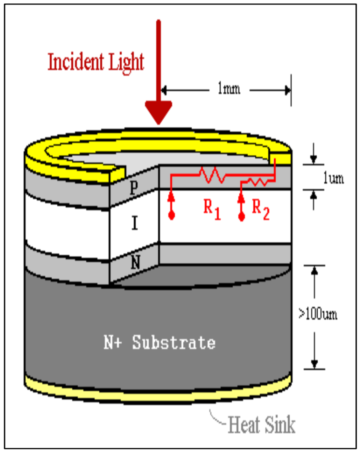
31% Through Mode Cleaner



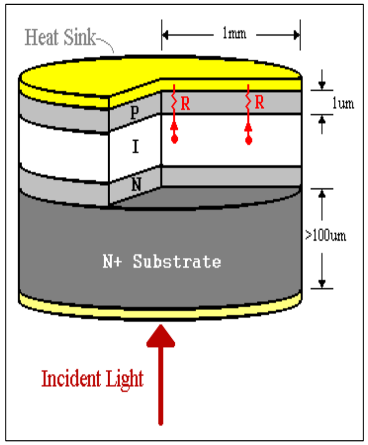
89% Through Mode Cleaner

Prior Work - Lasers, optics and interferometry

- **High power photodiode development**



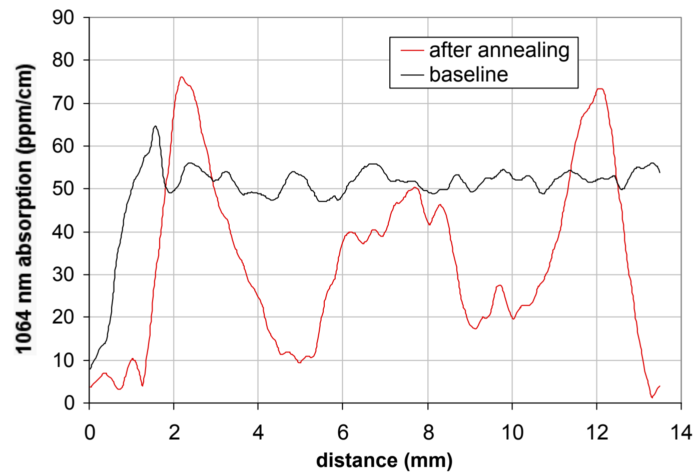
Conventional front illuminated design



Stanford back- illuminated design

- Adv. LIGO requires superior high speed - high power operation
- Novel back-illuminated photodiode design developed at Stanford
- InGaAs/InAlAs layers on GaAs substrate (graded buffer layer)
- Currently achieved 70% QE with 4MHz bandwidth
- Expect 90% QE through thinning substrate
- Verbal agreement with Hamamatsu Corp to manufacture diodes on successful completion
- **Providing Adv. LIGO with photodiode to meet required noise and linearity specs**

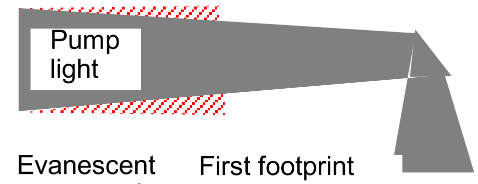
- **Core Optics Development**
  - Adv. LIGO circulating power limited by absorption of core optics
  - "Photothermal common path interferometry" (PCI) technique unique to Stanford - quantify absorption loss in sapphire
  - 40ppm/cm = "typical" loss in sapphire at 1064nm - requires adaptive thermal compensation of optics by heating
  - Our studies show moderate annealing could reduce absorption to <25ppm/cm - reduce (remove?) need to heat optics
  - Adv. LIGO specs require optical coating loss to be reduced by ~ x10 - program of study with MLD coating company
  - **Pathfinding processes to obtain low optical loss substrates and coatings to meet Adv. LIGO specs.**



Typical spatial profile of 1064nm absorption before and after annealing

Proposed Work - Lasers, optics and interferometry

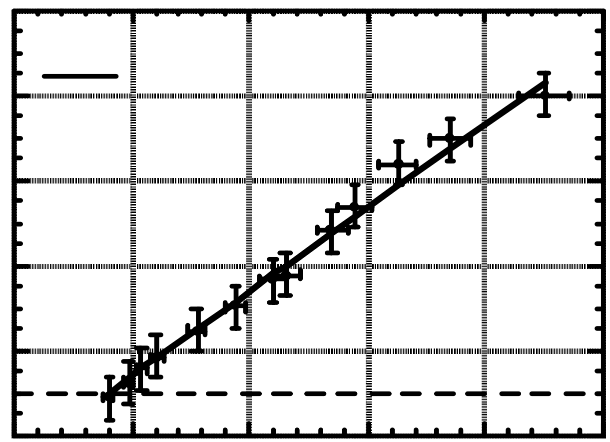
- **High power laser development**
  - Adv. LIGO requirements - ~ 200W single-frequency 1064nm
  - Demonstrate MOPA system to scale 20W LIGO MOPA to 200W level
  - Use three stage slab system - two end-pumped slabs then edge-pumped slab
  - System can to be scaled further to 500W level and above



Schematic of end-pumped slab (from Goodno 2001)

	Amplifier Pumping Topology	Pump Power (W)	Input Power (W)	Multi-mode Output Power (W)	TEM_{00} Output Power (W)
Amplifier 1	End-pumped slab	100	20	60	48
Amplifier 2	End-pumped slab	405	48	200	160
Amplifier 3	Edge-pumped slab	1400	160	500	400

- **Laser noise**
  - MOPA system will operate in **saturated** amplifier regime
  - Noise properties of this not yet well understood
  - Develop theory and measure experimentally
  - **Understanding of expected noise level essential for modecleaner design for Adv. LIGO**



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Proposed Work - Lasers, optics and interferometry

- **Modeling of thermal loading effects**
  - Adv. LIGO performance already constrained by thermal loading in transmissive optics
  - Extend our support of LIGO members using MELODY to model thermal effects in Adv. LIGO
  - Collaborate with LIGO Lab on integration of MELODY output with the End-to-End model
  - Study scaling properties of thermally loaded interferometers, starting with tabletop systems

- **Advanced configurations**
  - propose to develop **all-reflective** interferometer systems robust under high thermal loads

Three areas of study:

(1) The development of diffractive interferometers per se

(2) The extension of MELODY to model thermal effects in diffractive systems

(3) The development of suitable low-loss diffractive optical elements

(1) and (2):

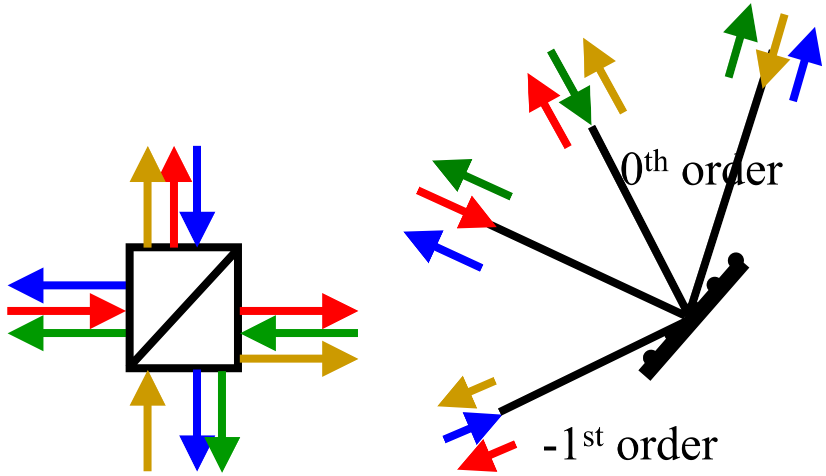
- Use an all-reflective Fabry-Perot as test-bed for for understanding all reflective systems
- Construct a fixed 3 - mirror 1m cavity with weak diffraction grating and thermally load.
- Develop MELODY code to study this and other all reflective topologies
- **Predict and study the behavior of 3-m system under thermally loaded conditions to understand power scaling issues**

Proposed Work - Lasers, optics and interferometry

Advanced configurations

(3) Development of **low-loss diffractive optics**

- In parallel with studying power scaling issues, propose to develop diffractive elements using **silicon substrates** suitable for high-power, low-scatter operation
- **Silicon is superior to sapphire under thermally loaded conditions**

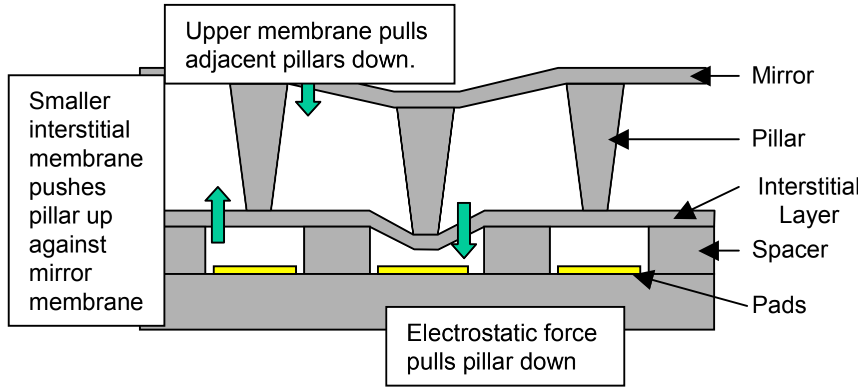


A transmissive beamsplitter and a grating are 4 port devices that are functionally equivalent

- We propose to collaborate with LLNL researchers, working in this field, firstly to develop weak (~1%) coatings required for input/output coupling in Fabry-Perot interferometers.
- Using knowledge gained from this, and the modeling studies, we propose to develop the 50% gratings required for beamsplitter applications
- Using the elements we develop, propose to demonstrate their use in an-reflective interferometer in the Stanford Engineering Test Facility
- Propose to use photo-thermal common-path interferometry (PCI) technique to study optical losses in diffractive silicon elements

Proposed Work - Lasers, optics and interferometry

- Active spatial mode control
  - Propose to develop an improved all-silicon 3-layer deformable mirror
  - Allows scaling to larger diameters without lowering resonant frequencies
  - All-silicon structure with gold coating and dielectric stack - enable **high-power operation**
  - Modify packaging to increase actuator numbers
  - Use to correct thermally induced higher spatial frequency aberrations
  - Use for “top-hat” beam-shaping for efficient power extraction in amplifiers



3-layer deformable mirror architecture

- **Core Optics Development**
  - Adv. LIGO pathfinding work on sapphire and coating absorption studies should be complete by start of program
  - Propose to extend characterization, diagnosis and analysis work on substrates and coatings for Adv. LIGO
  - Propose to use photo-thermal common-path interferometry (PCI) technique to study optical losses in diffractive silicon elements
- High power photodiode development
  - Propose use of totally new material system - Gallium Indium Nitride Arsenide (GaInNAs)
  - Take advantage of demand for material for high-brightness diodes for telecom applications
  - Significant advantage over InGaAs - lattice matched to substrate - no graded buffer layer
  - Varying N_2 content can optimize for 1064nm radiation
  - After fabrication, characterization, optimization - compare with previous InGaAs performance
  - **Downselect design for Adv. LIGO**

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Materials for Test Masses and Suspensions (Thermal Noise)

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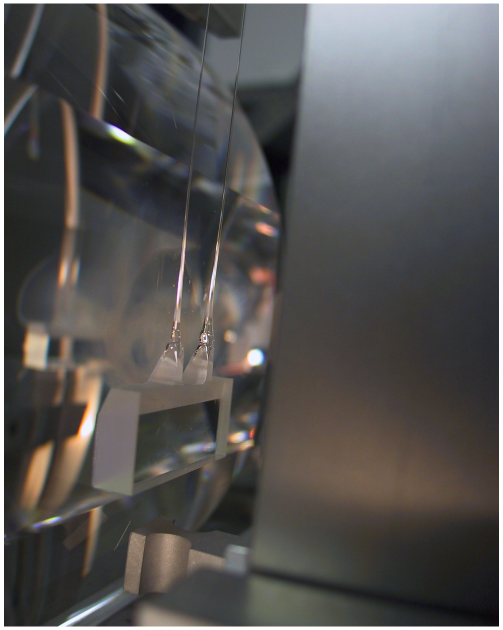
Materials for test masses and suspensions (thermal noise)

Research in collaboration with :

GEO 600, Syracuse University, Caltech, Moscow State University, University of Perugia, MIT

Prior Work - materials for test masses/suspensions

- **Thermal noise from test masses and suspensions - important limit for Adv. LIGO**
  - Adv. LIGO baseline design is upgraded GEO 600 suspension design - monolithic fused silica suspension
  - silicate bonding technique for jointing fused silica **invented at Stanford** (J. Gwo)
  - Developed for mirror suspension construction in collaboration with GEO - series of experiments - shown to add negligible excess mechanical loss.
  - **Lowest pendulum mode mechanical loss ever measured** on pendulum constructed using silicate bonding technique - collaboration with Moscow State

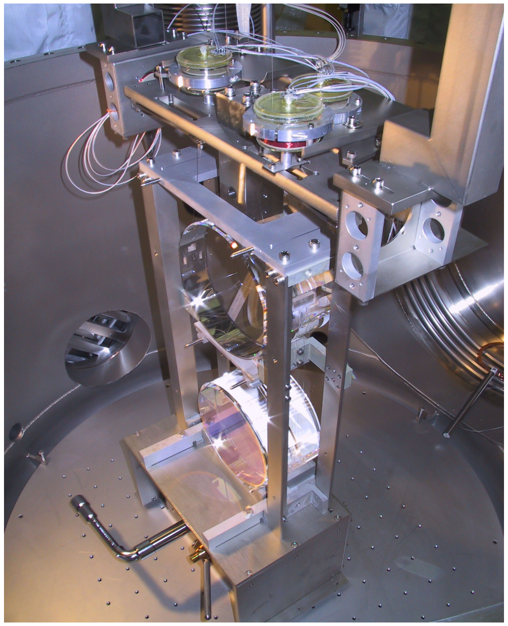


Fibers attached to bonded ear

Prior Work - materials for test masses/suspensions

- GEO600 suspensions bonded at Stanford - first two now installed in GEO
- Estimates show that fused silica ribbons /fibers should be able to meet Adv. LIGO requirements (GEO,Syracuse)
- Transferred silicate bonding technology to LIGO lab (Caltech)
- Bond strengths tested (H. Armandula) - sufficient for Adv. LIGO
- Information on noise performance of these suspensions of considerable interest to LIGO

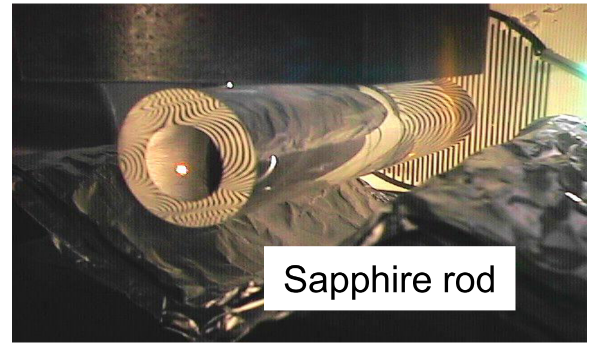
H. Armandula and bonded optics at Stanford



GEO optics bonded at Stanford - now installed in GEO interferometer

Prior Work - materials for test masses/suspensions

- **Studied alternate crystalline test mass materials to improve thermal noise**
  - YAG, Sapphire, GGG, Spinel
  - Exceptionally low mechanical loss (< 10^{-8}) at frequencies of 10kHz and higher in high quality sapphire suitable for large masses (with GEO, Moscow State)



  - **So, sapphire chosen as LIGO baseline test mass material**
  - Silicate bonding studies extended to sapphire (collaboration with Caltech, GEO)

- **Mechanical loss of mirror coatings**
  - Measurements made of mechanical loss of dielectric mirror coatings (collaboration GEO, Syracuse)
  - **Results showed measurable levels loss**
  - Modeling work with Nakagawa et al using showed **thermal noise of coatings to be significant for Adv LIGO**
  - **Program of coating characterization and improvement underway with LSC colleagues**

Proposed work - materials for test masses/suspensions (1)

- **Adv. LIGO**
  - Participate in bonding test masses for Adv. LIGO noise prototypes at MIT
  - Extend work on bonding and suspension techniques, coating research (with Caltech, GEO, Syracuse)

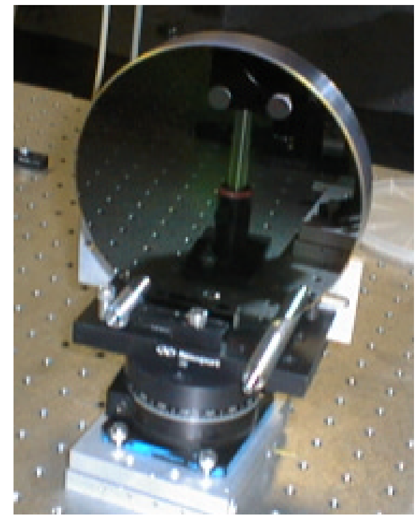
Evolution of GEO
silica " ear"
design

  - Collaborate with GEO on improved techniques for passive damping violin modes using layers of metal/dielectrics - may be necessary for stable operation of Adv. LIGO global control system

Proposed work - materials for test masses/suspensions (2)

- **Future improvements**
  - **Thermal noise** from test masses and suspensions important below few 100 Hz
  - **Silicon** has various desirable material properties (optical and thermal noise)
  -
    - High thermal conductivity, κ
    - Available in large pieces (~100kg)
    - Can be polished and coated to form high quality dielectric mirrors
    - Measurements suggest intrinsic mechanical loss (and **thermo-elastic loss***) comparable to sapphire at room temperature
    - Can be silicate bonded to silica (and by extension to itself)

Coated silicon mirror



  - At room temperature, thermo-elastically driven displacement noise forms hard limit to detector sensitivity
  - **By cooling test masses, expect significant gains in thermal/thermo-elastic noise performance**

* **Braginsky et al**

Proposed work - materials for test masses/suspensions (3)

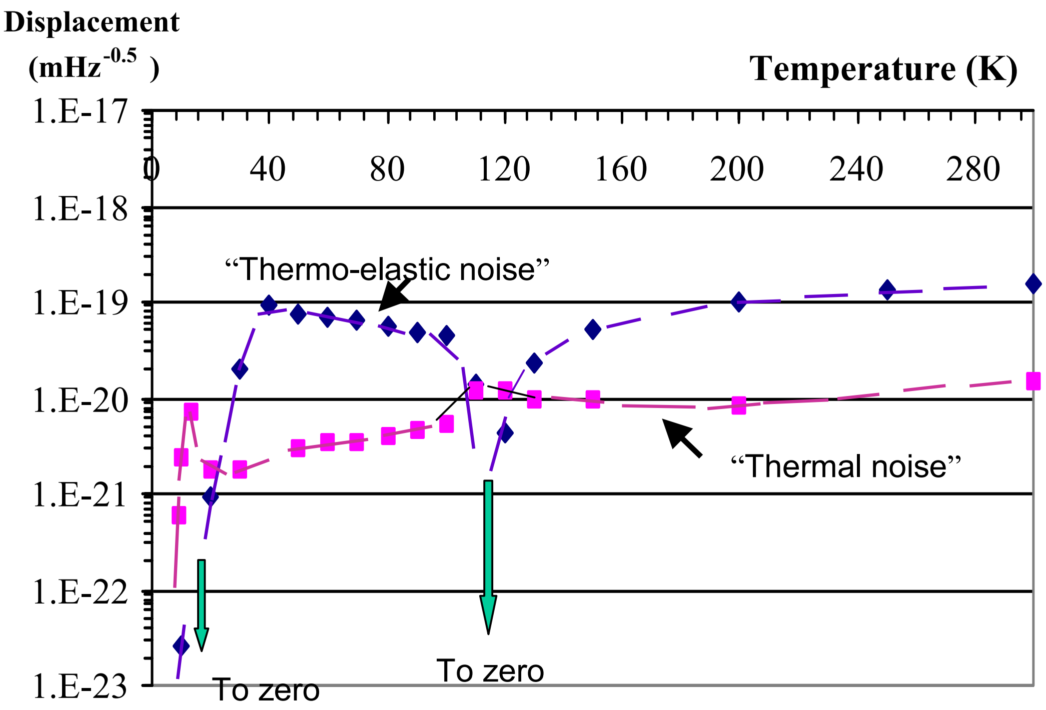
– Silicon: unique material properties on **cooling:**
  - Intrinsic mechanical loss decreases
  - Two zero's in coefficient thermal expansion, α, at ~130K and ~20K

Dual benefits:

– thermal deformation proportional to α/κ

– thermo-elastic noise proportional to α

– **both should vanish as α tends to zero**



"Thermo-elastic" displacement noise and "thermal" noise in a silicon test mass as a function of temperature

– **silicon substrates opens avenues for significant thermal noise improvements at low temperatures but material properties need further study**

Proposed work - materials for test masses/suspensions (4)

- Propose to study **thermal noise properties** of silicon at room temperature and below:

  (1) intrinsic loss factor and (2) thermo-elastic loss

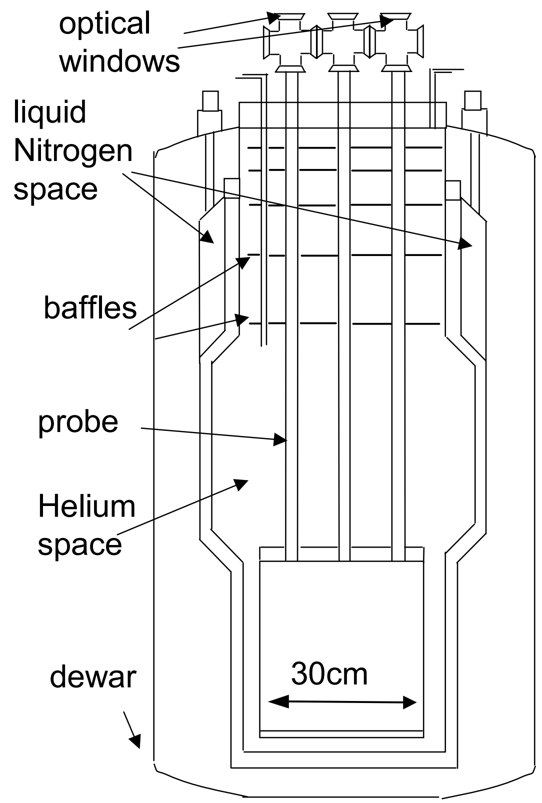
(1) Measure loss factors of bulk samples at frequencies where thermo-elastic damping negligible (standard "ringdown" technique)

  – investigate effect of doping on intrinsic loss

(2) Fabricate samples of silicon where effects of thermo-elastic damping are enhanced - thin cantilevers of silicon.~ 100microns to 1mm. Measure loss factors of resonant modes of samples.

  – investigate effect of doping on thermo-elastic damping

- From these experiments, determine if possible to engineer further improvements in properties



Schematic diagram of cryostat and experimental probe

Proposed work - materials for test masses/suspensions

- Further, need to investigate in collaboration with LSC colleagues :
  - **Effects of coatings** on mechanical loss of silicon substrates (room T and cryogenic)
  - **Silicate bonding** to joint silicon suspension elements to the silicon test masses
  - Measurement of **loss factors** associated with the all-silicon silicate bonding
  - Use of **GEO600 detector** for demonstration of silicon technology

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Stanford University's Seismic Isolation and Alignment Group

Contributors

Daniel DeBra, Norna Robertson, Brian Lantz, Mike Hennessy,
Corwin Hardham, Wensheng Hua,
Jeremy Faludi, Amit Ganguli, Graham Allen,
Jamie Nichol*, Sam Cowley*, Hong Sang-Bae*, Robert Yi*

Much of the LIGO work is done in close collaboration with:

LSU, JILA, MIT (LASTI), Caltech, LLO

Goals of Stanford's Seismic Group

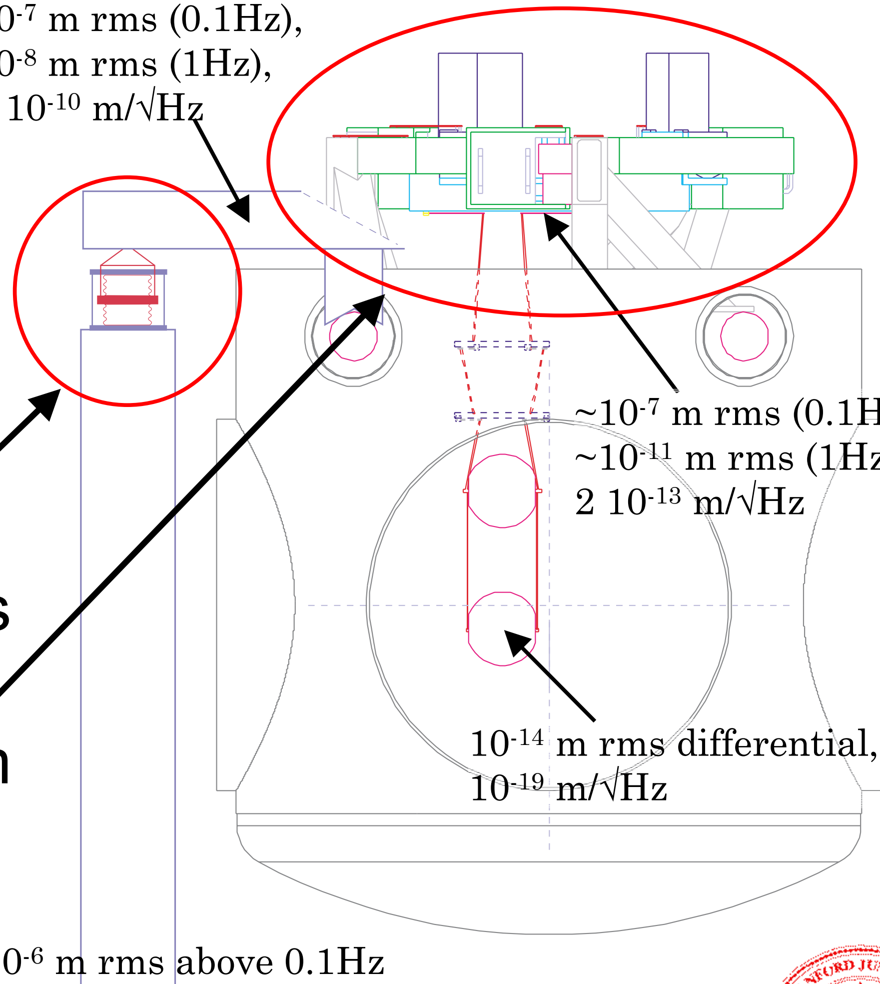
Conducting R&D on the "Isolation System" for Advanced LIGO

Provide a stable, quiet platform for the Advanced LIGO optics.

Substantial reduction of motion at frequencies above 0.1Hz.

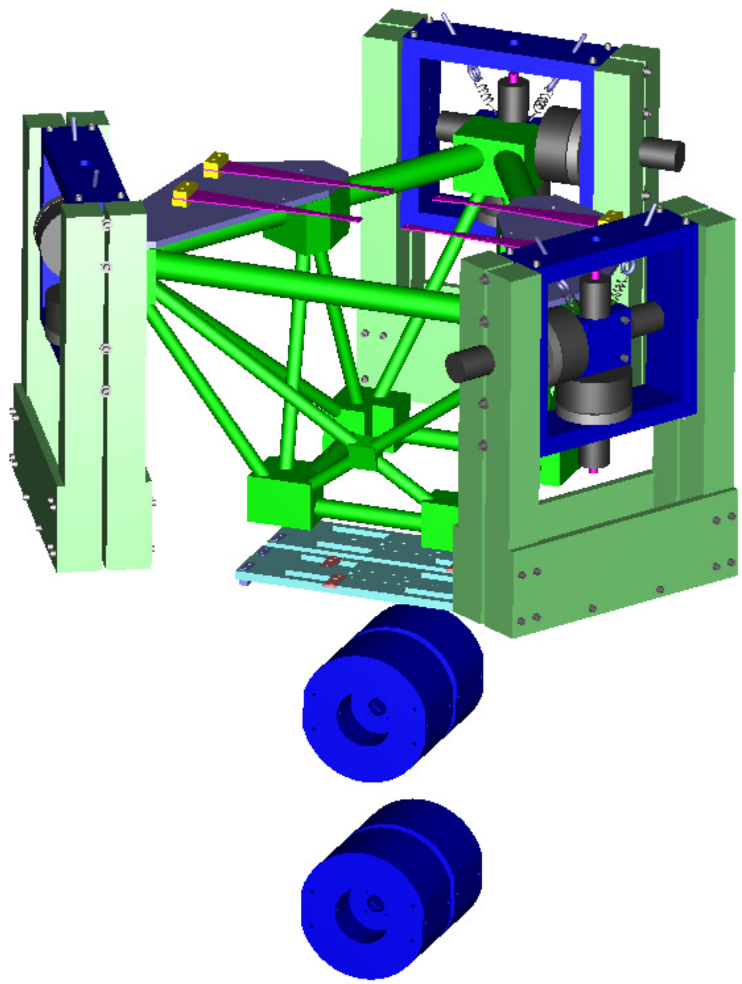
External Hydraulics

Internal 2-stage active system

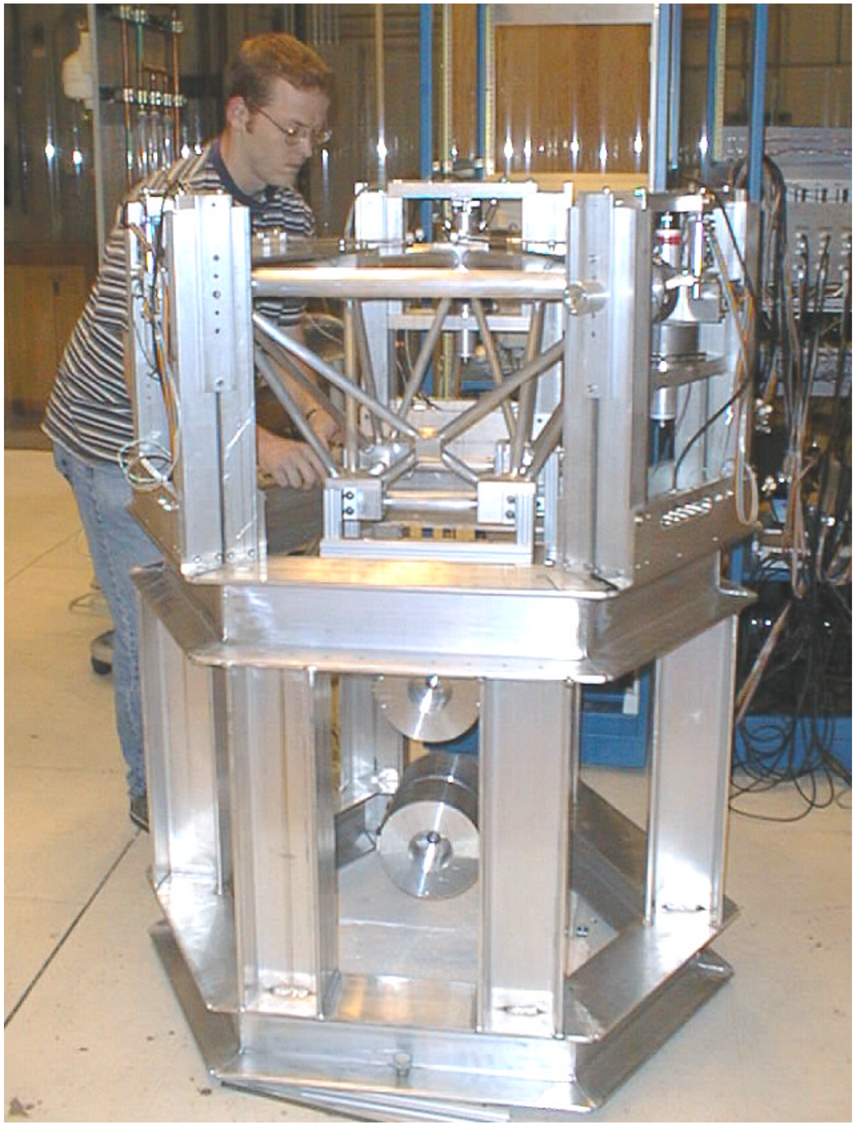


Previous Work - Single Layer Platform with Pendulums

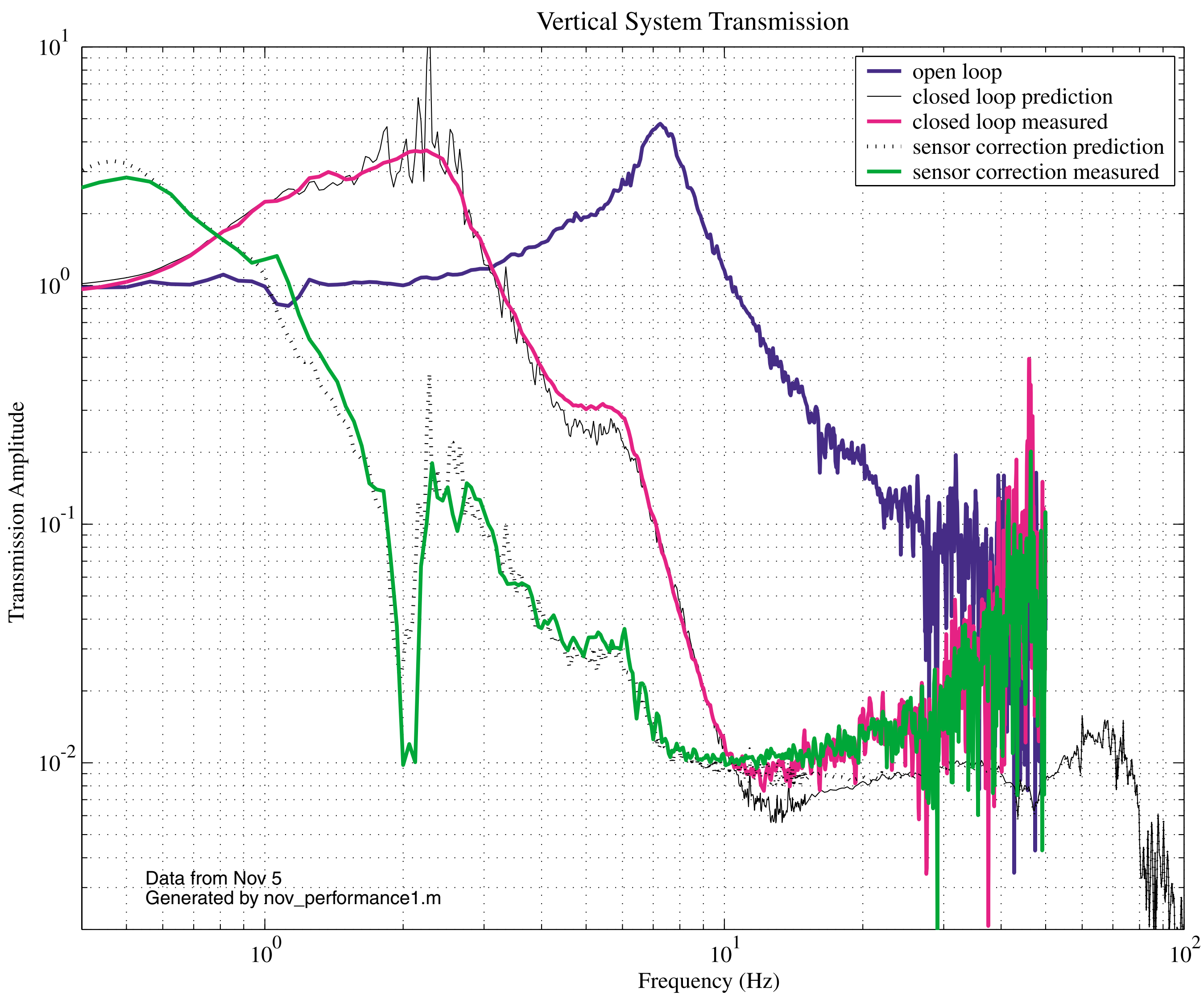
- Demonstrate 6 DOF active platform with collocated sensors and actuators.
- Demonstrate sensor blending.
- Validate computer model used to design LIGO system.
- Demonstrate sensor correction to reduce ground motion.
- Demonstrate reliable operation of stiff platform and pendulum working together.



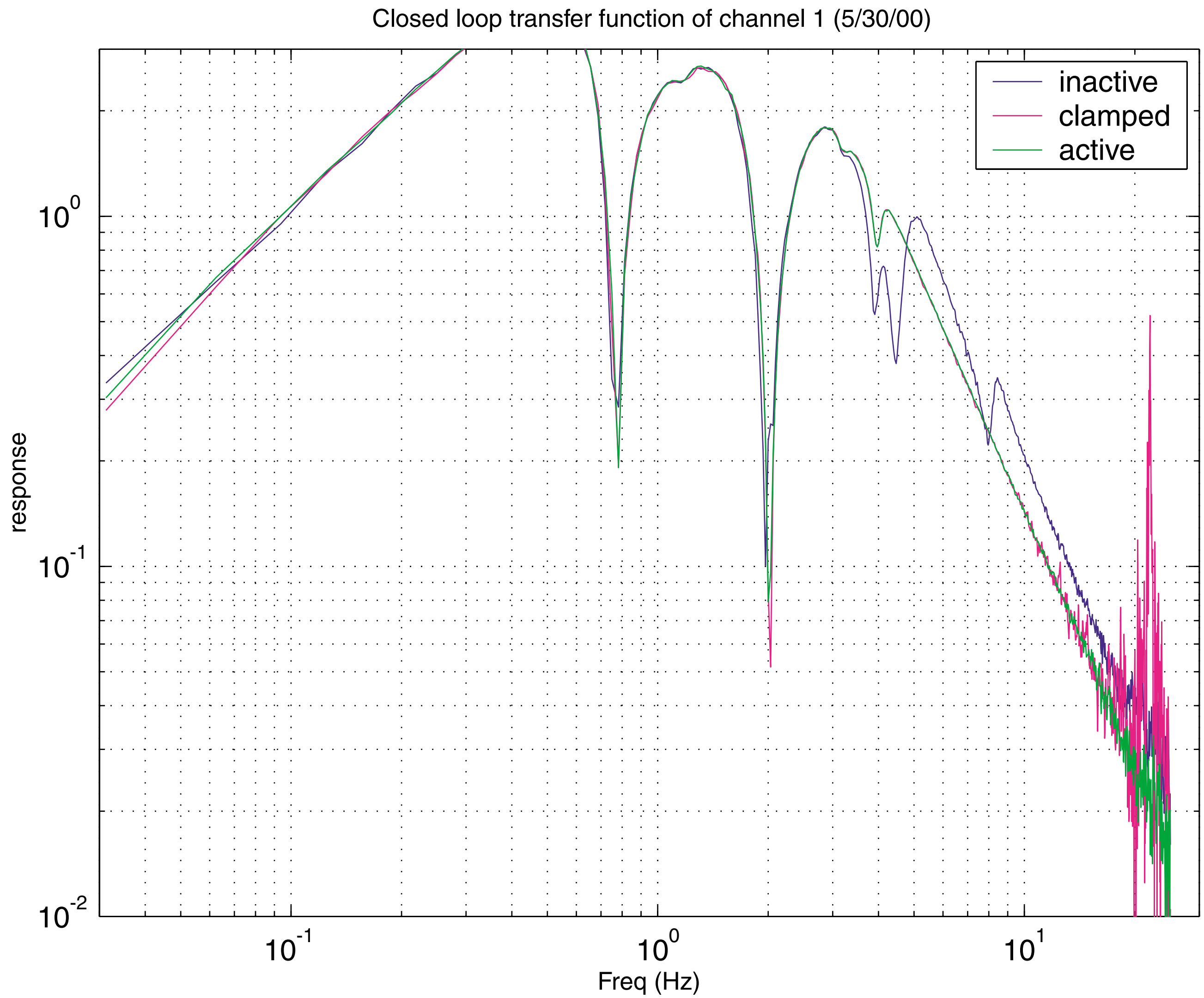
The Single Layer Platform



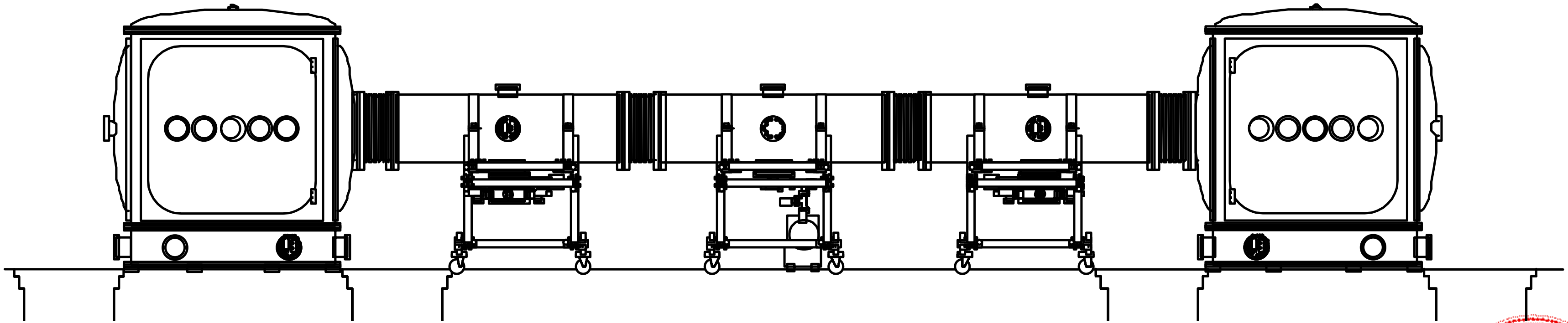
Previous Work - Results from Single Layer Platform



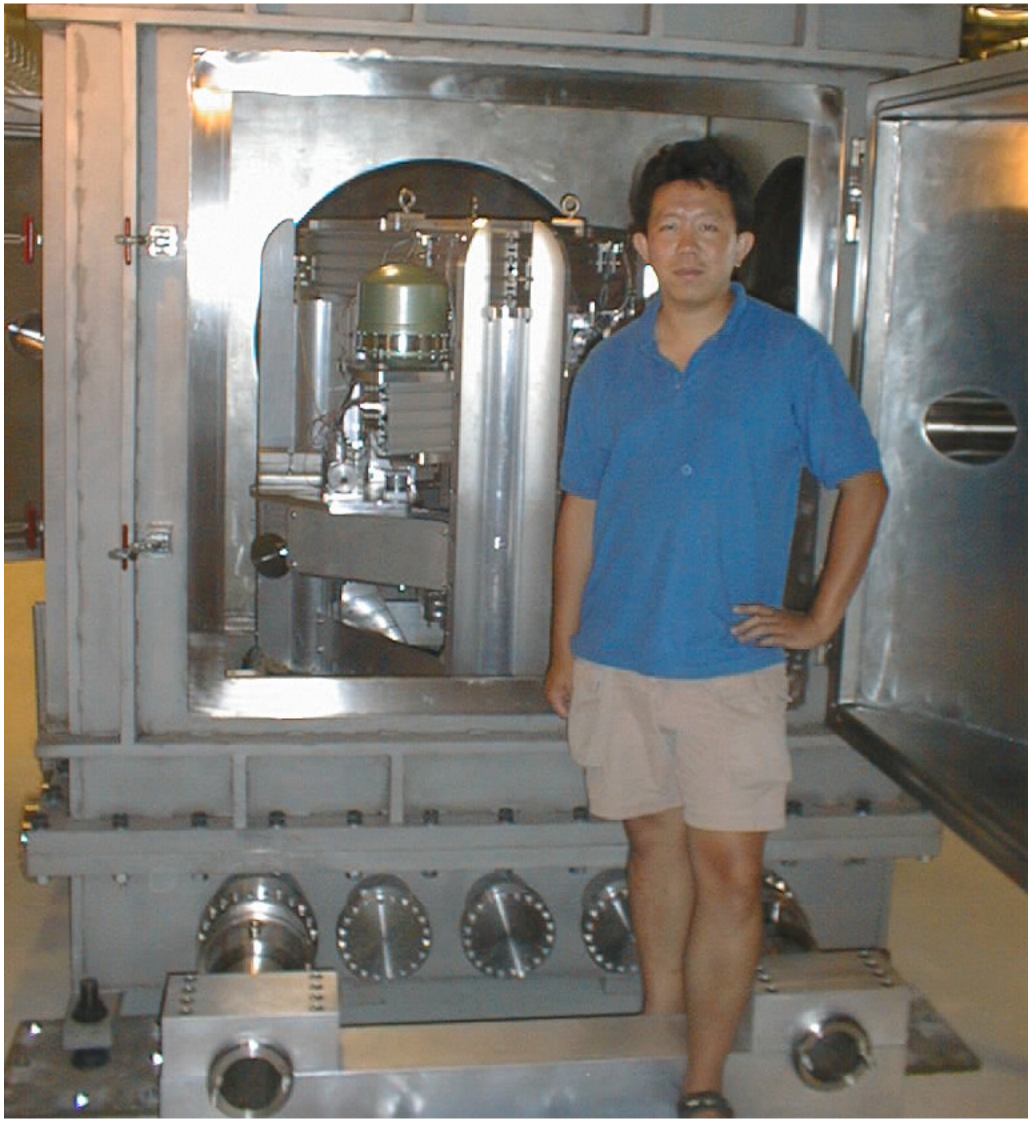
Previous Work - Pendulum Interactions



Installation of Two-Stage Systems into the ETF Vacuum Chambers



Ongoing Work - Rapid Prototype Installed in ETF



Improve performance

New flexures to reduce T/H coupling

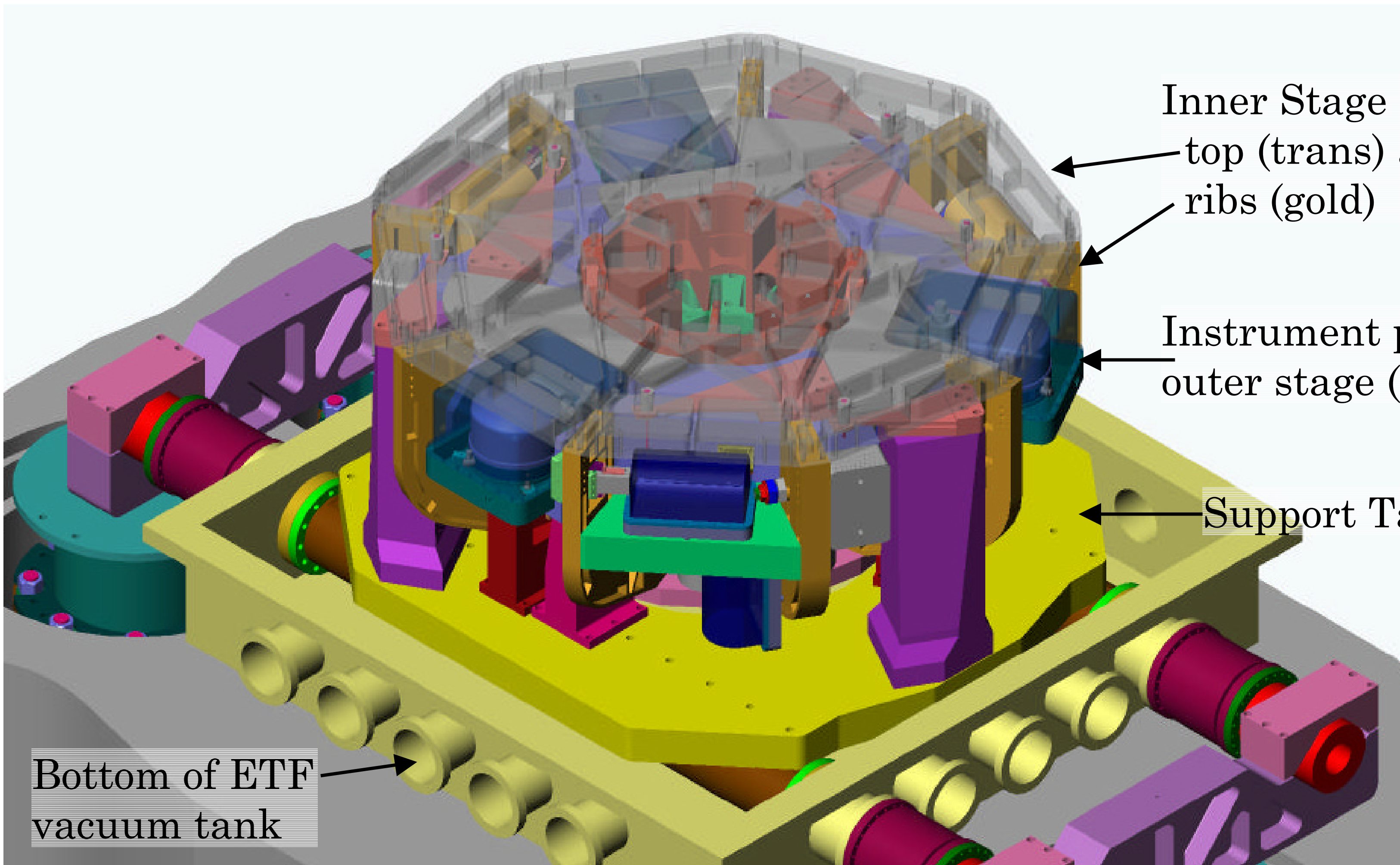
Study ways to combat tilt

Improved System ID

Next Step: Two Stage Prototype for Advanced LIGO

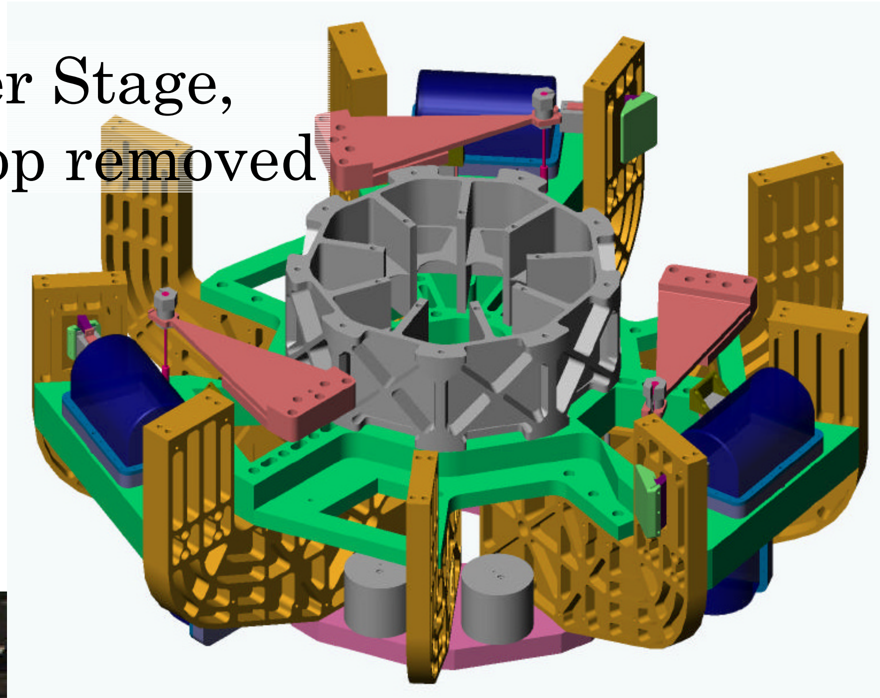
- Prototype for the HAM chamber system, to be installed in vacuum at the Stanford ETF.
- Same sensors, similar actuators as the Advanced LIGO system.
- Same dynamics as the Advanced LIGO system.
- Centers of mass of two stages at the same location.
- Sensors and actuators well aligned.
- Begin installation in January.

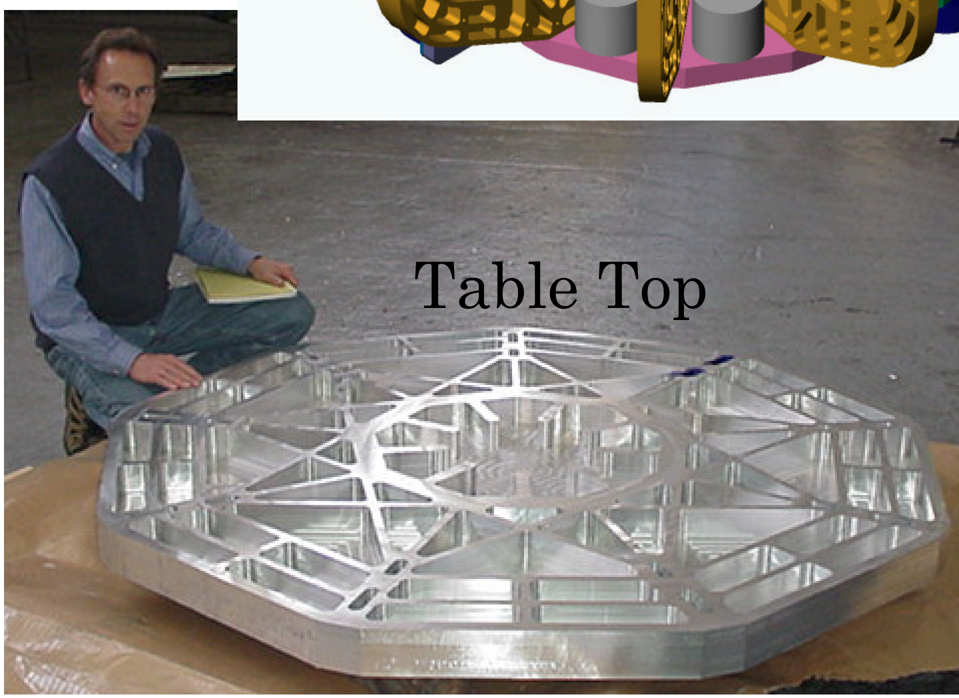
Ongoing and Future Work:
HPD Design for the New Prototype



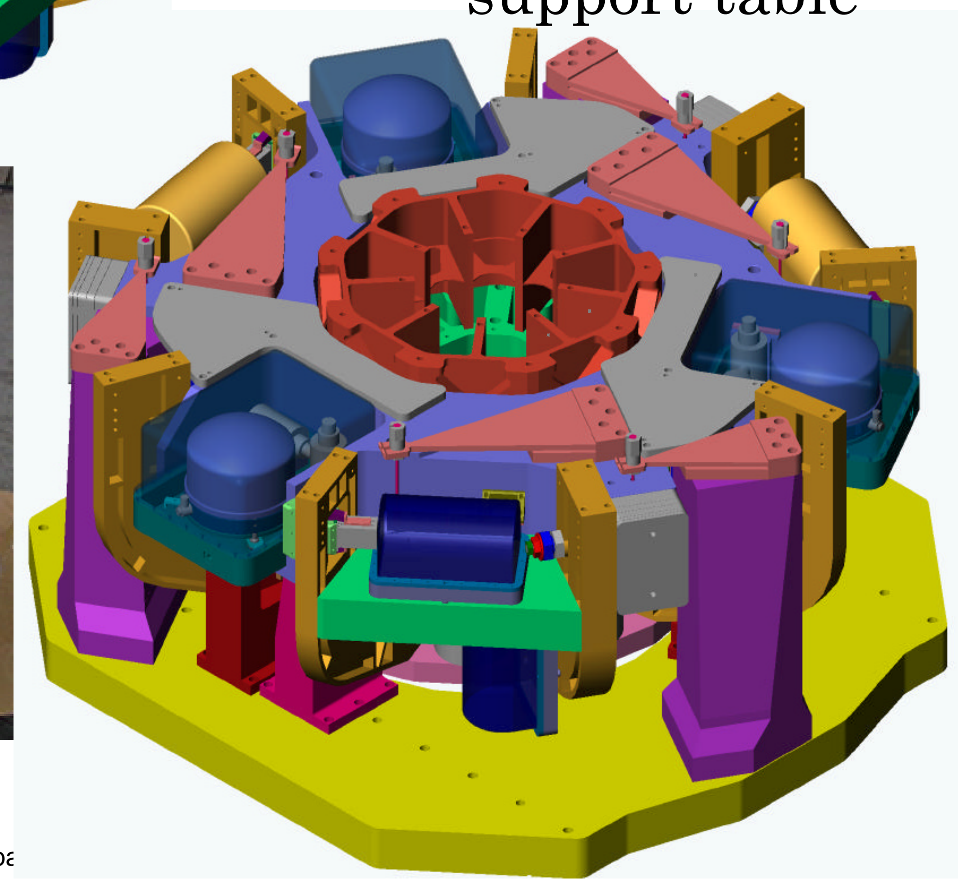
Views of the Prototype Design

Inner Stage, table top removed





Both stages and support table



Goals for the Advanced LIGO Technology Demonstrator

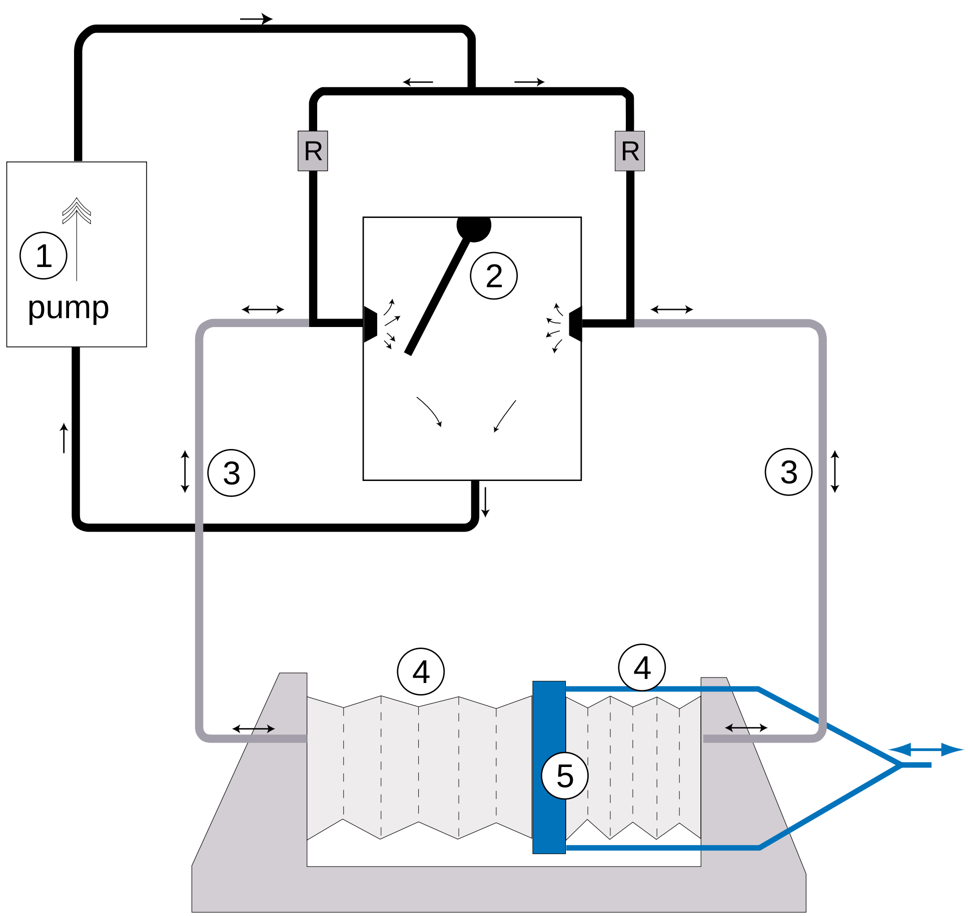
- Feed design information to the Pathfinder design at LASTI.
- Study 1 Hz performance – try to achieve reduction of 1000.
- Study 0.1 Hz performance – tilt/ horizontal coupling
    - Test the improved mechanical design of blades and flexures.
    - Differential vertical seismometers (matching, floor vs. platform.)
    - Gyros?
- Study System ID and MIMO techniques for primarily diagonal control matrix.
- Optimize sensor blending.
- Use two platforms to better study true performance and tilt.
- Design the next generation of prototypes for LASTI.

Quiet Hydraulics

Laminar-flow “quiet” hydraulic system provides the first stage of isolation, and large external actuators for aligning the optics.

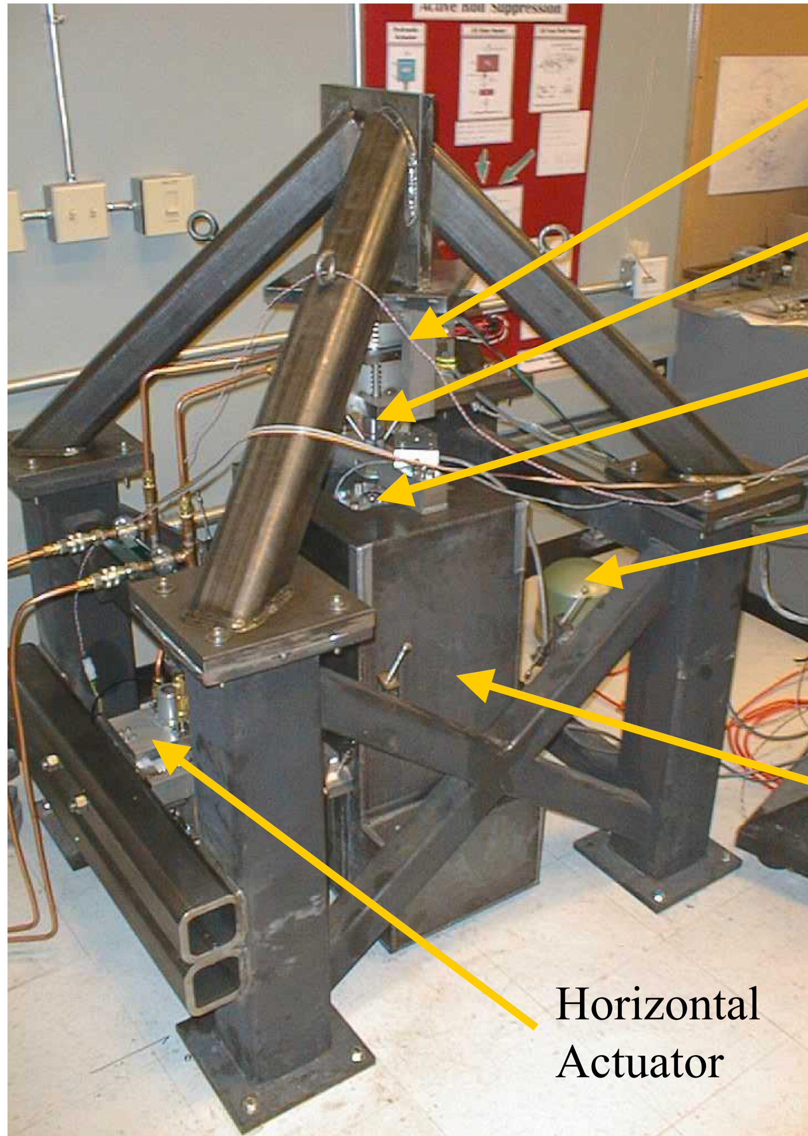
+/- 1mm of range (in 10 sec)
Enough authority to compensate for the Earth tides and the microseismic peak,

Enough bandwidth to provide isolation up to 10 Hz.

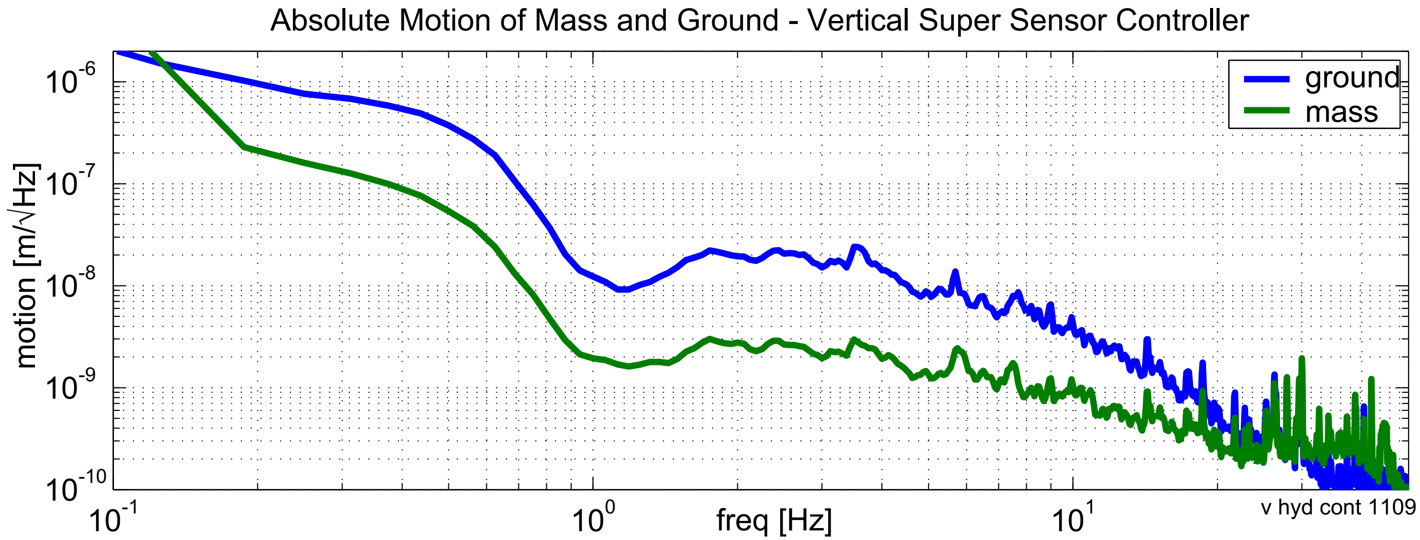


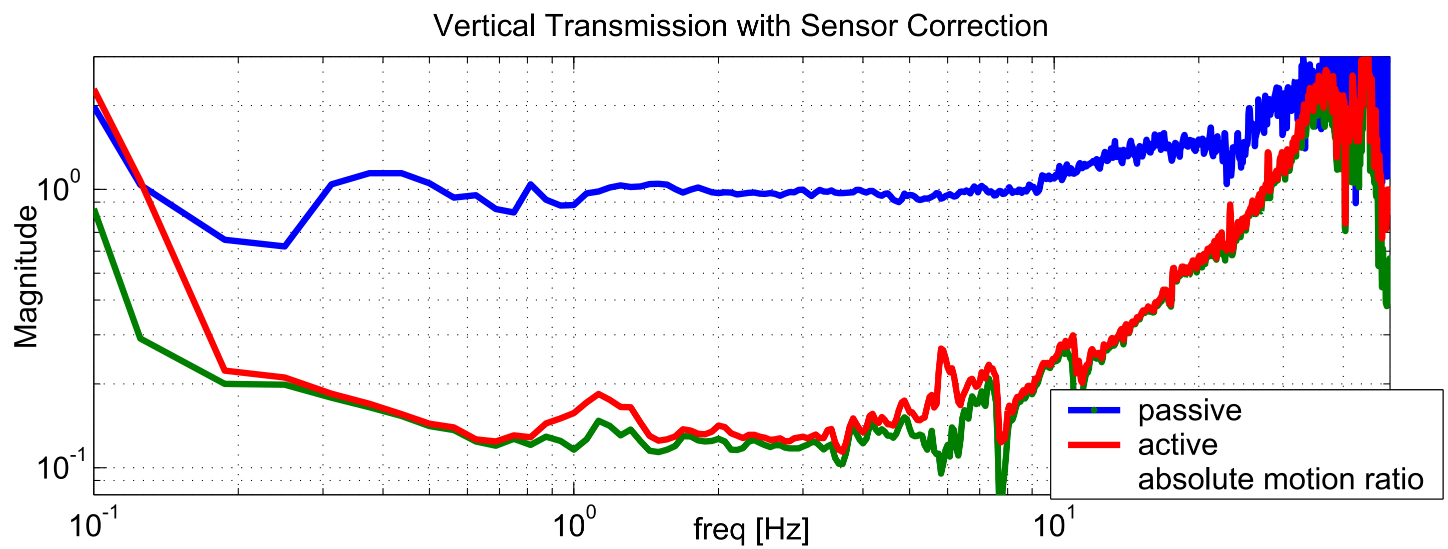
The Test Platform at Stanford

Vertical Actuator



Vertical Isolation





Plans for the Hydraulics

Original Goal – Put hydraulics into Advanced LIGO.

New Goal – Put hydraulic pre-isolators into Initial LIGO.

In the next calendar year (part old, part new)

- Finish prototyping the actuators
- Provide the science lead for installation of a full system into LASTI, and
- Integrate the system into LLO.

Gravitational Wave Sources and Data Analysis

(R. Wagoner)

- Ongoing analysis of the sources of gravitational waves
- Modeling of accreting Neutron Stars

- Identified by the Astrophysical Source Identification and Signatures subgroup of the LSC to lead effort on developing 'robust algorithms' for detecting such sources
- propose to extend this work on development of a parameterized model of the evolution of gravitational wave frequency and amplitude

- Participate in the work of the upper limit groups within the LSC

Summary

- Stanford program:

Lasers and Optics	Laser development, laser noise, mode control	(Adv LIGO, Future det.)
	High power photodiode development	(Adv LIGO)
	Core optic and coating absorption studies	(Adv LIGO, Future det.)
Advanced Configurations	Thermal loading studies	(LIGO, Adv. LIGO, Future det.)
	Development of diffractive optical elements + reflective interferometers	(Future detectors)
	Advanced techniques (delay lines, flat-top beams)	(Future detectors)
Materials (test masses/suspensions)	Participate in bonding LASTI suspensions	(Adv. LIGO)
	Extend bonding/suspension techniques	(Adv. LIGO)
	Study of silicon for test masses/suspensions	(Future detectors)
Seismic Isolation +control	Development of two-stage prototype	(Adv. LIGO)
	Study of tilt/horizontal coupling issues	(Adv. LIGO)
	Development of hydraulic actuators/control	(LIGO, Adv. LIGO)
Gravitational wave sources	extend models of accreting NS as sources	(Adv. LIGO)
	Participate in upper limit groups	(Adv. LIGO)