Advanced LIGO

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Elba “Aspen” Meeting

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Assumptions for LIGO future

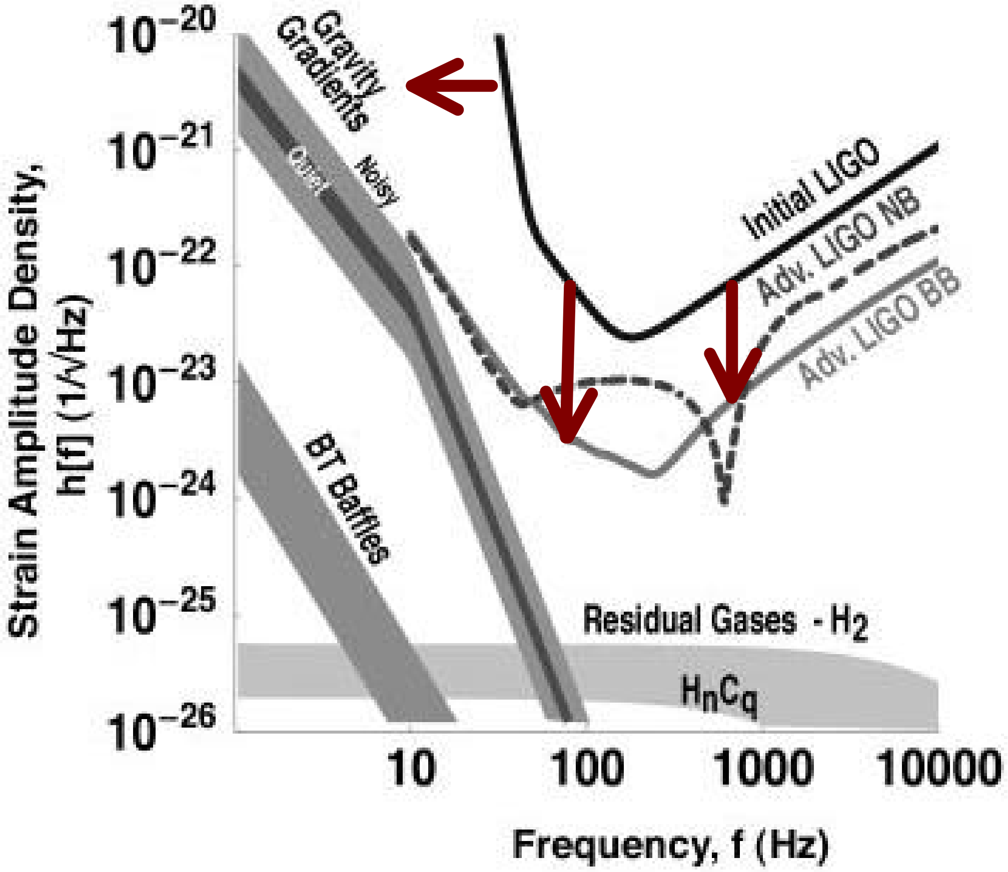
- LIGO mission: detect gravitational waves and initiate astronomy
- Next detector
  - » Should be of astrophysical significance if it observes GW signals or **if it does not**
  - » Should be at the limits of reasonable extrapolations of detector physics and technologies
  - » Should lead to a realizable, practical instrument
- An effort of the entire LIGO Scientific Collaboration (LSC)
  - » LIGO Lab and other LSC members in close-knit teams
  - » R&D and designs discussed here are from the Collaboration – including the Lab

Choosing an upgrade path

- Maximize astrophysics in the coming decade
  - » Must “fully” exploit initial LIGO
  - » Any change in instrument leads to lost observing time
  - » Minimum 1.5 years required between decommissioning one instrument and starting observation with the next
  - » → Want to make one significant change, not many small changes
    - – Advanced LIGO searches in ~2.5 hours what initial LIGO does in ~1 year
- Technical opportunities and challenges
  - » Exploit evolution of detector technologies since the freezing of the initial LIGO design
  - » ‘Fundamental’ limits: quantum noise, thermal noise, Newtonian background provide point of diminishing returns (for now!)

Present, Advanced, Future limits to sensitivity

- Advanced LIGO
  - Seismic noise 40→10 Hz
  - Thermal noise 1/15
  - Shot noise 1/10, tunable
  - Initial → Advanced: factor <1000 in rate
- Facility limits
  - Gravity gradients
  - Residual gas
  - Scattered light
- Beyond Adv LIGO
  - Seismic noise: Newtonian background suppression
  - Thermal noise: cooling of test masses
  - Quantum noise: quantum non-demolition



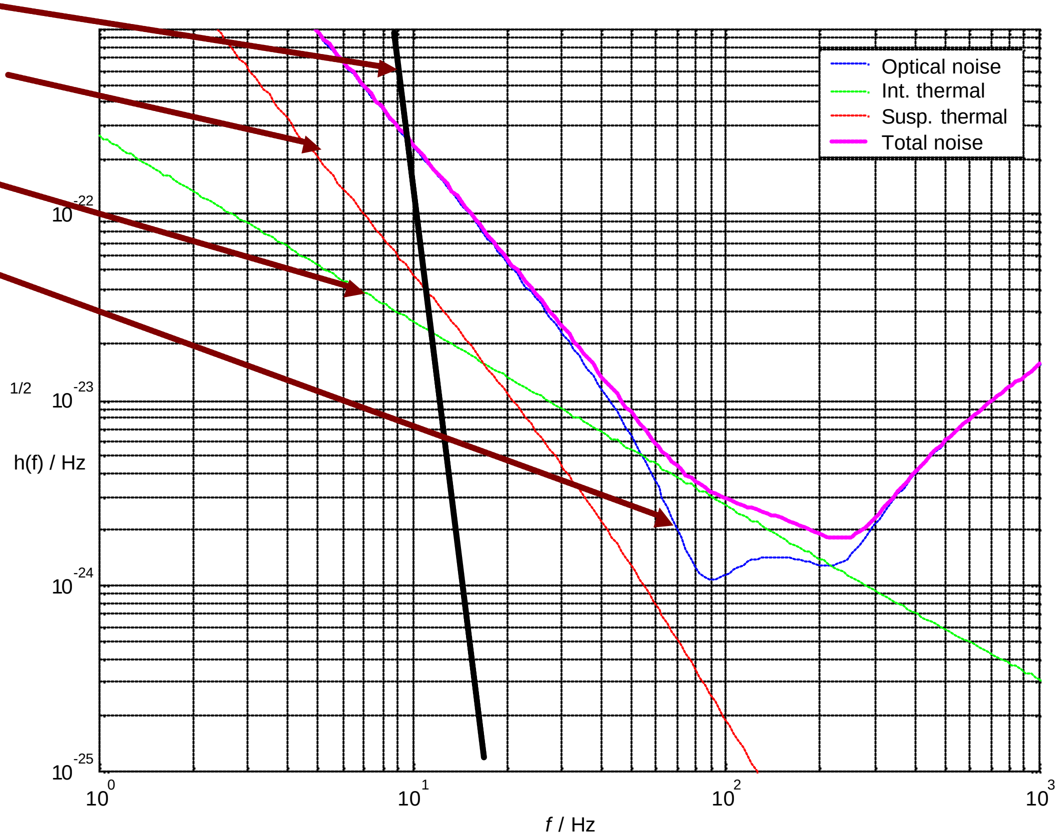
Top level performance & parameters

Parameter	**LIGO I**	**LIGO II**
Equivalent strain noise, minimum	**3×10^{-23}/rtHz**	**2×10^{-24}/rtHz**
Neutron star binary inspiral range	**19 Mpc**	**300 Mpc**
Stochastic background sensitivity	**3×10^{-6}**	**$1.5\text{-}5\times10^{-9}$**
Interferometer configuration	**Power-recycled MI w/ FP arm cavities**	**LIGO I, plus signal recycling**
Laser power at interferometer input	**6 W**	**125 W**
Test masses	**Fused silica, 11 kg**	**Sapphire, 40 kg**
Seismic wall frequency	**40 Hz**	**10 Hz**
Beam size	**3.6/4.4 cm**	**6.0 cm**
Test mass Q	**Few million**	**200 million**
Suspension fiber Q	**Few thousand**	**~30 million**

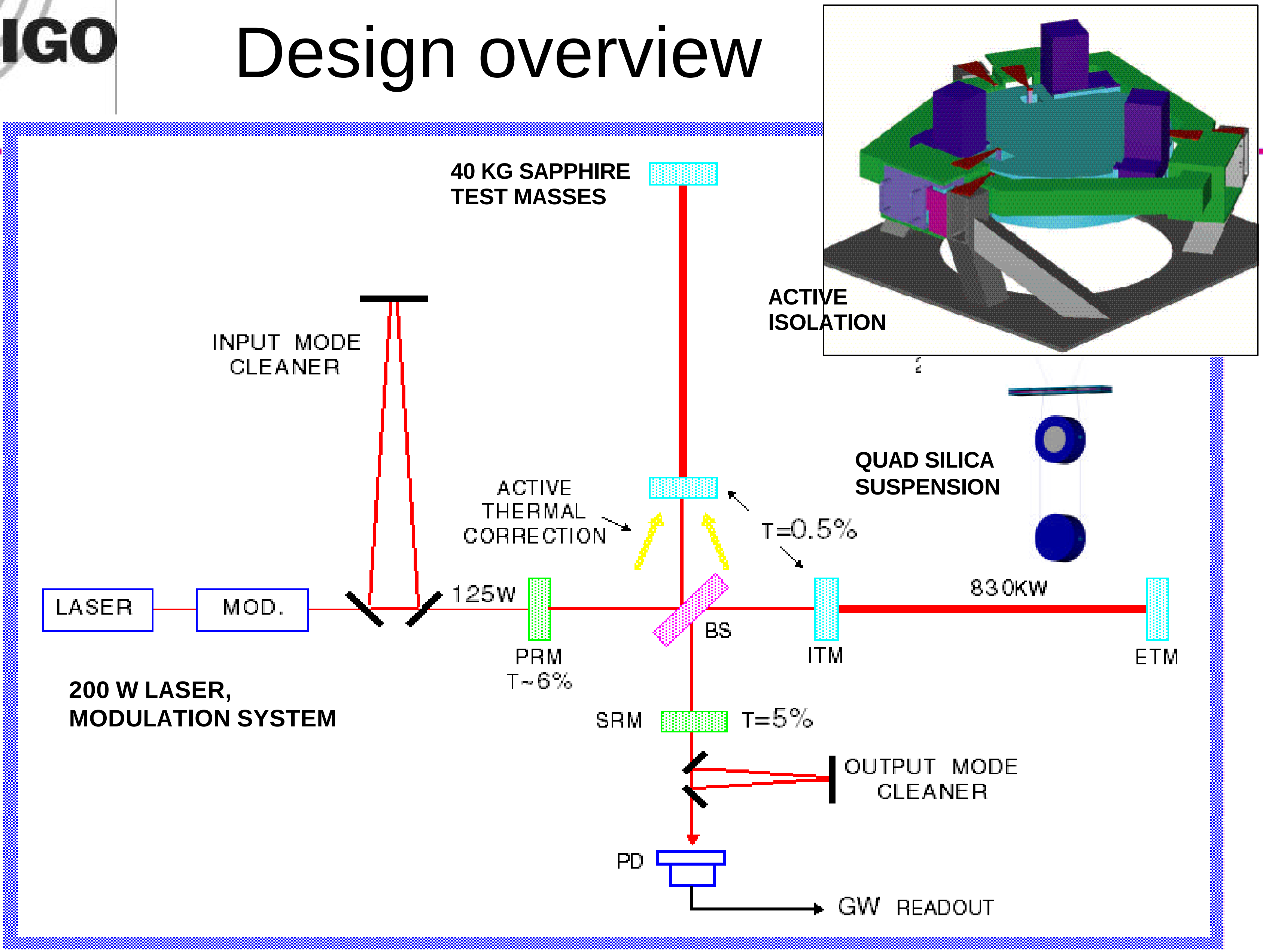
Anatomy of the projected detector performance

- Seismic ‘cutoff’ at 10 Hz
- Suspension thermal noise
- Internal thermal noise
- Unified quantum noise dominates at most frequencies

- ‘technical’ noise (e.g., laser frequency) levels held, in general, well below these ‘fundamental’ noises



Design overview



Advanced LIGO Development Team

Group	Seismic Isolation (SEI)	Suspension (SUS)	Core Optics (COC)	Input Optics (IO)	Pre-Stab. Laser (PSL)	Aux. Optics (AOS)	Ifo Sense & Control (ISC)	Systems Engineering
CIT	requirements	requirements; Fiber & bonding research; final design; TNI noise measure	requirements; leads design; coordinates materials develop.; polishing; inhomogeneity compensation; metrology	requirements; intensity stabilization feedback to PSL	requirements; engin support & epics integration; performance eval.	requirements; photon actuation;	requirements; electronics; system identification; 40m experiment/controls testbed	requirements; standards; extend E2E simulation; system trade studies; optical layout; FFT studies
MIT	requirements; LASTI prototype testing	requirements; measure coating effect on Q; LASTI prototype testing	requirements	requirements; integrated IO/PSL system test	requirements; LASTI prototype & IO/PSL integrated sys test	requirements; active thermal compensation	requirements; system trade studies; bench top DC read-out exp.; PD testing; ISC design lead	requirements; define noise budget, define shared signal port power allocation, etc.
LLO	engineering support							
LHO								
Stanford/HP							Melody code	
ACIGA				high power system testing	injection-locked, stable/unstable resonator	cavity test of active thermal compensation		
GEO/ Glasgow		welding; coating effect on mech Q; local control studies; triple performance in GEO-600; prelim design lead					10m signal recycling exp.; lock acq. & sensing matrix guidance	
GEO/ Hannover					Rod pumped system; leads PSL system design			
IAP			in-situ figure metrology	high power Faraday isolator development				
PS								Bench code
Iowa		coating mech modeling						
LSU	MIMO control; SEI design lead	transient (excess) noise measure; mode coupling study & diagnostics						
MSU		chem & flame polishing effect on Q; surface charge measure						
Stanford	hydraulic pre-isolation; ETF controls testbed	welding, bonding & coating effect on mech Q; bonding strength	low absorption sapphire development		MOPA system with LIGO 20W MO		back-illuminated InGaAs detectors	
Southern U			trace element identification; absorption					
SMA/Lyon			high mech Q, low absorption coatings					
Syracuse		direct loss measure; effect of polishing, coating, bonding						
UFL				IO system design; high power component tests				

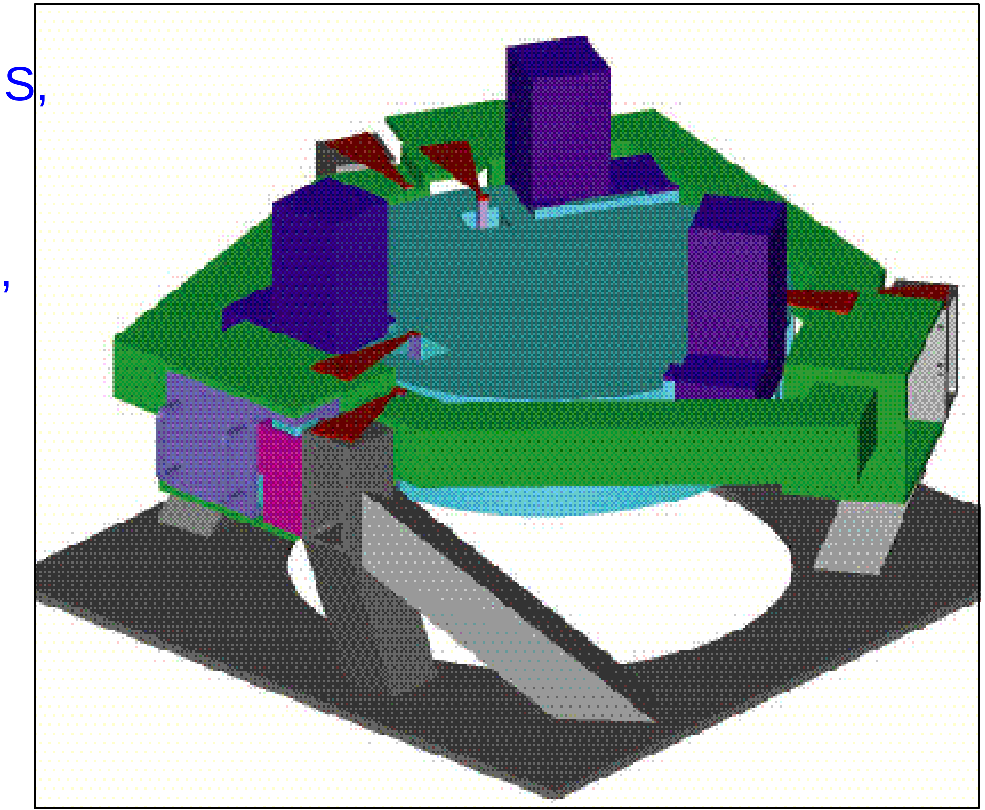
Interferometer Sensing & Control

- Signal and power recycling
- Considering DC (fringe offset) readout
- GEO 10m “proof of concept” experiment:
  - Preparation proceeding well
  - Results for 40m Program in early 2003 (lock acquisition experience, sensing matrix selection, etc.)

- 40m Lab for Precision Controls Testing:
  - Infrastructure has been completed (i.e. PSL, vacuum controls & envelope, Data Acquisition system, etc.)
  - Begun procurement of CDS and ISC equipment
  - Working on the installation of the 12m input MC optics and suspensions, and suspension controllers by 3Q02

Seismic Isolation

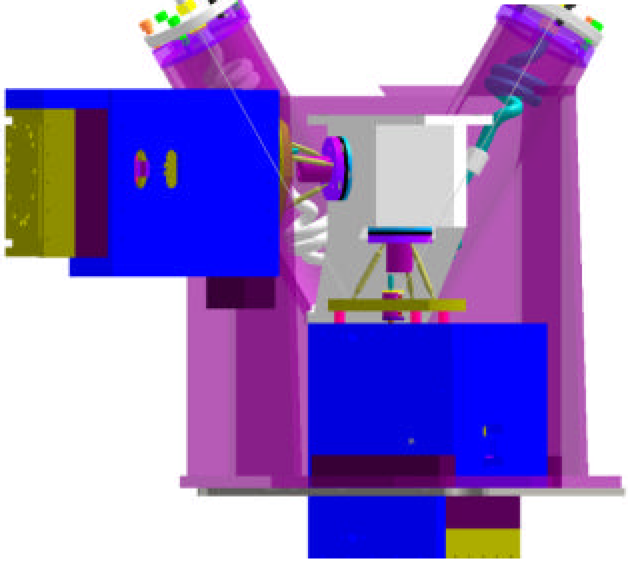
- Choice of 10 Hz for ‘seismic wall’
- Achieved via high-gain servo techniques, passive multiple-pendulum isolation
- Isolation design has 3 stages:
  - » External pre-isolator: reduces RMS, 0.1 → 10 Hz
  - » Two in-vacuum 6 DOF stages, ~5 Hz natural resonant frequency, ~50 Hz unity gain
  - » Hierarchy of sensors (position, Streckeisen seismometers, L4-C geophones)

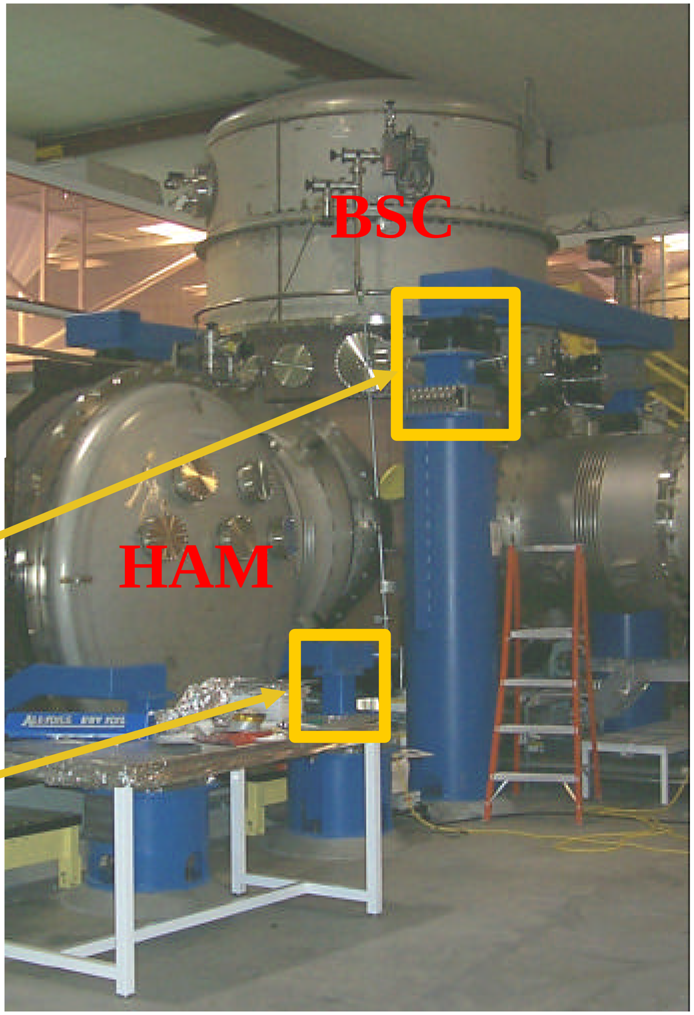


- Second-generation prototype in assembly and test at Stanford

Seismic Isolation: Pre-Isolator

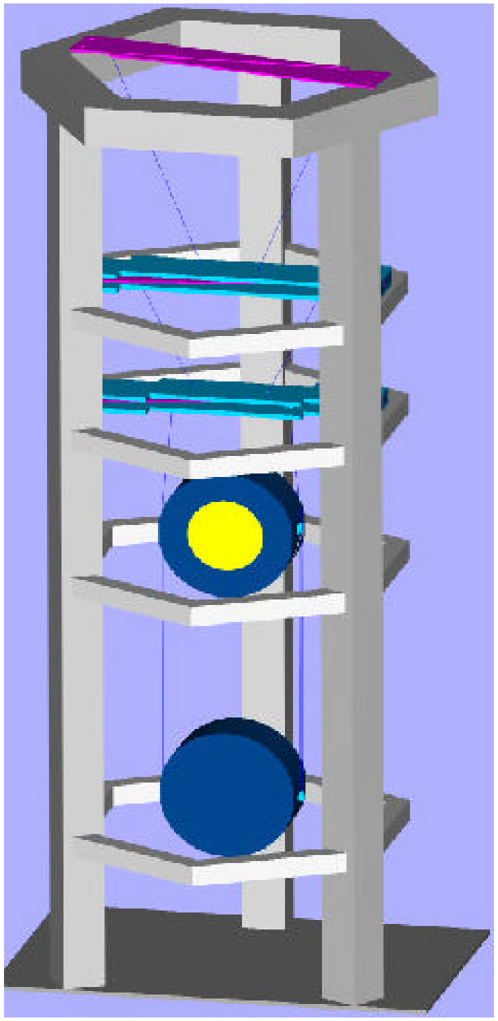
- External pre-isolator development has been accelerated for possible deployment in initial LIGO to address excess noise at LLO
  - » Feedback and feed-forward to reduce RMS
  - » Hydraulic, electro-magnetic variants
- Prototype to be tested in LASTI mid-2002
- Initial LIGO passive SEI stack built in the LASTI BSC and HAM
- Plan to install pre-isolator at LLO 1Q/2003





Suspensions

- Adaptation of GEO/Glasgow fused-silica suspension
  - » Quad to extend operation to ~10 Hz
- Suspension fibers in development
  - » Development of ribbons at Glasgow
  - » Modeling of variable-diameter circular fibers at Caltech – allows separate tailoring of bending stiffness (top and bottom) vs. stretch frequency
  - » Choosing vertical 'bounce' frequency – 12 Hz
  - » Can observe below (to Newtonian limit)
  - » Investigating 12 Hz line removal techniques to observe to within a line width of bounce frequency
- Attachment of fibers to sapphire test masses
  - » Hydroxy-catalysis bonding of dissimilar materials
  - » Silica-sapphire tested, looks workable



LASTI Laboratory

- LIGO-standard vacuum system, 16-m ‘L’
- Enables full-scale tests of Seismic Isolation and Test Mass Suspension
  - Allows system testing, interfaces, installation practice.
  - Characterization of non-stationary noise, thermal noise.
- Pre-stabilized laser in commissioning, 1m in-vacuum test cavity
  - Pursuing wider-bandwidth ‘fast’ loop configuration
  - Will also be used for Adv LIGO intensity stabilization work
- Pre-isolator work for initial LIGO has taken upper hand
  - Initial LIGO isolation system installed

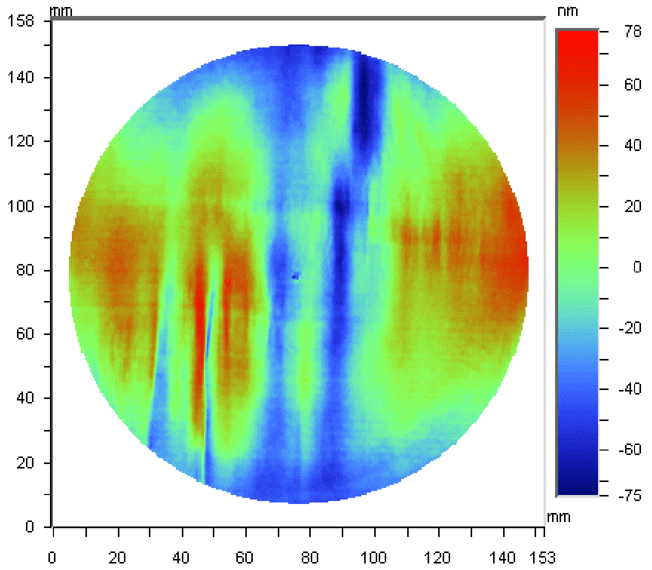
- Advanced LIGO seismic isolation to arrive in 2003, suspensions to follow

Sapphire Core Optics

- Developing information for Sapphire/Fused silica choice
- Mechanical Q (Stanford, U. Glasgow)
  - » Q of 2 x 10^8 confirmed for a variety of sapphire substrate shapes
- Thermoelastic damping parameters
  - » Measured room temperature values of thermal expansion and conductivity by 2 or 3 (or four!) methods with agreement
- Optical Homogeneity (Caltech, CSIRO)
  - » New measurements along 'a' crystal axis are getting close to acceptable for Adv LIGO (13 nm RMS over 80mm path)
  - » Some of this may be a surface effect, under investigation

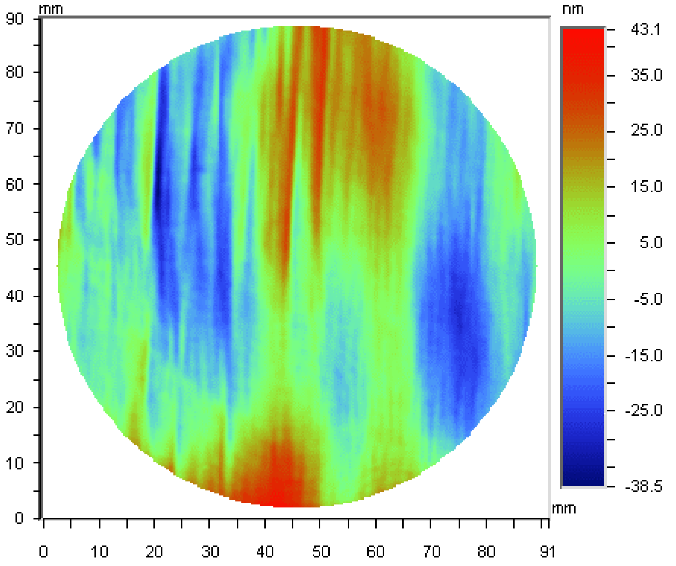
Homogeneity measurements

- Measurement data: m-axis and a-axis



Date: 08/11/2000
Time: 14:23:44
Wavelength: 690.700 nm
Pupil: 100.0 %
PV: 152.5563 nm
RMS: 27.0963 nm

X Center: 153.00
Y Center: 150.00
Radius: 143.43 pix
Terms: None
Filters: None
Masks:

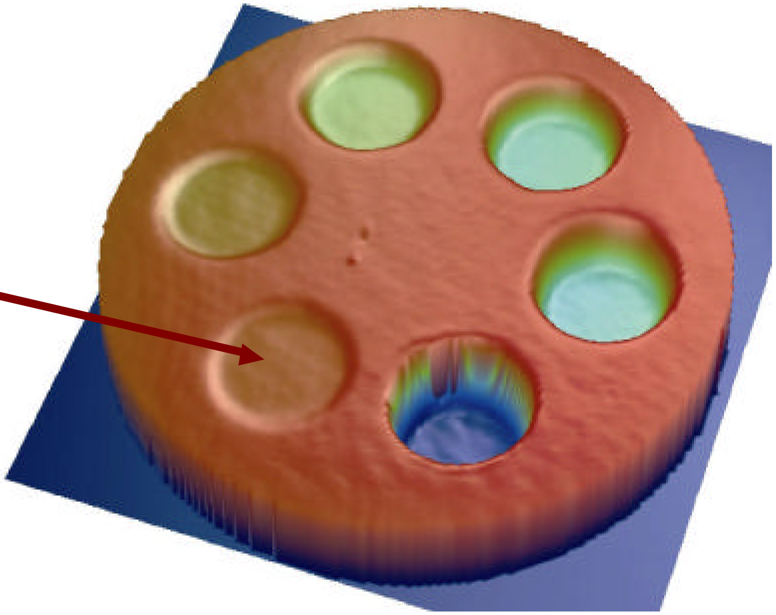


Date: 10/25/2001
Time: 13:59:18
Wavelength: 1.064 um
Pupil: 100.0 %
PV: 81.6271 nm
RMS: 13.2016 nm

X Center: 172.00
Y Center: 145.00
Radius: 163.00 pix
Terms: None
Filters: None
Masks:

Sapphire Core Optics

- Effort to reduce **bulk absorption** (Stanford, Southern University, CS, SIOM, Caltech)
- LIGO requirement is <10 ppm/cm
- Recent annealing efforts are encouraging
  - » Stanford is pursuing heat treatments with forming gas using cleaner alumina tube ovens; with this process they saw reductions from 45ppm/cm down to 20ppm/cm
  - » Higher temperature furnace commissioned at Stanford
- Demonstration of **super polish** of sapphire by CSIRO (150mm diameter, m-axis)
  - » Effectively met requirements
- Optical Homogeneity **compensation**
  - » Ion beam etching, by CSIRO
  - » 10 nm deep, 10 mm dia, 90 sec
  - » Microroughness improved by process!
  - » Also pursuing ‘pencil eraser’ approach with Goodrich, good results



Coatings

- Mechanical losses of optical coatings leading to high thermal noise – starting to understand where losses are
  - » SMA/Lyon (France) pursuing a series of research coating runs to understand mechanical loss
  - » multi-layer coating interfaces are not significant sources of loss
  - » most significant source of loss is probably within the Ta_2O_5 (high index) coating material; investigating alternative
  - » now investigating, with SMA/Lyon, the mechanical loss of different optical coating materials and “engineered” Ta_2O_5 coatings
- Optical absorption in coating leading to heating & deformation in substrate, surface
  - » Can trade against amount, complexity of thermal compensation; initial experimental verification near completion
  - » MLD (Oregon) pursuing a series of research coating runs targeting optical losses
  - » Sub-ppm losses (~0.5 ppm) observed in coatings from both MLD and from SMA Lyon

Light source: Laser, Mode Cleaner

- Input Optics (Univ. of Florida)
  - » Modulator with RTA shows no evidence of thermal lensing at 50W
  - » RTA-based EOMs are currently being fabricated
  - » Demonstrated 45 dB attenuation and 98% TEM00 mode recovery with a thermally compensated Faraday Isolator design (-dn/dT materials)
- Pre-Stabilized Laser (PSL)
  - » Coordinated by Univ. of Hannover/LZH
  - » Three groups pursuing alternate design approaches to a 100W demonstration
    - – Master Oscillator Power Amplifier (MOPA) [Stanford]
    - – Stable-unstable slab oscillator [Adelaide]
    - – Rod systems [Hannover]
  - » Concept down select Aug 2002

High Power Testing: Gingin Facility

- ACIGA progressing well with high power test facility at Gingin
  - » Test high power components (isolators, modulators, scaled thermal compensation system, etc.) in a systems test
  - » Explore high power effects on control – length, alignment impulse upon locking
  - » Investigate the cold start optical coupling problem (e.g, pre-heat?)
  - » Compare experimental results with simulation (Melody, E2E)

- Status
  - » LIGO Lab delivering two characterized sapphire test masses and a prototype thermal compensation system
  - » The facility and a test plan are being prepared

Development Plan

- R&D, distributed throughout LSC, well underway
  - » No ‘showstoppers’ found yet! …and lot’s of progress !
- Integrated Systems Tests of all new aspects of design
  - » Seismic Isolation Test at Stanford ETF, LASTI; Pre-Stabilized Laser (PSL), Input Mode Cleaner, Suspensions at LASTI
  - » High power testing at ACIGA Gingin facility
  - » Configurations, Servo Control Electronics Testing at the GEO Glasgow 10m lab, and in the LIGO 40m Lab
- Construction funding proposal, late ‘02
  - » For fabrication, installation, commissioning
  - » Could be funded by early ’05
  - » Operating late in the decade
- May upgrade one observatory, then second system upon proof of success; or all at once – depending upon observations, network at that time, and technical readiness

Advanced LIGO

- A significant step forward
  - » Exciting astrophysical sensitivity
  - » Challenging but not unrealistic technical goals
  - » Advances the art in materials, mechanics, optics, lasers, servo controls
- Very active collaboration
  - » NSF-funded research community
  - » International partners
- Program planned to mesh with fabrication of interferometer components leading to installation of new detectors starting in 2006 or 2007
  - » Lessons learned from initial LIGO
  - » Thorough testing at LSC facilities to minimize impact on LIGO observation
  - » **Coordination with other networked detectors to ensure continuous global observation**