Advanced LIGO

David Shoemaker
LIGO PAC
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Assumptions for LIGO future

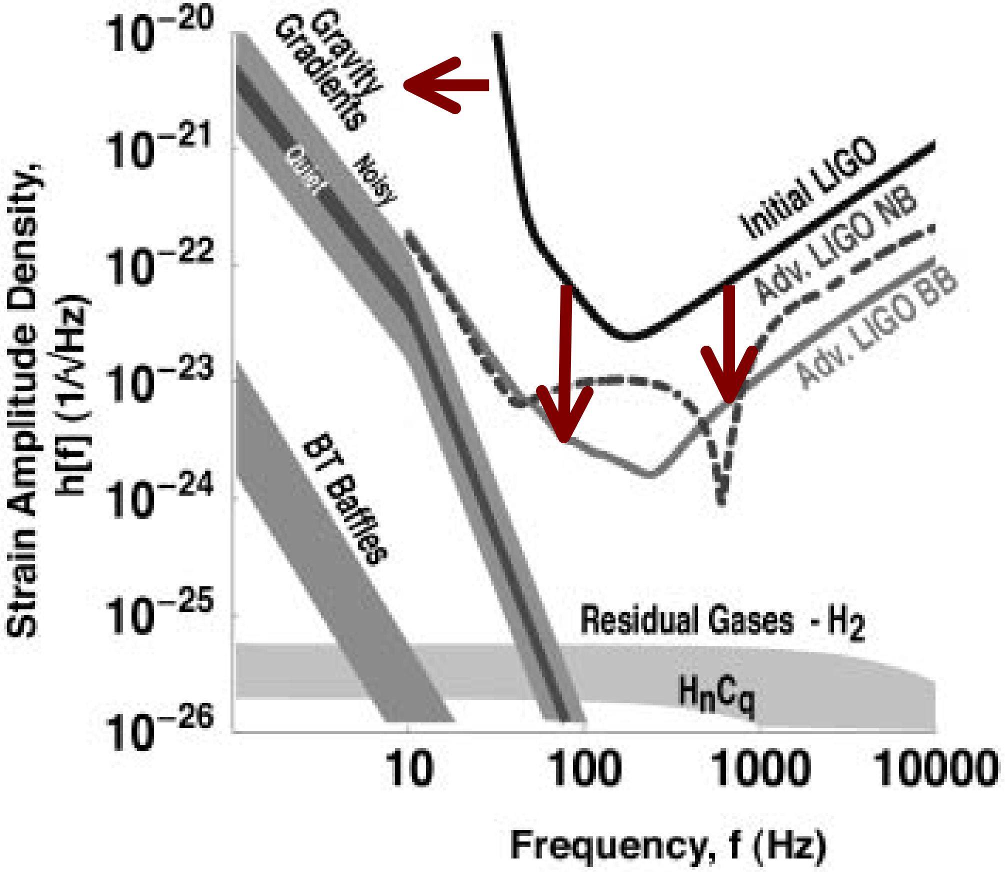
- LIGO mission: detect gravitational waves and initiate astronomy
- Next detector
  - Should be of astrophysical significance if it observes GW signals or **if it does not**
  - Should be at the limits of reasonable extrapolations of detector physics and technologies
  - Should lead to a realizable, 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

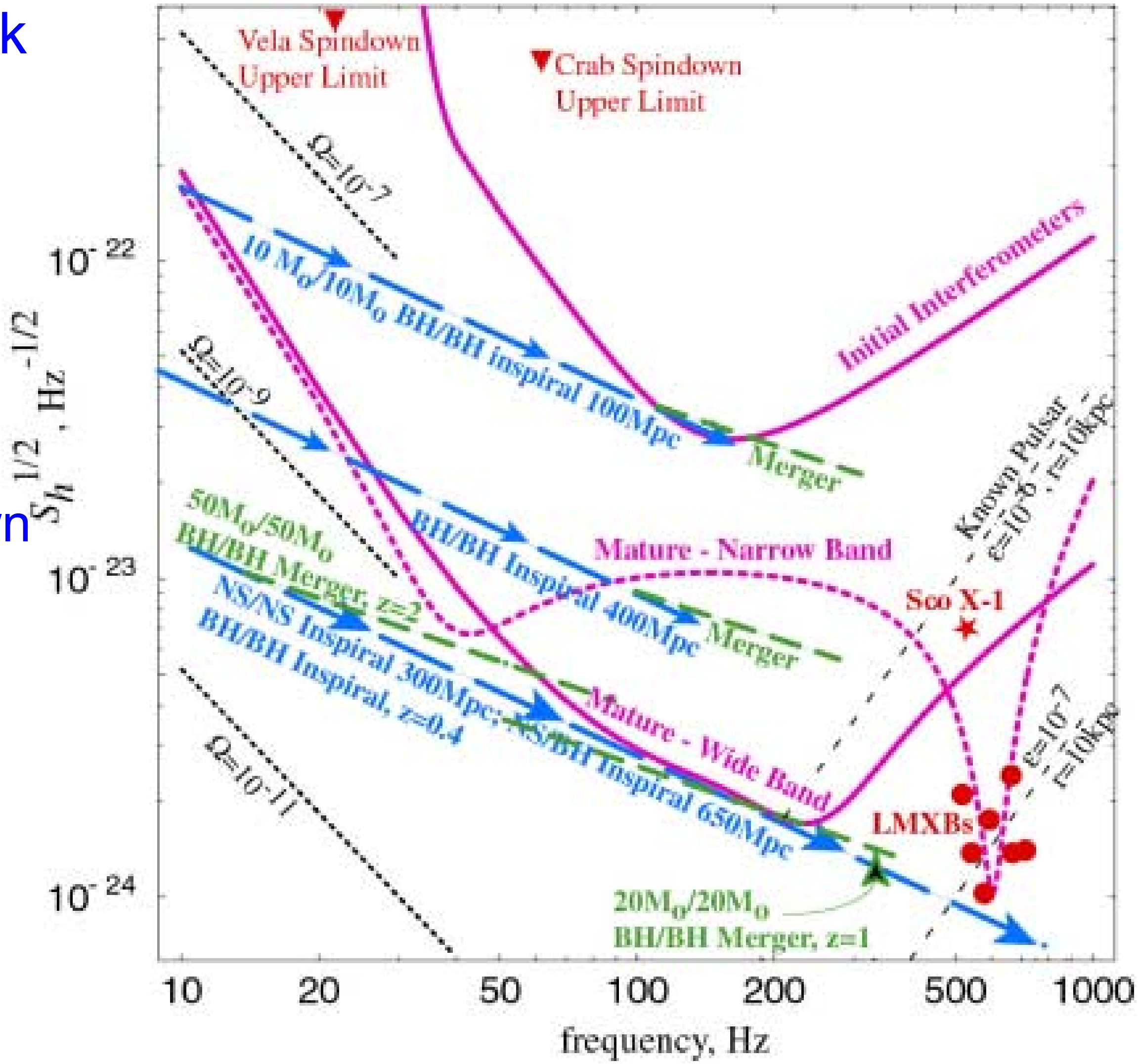
- Advanced LIGO
  - Seismic noise 40→10 Hz
  - Thermal noise 1/15
  - Shot noise 1/10, tunable
  - Initial → Advanced: factor <1000 in rate
- Facility limits
  - Gravity gradients
  - Residual gas
  - Scattered light
- Beyond Adv LIGO
  - Seismic noise: Newtonian background suppression
  - Thermal noise: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



Astrophysical Reach

(Kip Thorne)

- Neutron Star & Black Hole Binaries
  - » inspiral
  - » merger
- Spinning NS's
  - » LMXBs
  - » known pulsars
  - » previously unknown
- NS Birth (SN, AIC)
  - » tumbling
  - » convection
- Stochastic background
  - » big bang
  - » early universe



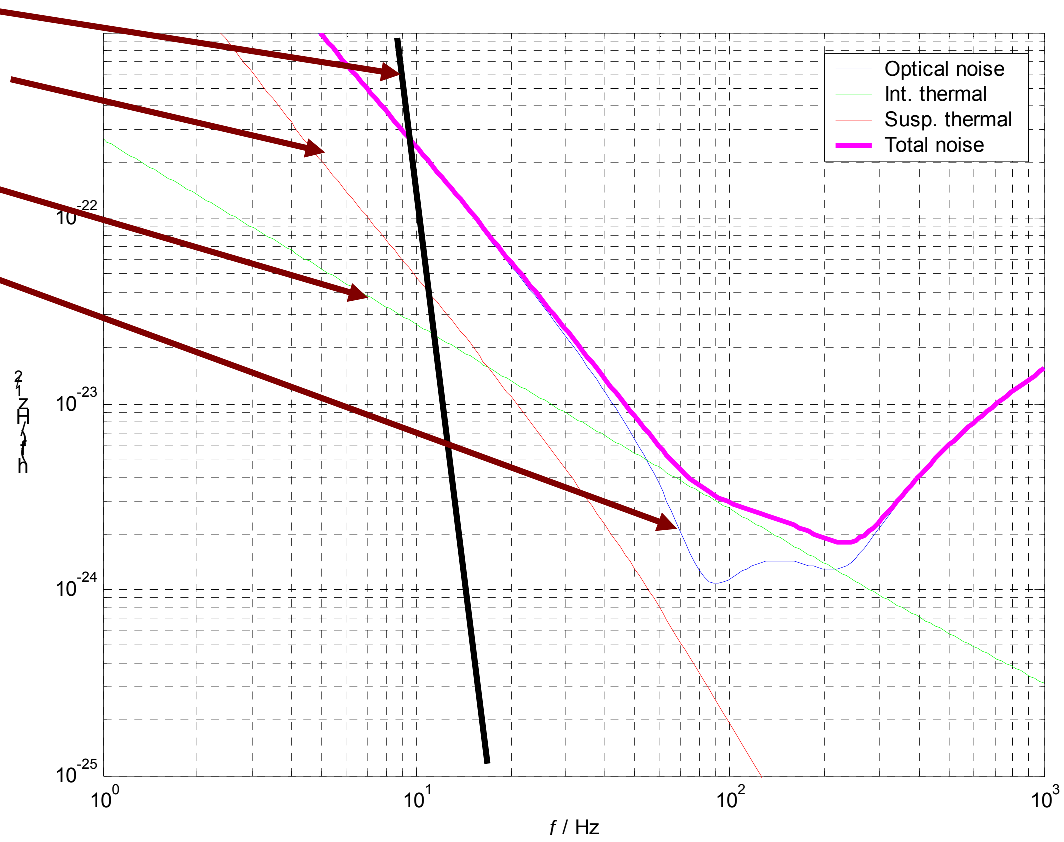
LIGO Top level performance & parameters

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

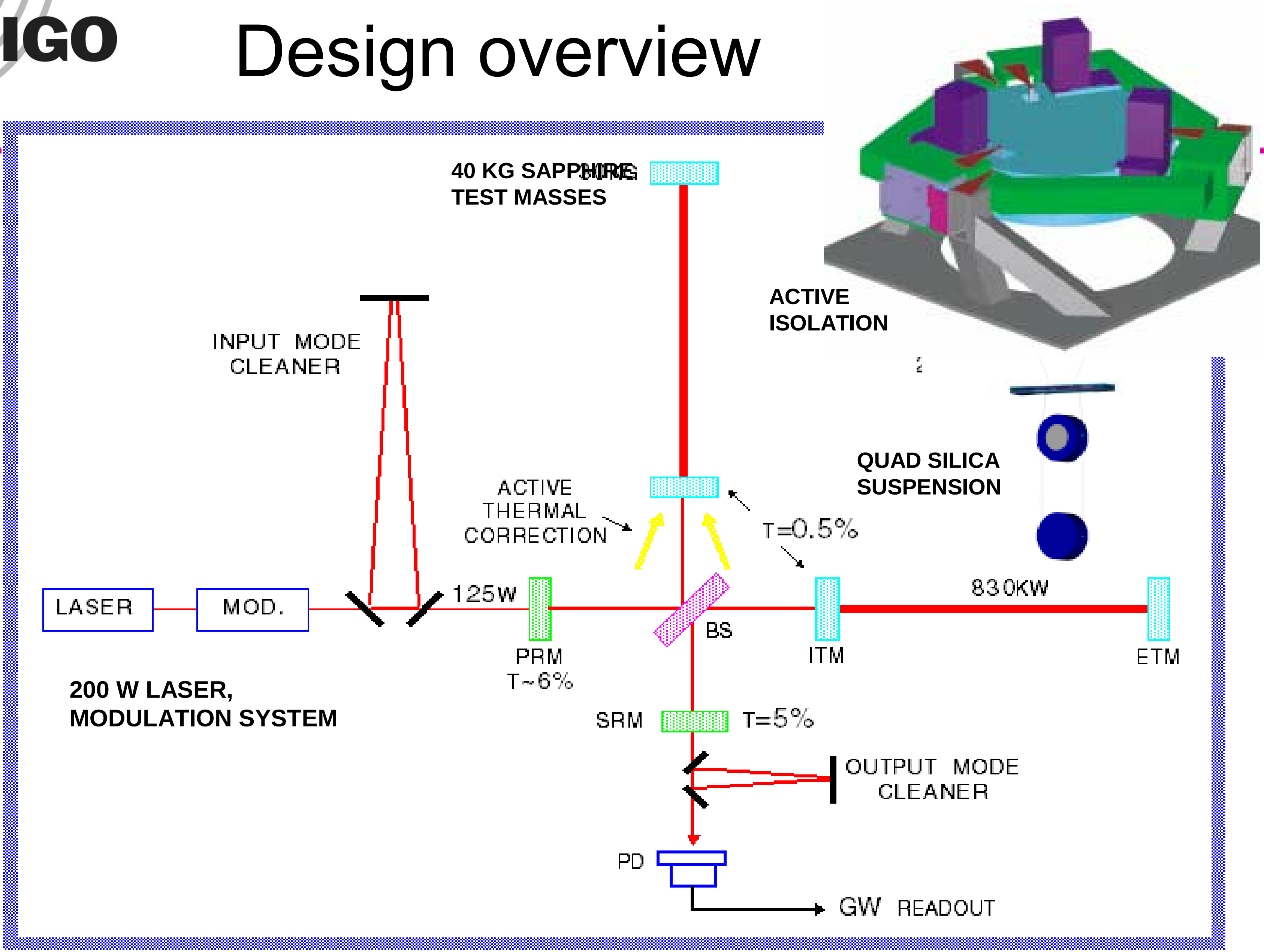
Anatomy of the projected detector performance

- 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



40 KG SAPPHIRE TEST MASSES

ACTIVE ISOLATION

QUAD SILICA SUSPENSION

200 W LASER, MODULATION SYSTEM

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				

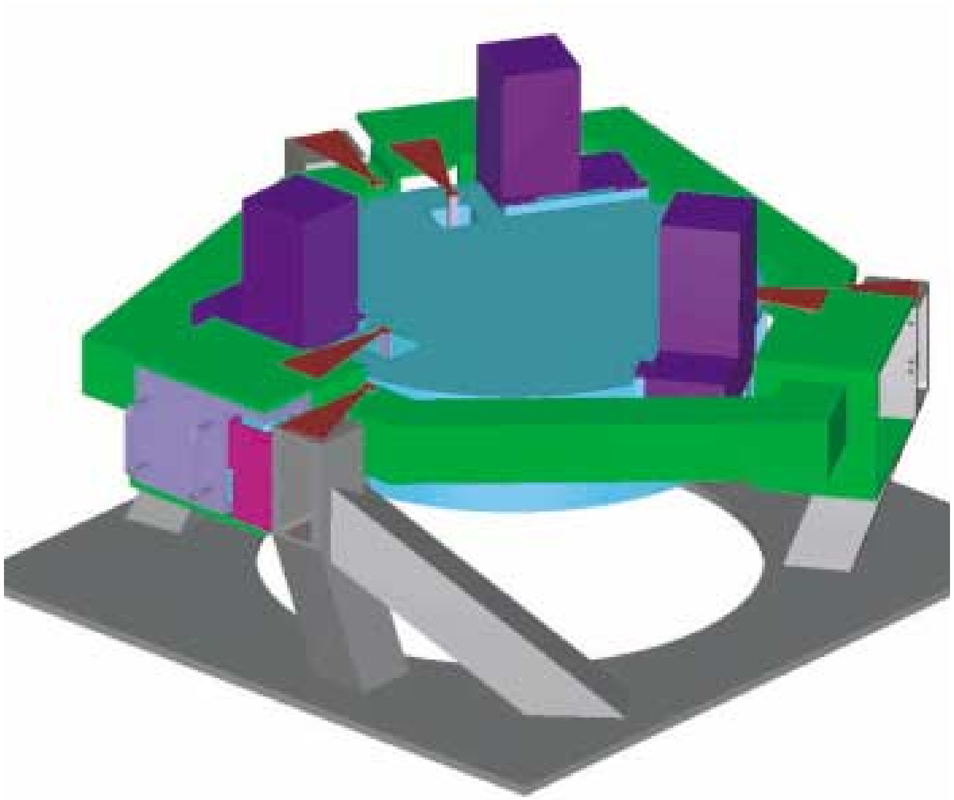
Interferometer Sensing & Control

- 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 to be completed by 3Q02

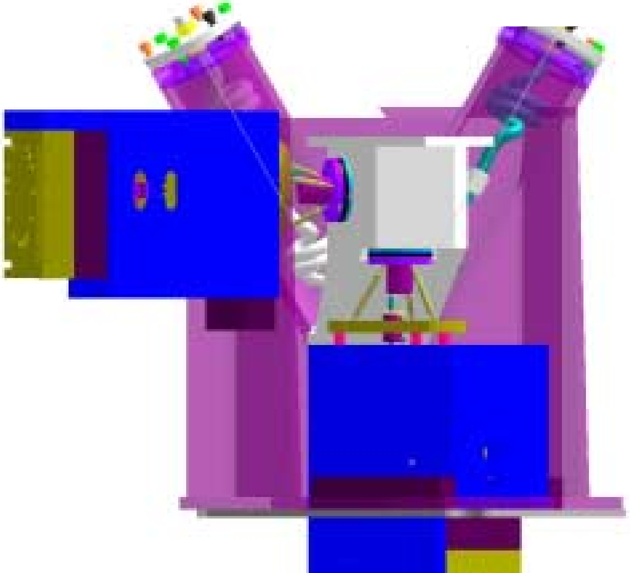
Seismic Isolation

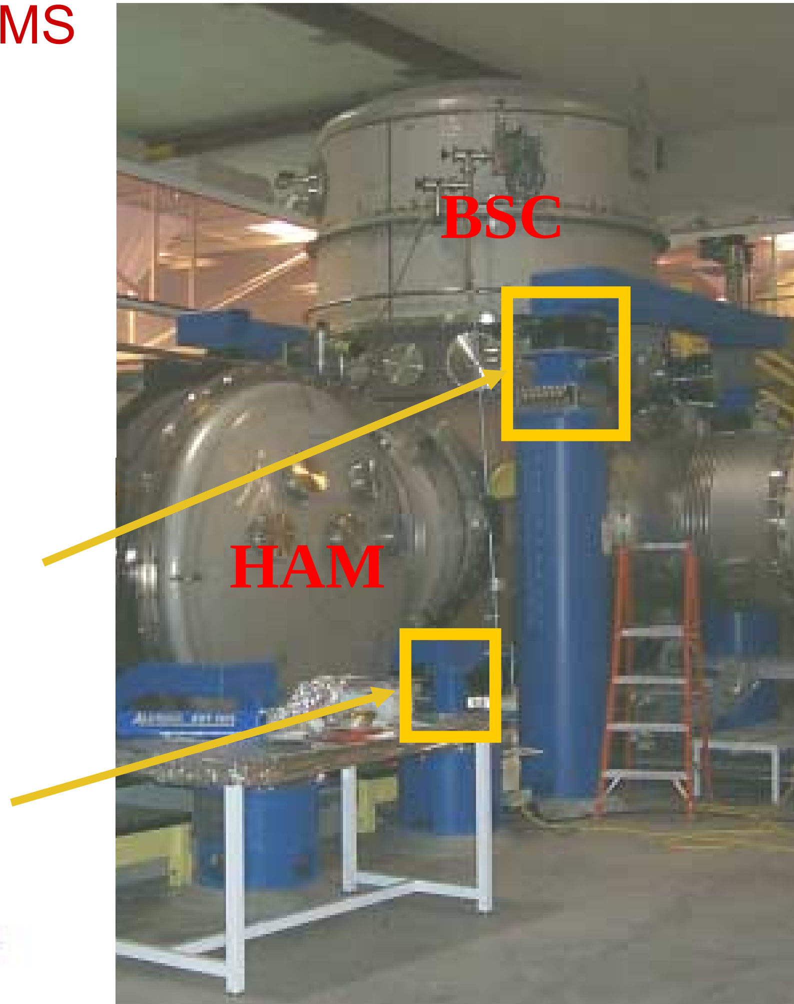
- Choice of 10 Hz for ‘seismic wall’; makes seismic noise irrelevant to scientific performance of system
- Achieved via high-gain servo techniques, passive multiple-pendulum isolation
- Isolation design has 3 stages:
  - External pre-isolator: reduces RMS, 0.1 → 10 Hz
  - Two in-vacuum 6 DOF stages, ~5 Hz natural resonant frequency, ~50 Hz unity gain
  - Hierarchy of sensors (position, Streckeisen seismometers, L4-C geophones)
- LSU/Stanford science lead
- Recent progress on reducing tilt-horizontal coupling
- Second-generation prototype in assembly and test at Stanford



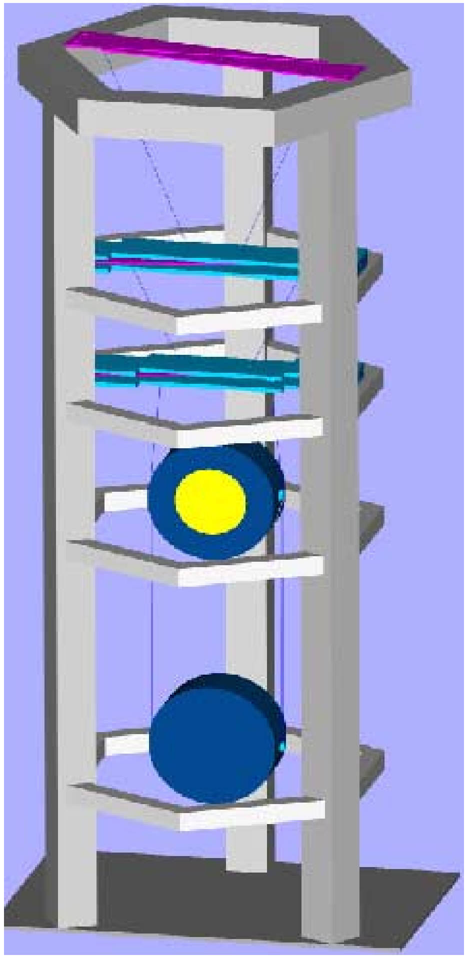
Seismic Isolation: Pre-Isolator

- 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



- Strong GEO/Glasgow contribution in $ and sense
- Quadruple suspension (seismic filtering)
  - » Fused quartz suspensions (low thermal noise)
- 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
  - » Have chosen vertical ‘bounce’ frequency – 12 Hz
  - » Can observe below (to Newtonian limit)
  - » Investigating 12 Hz line removal techniques to observe very close to bounce frequency
- Attachment of fibers to sapphire test masses
  - » Hydroxy-catalysis bonding of dissimilar materials
  - » Silica-sapphire tested, looks workable
  - » Detailed measurements of bond mechanical loss underway

LASTI Laboratory

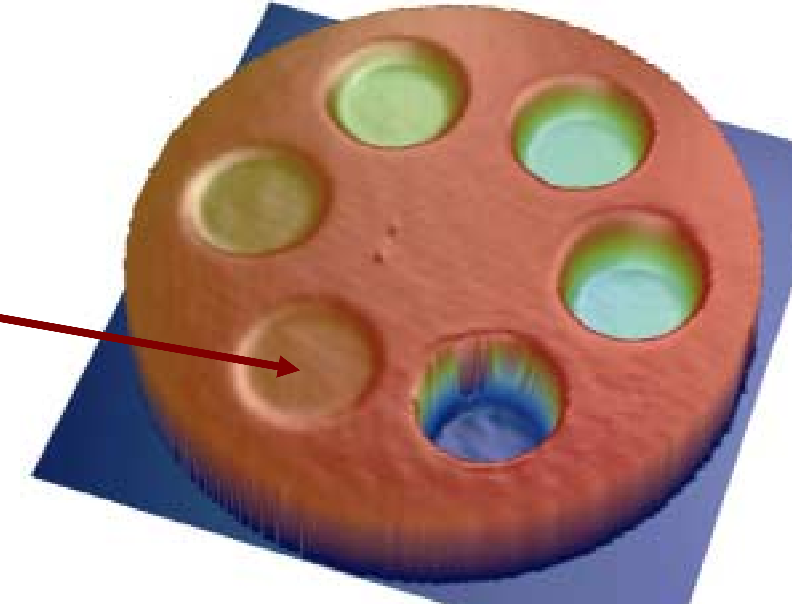
- LIGO-standard vacuum system, 16-m ‘L’
- Enables full-scale tests of Seismic Isolation and Test Mass Suspension
  - » Allows system testing, interfaces, installation practice.
  - » Characterization of non-stationary noise, thermal noise.
- Pre-stabilized laser in commissioning, 1m in-vacuum test cavity
  - » 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 systems installed
  - » Parts arriving in great quantitiy
- Advanced LIGO seismic isolation to arrive in 2003, suspensions to follow

Sapphire Core Optics

- Developing information for Sapphire/Fused silica choice
  - » Planned for Nov ‘02
- Mechanical Q under characterization
  - » Some pieces meet requirements (2e8 Q; Moscow, Glasgow); want a greater number of relevant measurements, in planning
- Thermoelastic damping parameters
  - » Measured room temperature values of thermal expansion and conductivity by 4 methods with agreement
    - – Spinoff from thermal compensation R&D
- Optical Homogeneity
  - » Measurements along ‘a’ crystal axis are getting close to acceptable for Adv LIGO (13 nm RMS over 80mm path)
- Working with vendors to generate suitable substrates
  - » Several 15” boules now fabricated (Crystal Systems)

Sapphire Core Optics

- Effort to reduce **bulk absorption** (Stanford, Southern University, CS, SIOM, Caltech)
- LIGO requirement is <10 ppm/cm (complements compensation requirement)
- 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, capable of handling full-size optics



Advanced LIGO

Coatings

- Mechanical losses of optical coatings leading to high thermal noise
  - Masks sapphire advantage; loss φ~4e-4
  - SMA/Lyon (France) has performed 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 alternatives
  - Nb2O5/Al2O3, Al2O3/SiO2 are under study (probably ok optically)
- Optical absorption in coating leads to heating & deformation in substrate, surface
  - Can trade against amount, complexity of thermal compensation; initial experimental verification complete
  - 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 – meets requirement (smaller ok too!)

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, will lead subsystem
  - » 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 – not there yet with any technology

LIGO High Power Testing: Gingin Facility

- ACIGA 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, probably suspensions, and a prototype thermal compensation system
  - » The facility and a test plan are being refined, some flux due to scope changes, availability of sapphire

Summary of technical status

- A great deal of momentum and real progress in every subsystem
- No fundamental surprises as we move forward; concept and realization remain intact with adiabatic changes

- …now, when and how to do turn this into instruments?