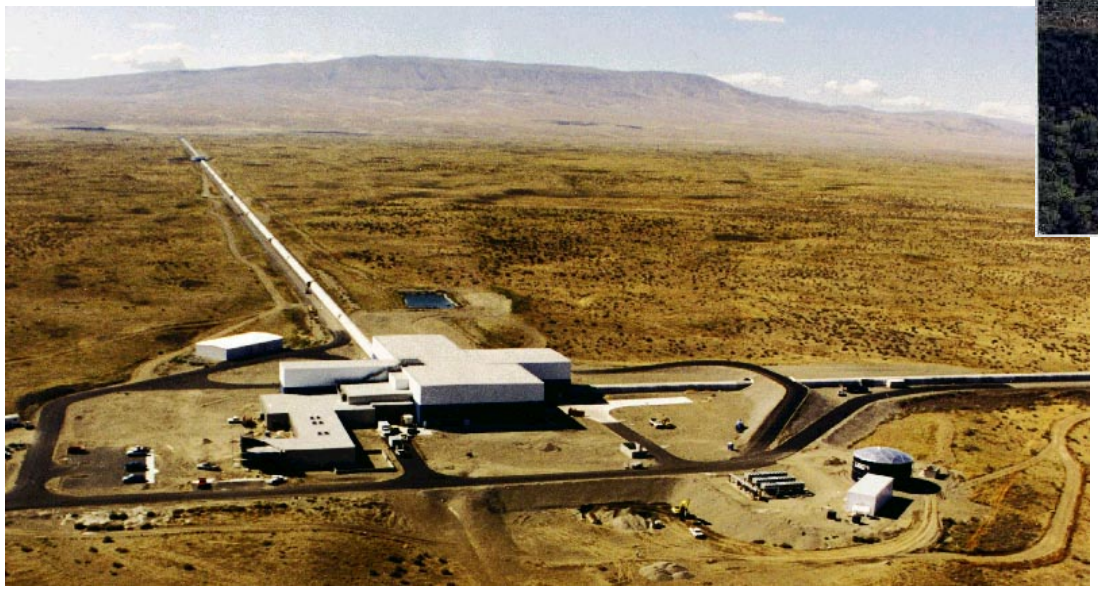
Advanced LIGO Update

Dennis Coyne

Program Advisory Committee (PAC) Meeting

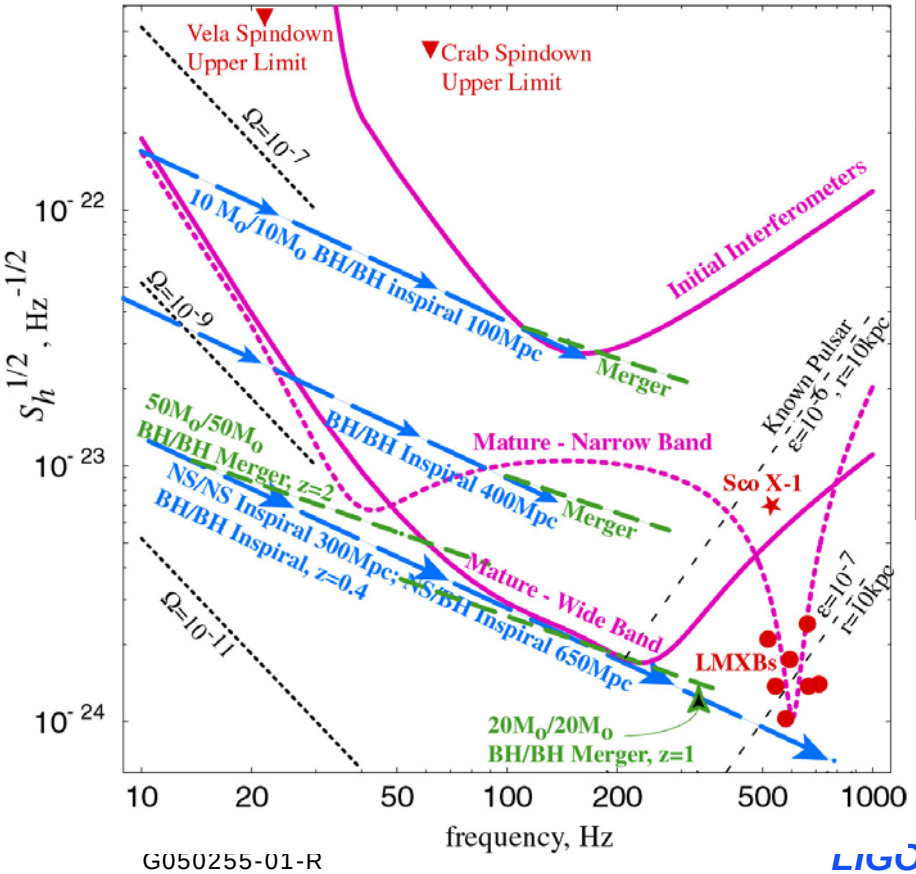
@ LIGO Livingston Observatory

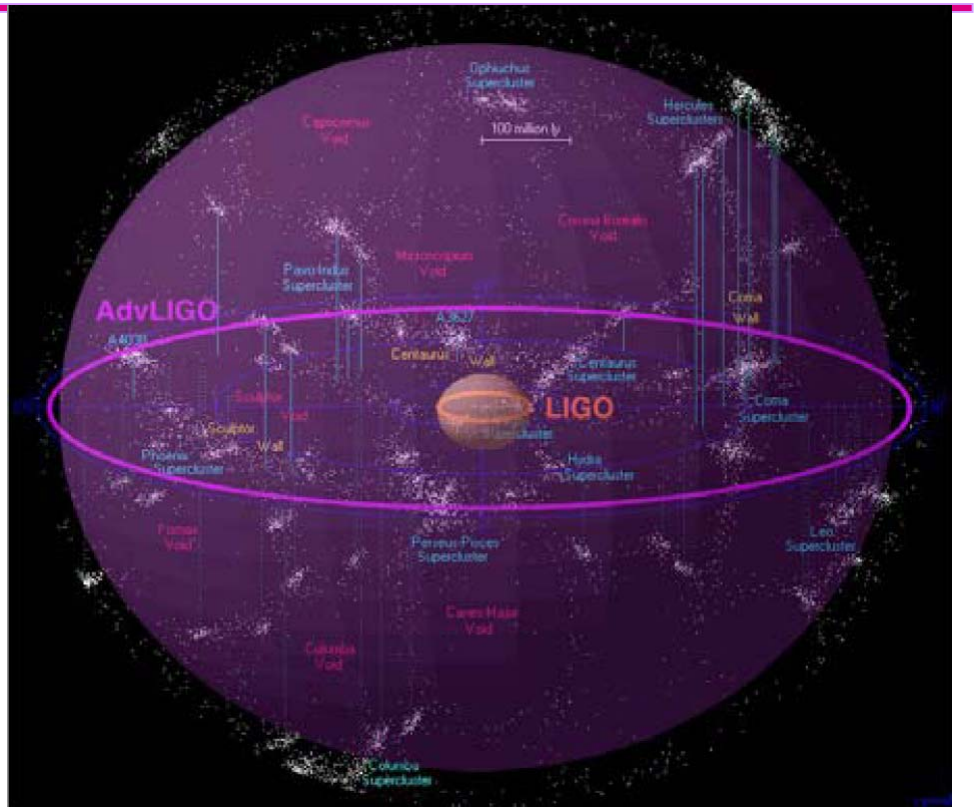
March 2005



Advanced LIGO

- A reminder ...
  - » ~Factor 10 in amplitude sensitivity
  - » ~Factor 4 lower frequency
  - » Tunable





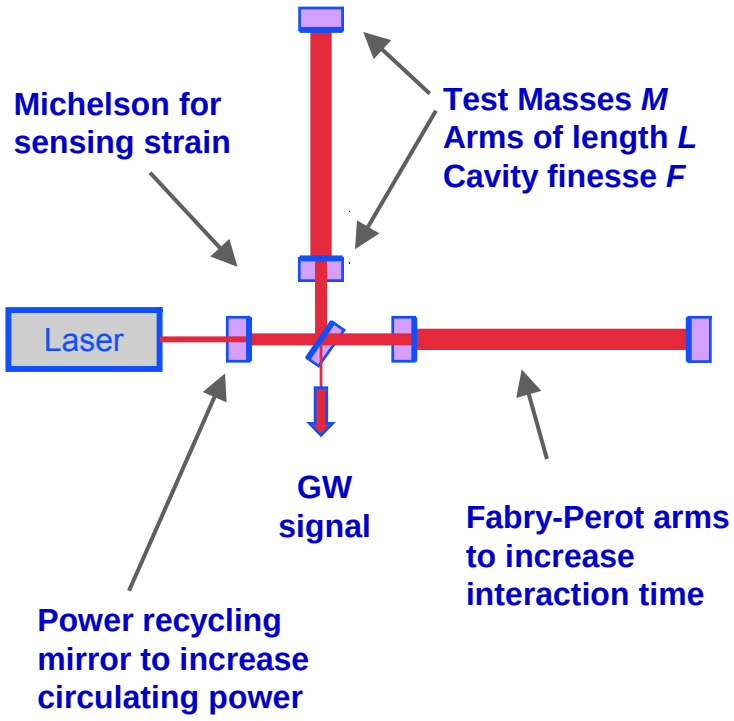
Sky map showing locations of superclusters, walls, and voids of galaxies within about 500 million light years. Superimposed circles show the range of LIGO (orange inner circle) and the 10 times larger range of AdvLIGO (purple outer circle). The milky way is at the center in this representation. *Credit: the underlying black and white image with names of clusters and voids is by Richard Powell; the superimposed color circles were added by Beverly Berger, Division of Physics, NSF.*

Advanced LIGO Detector Improvements

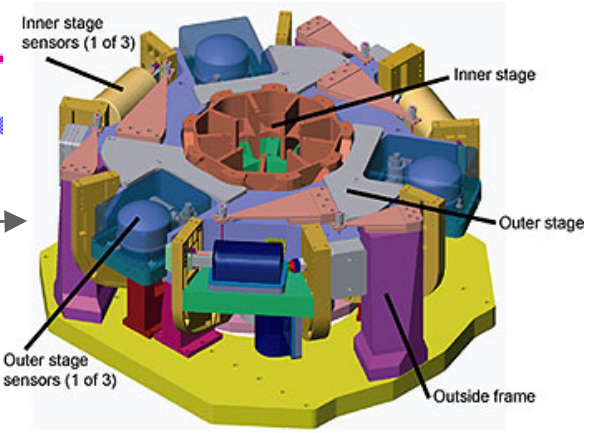
Retain infrastructure, vacuum chambers, and Initial LIGO layout of power recycled interferometer

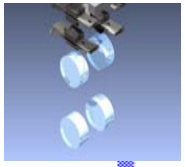
- Recombined Fabry-Perot Michelson
  - » Signal recycling
  - » ~20x higher input power
  - » 40 kg masses
  - » Fused silica suspension
  - » Active seismic isolation, quad pendulum suspension

INITIAL LIGO LAYOUT



Advanced LIGO Design Features





40 KG FUSED SILICA TEST MASSES

ACTIVE SEISMIC ISOLATION

FUSED SILICA, MULTIPLE PENDULUM SUSPENSION

INPUT MODE CLEANER

180 W LASER, MODULATION SYSTEM

ACTIVE THERMAL CORRECTION

T=0.5%

LASER

MOD.

125W

PRM T~6%

BS

ITM

830KW

ETM

SRM T=5%

OUTPUT MODE CLEANER

PD

GW READOUT

PRM Power Recycling Mirror
BS Beam Splitter
ITM Input Test Mass
ETM End Test Mass
SRM Signal Recycling Mirror
PD Photodiode

Construction Project Status

- NSB endorsed the Advanced LIGO construction proposal (Oct '04)
  - Contingent upon an integrated year of observation with Initial LIGO
  - Requested $185M
- NSF & Presidential Out-year Budget includes LIGO!
  - LIGO is one of 3 proposed new start projects in the next 3 years
  - NSF has proposed an FY08 funding start (FY07 start is a remote possibility)
- International Partner Contributions of Approximately $25M
  - United Kingdom (PPARC): UK Team (U of Glasgow, U of Birmingham, Rutherford Appleton Lab.) approved, funded and proceeding with R&D, design
  - Germany (MPS): Presidential Board of the Max Planck Society has endorsed AEI plans for Adv. LIGO material contribution
  - Australia (ARC + other): Proposing June, 2005
- Lab Planning:
  - Research, Design & Development (RD&D) phase aimed toward FY07 MREFC start
  - Continuing to refine plans, costs and contingencies
  - Anticipate a detailed baseline review for MREFC ~mid 2006
- Construction Schedule (for NSF FY08 funding start):
  - Start fabrication in FY2008
  - Shutdown Livingston in FY10, but continue Hanford operations
  - Shutdown Hanford in FY11
  - Schedule installation work to minimize downtime and make effective use of "specialized" work force
  - Resume coincidental observations in FY13

"Systems"

- Two major LIGO prototype test facilities:
  - » LIGO Advanced System Test Interferometer (LASTI) @MIT – full scale tests of seismic isolation, suspensions, laser, mode cleaner
  - » 40m Interferometer @Caltech – sensing/controls tests of readout, engineering model for data acquisition, software
- Support from LSC testbeds
  - » Gingin Facility @Gingin, Australia – thermal compensation (measure substrate absorption, test wavefront sensors & actuators)
  - » 10m Interferometer @U of Glasgow – readout
  - » Engineering Test Facility (ETF) @Stanford – seismic isolation
  - » GEO600 @Hanover, Germany – much more than a prototype! (test of the quasi-monolithic fused silica suspension)
  - » Initial LIGO – much more than a prototype! (Hydraulic External Pre-Isolator (HEPI), Thermal Compensation System, Large Aperture, Thermally Compensated Faraday Isolator, …)
- Systems Engineering
  - » Refining the optical layout
  - » Starting an integrated 3D optomechanical layout
  - » E2E Adv. LIGO modeling well underway
  - » Systems trades & Requirements/Interface definition proceeding

LASTI (Triple Suspension in a HAM Chamber)

Gingin Facility

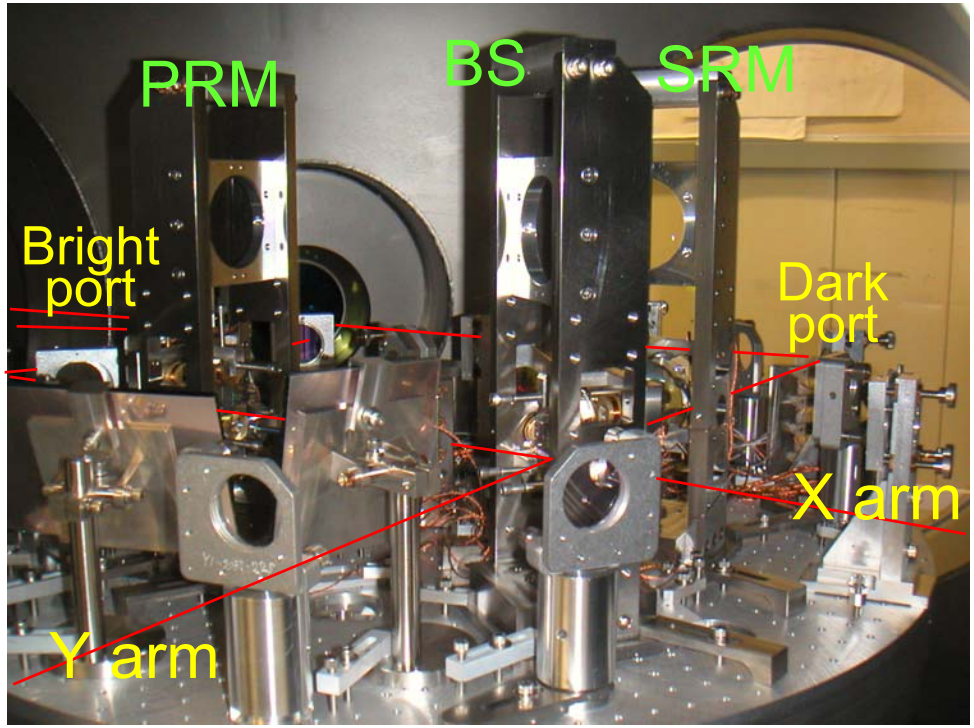
40 M Lab

Caltech 40 meter prototype interferometer

Objectives

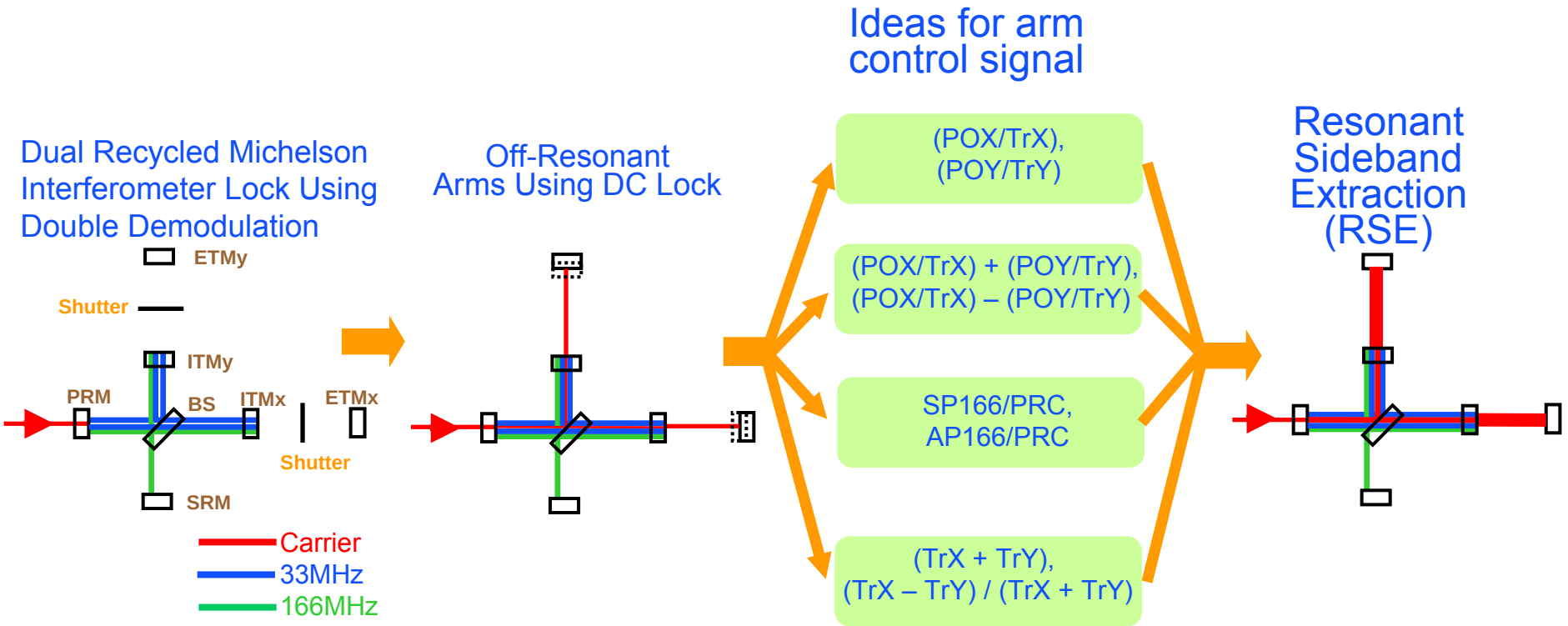
- Develop **lock acquisition procedure** of detuned Resonant Sideband Extraction (RSE) interferometer, as close as possible to Advanced LIGO optical design

- Characterize noise mechanisms
- Verify optical spring and optical resonance effects
- Develop DC readout scheme
  - » Best SNR, simplifies laser, photo-detection requirements
- Extrapolate to AdLIGO via simulation
- Caltech 40m prototype giving guidance to design
  - » Exploring modulation techniques; adoption of Mach-Zehnder design to avoid 'sidebands on sidebands'
  - » Off-resonance arm lock with Dual-recycled Michelson
- etc.



40 m Interferometer Update

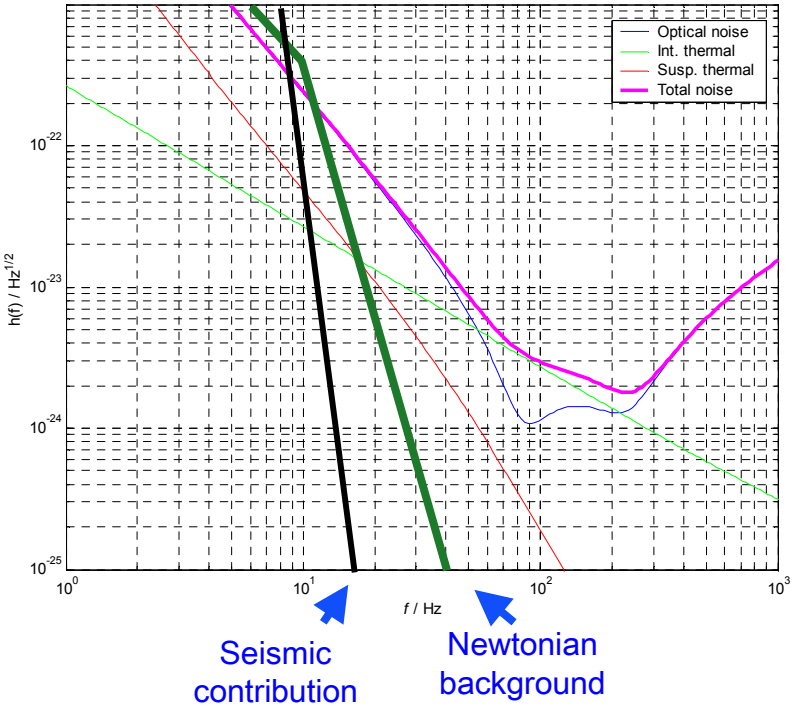
- Full Interferometer Lock expected Soon
- Preparing for DC readout implementation in 2005
  - » Output Mode Cleaner
  - » Mode Matching & Steering Telescope

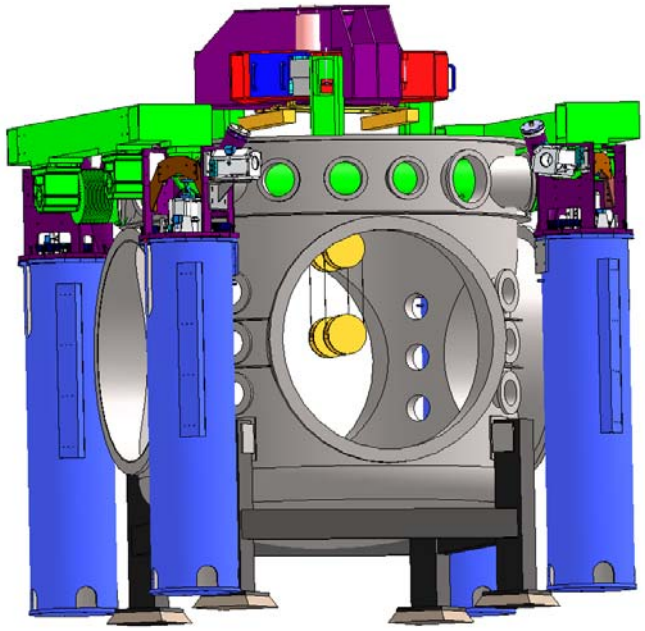


Done *Done* *In progress*

Seismic Isolation: Multi-Stage Solution
(LSU, Stanford, CIT, MIT Effort)

- Render seismic noise a negligible limitation to GW searches
  - » Newtonian background will dominate for frequencies less than ~15 Hz
  - » Both suspension and isolation systems contribute to attenuation
- Reduce actuation forces on test masses

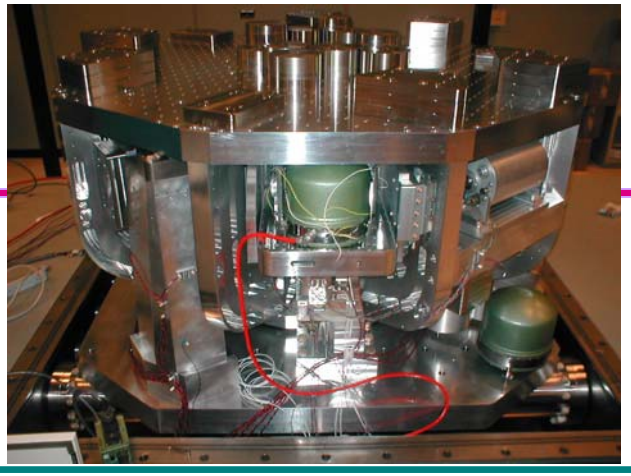




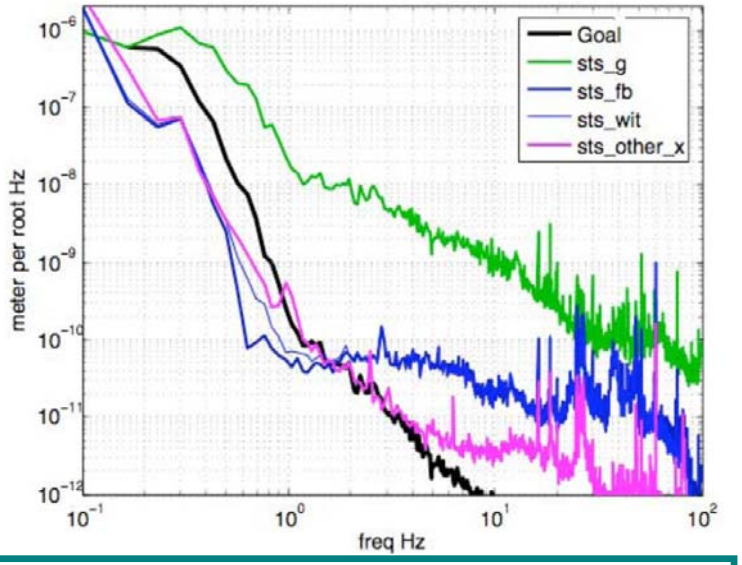
- Choose an active isolation approach:
  - » 3 stages of 6 degree-of-freedom each
  - » Hydraulic External Pre-Isolation (HEPI)
  - » Two Active Stages of Internal Seismic Isolation
- Increase number of passive isolation stages in suspensions
  - » From single suspensions in initial LIGO to quadruple suspensions for Adv. LIGO

LIGO Seismic Isolation Update

- BSC Chamber Design
  - » Our design contractor (ASI) has completed and delivered the detailed BSC design
  - » Critical Review: Are we still on track?
    - – Cost and programmatic review completed (Jan) -- ~$11M over proposed budget
    - – Technical Review, informed by Stanford ETF testing & modeling, planned for 5/25
    - – Recommendation to LIGO Management in ~June
  - » LIGO Lab will competitively compete the piece part fabrication
    - – After a go-ahead from the critical review, and any minor design modifications
    - – Procurement strategy being developed
- HAM Chamber design
  - » ASI has delivered a preliminary (layout) design
  - » After BSC fabrication is underway, LIGO Lab will complete the final design effort (likely as a subcontracted design effort)
  - » Recycling Cavity Seismic Isolation Requirements to be re-evaluated (July 2005)

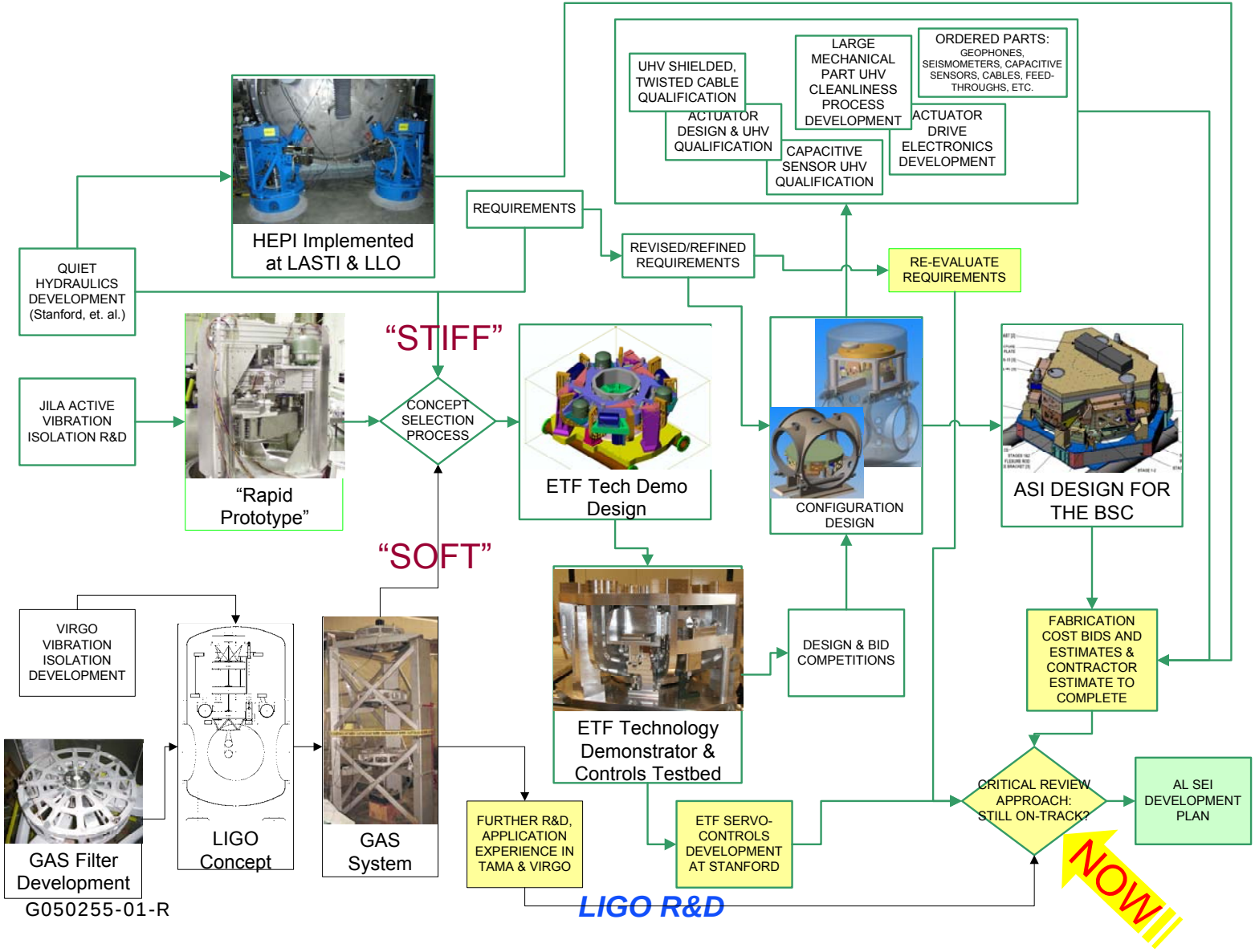


SEI Technology Demonstrator at the Stanford Engineering Test Facility (ETF)



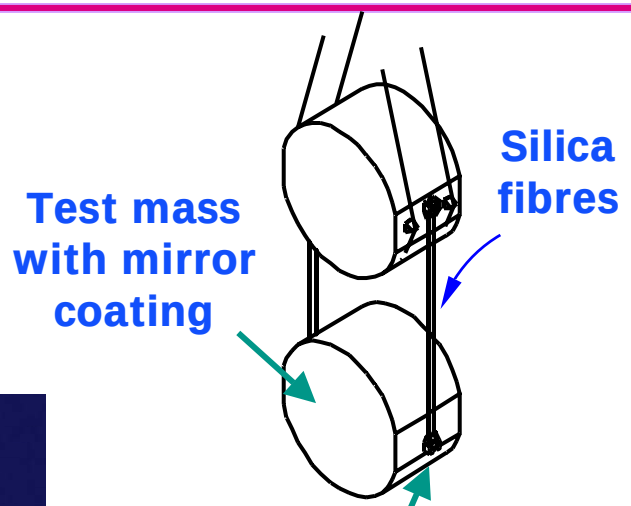
Meets Goal @ 1 Hz
Working to Improve Performance @10 Hz
(all 12 damping & isolation loops engaged)

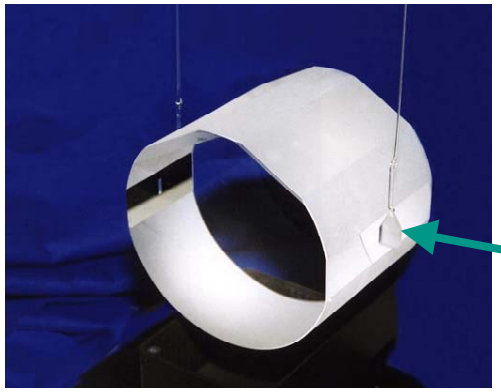
LIGO Seismic Isolation (SEI) Development Path

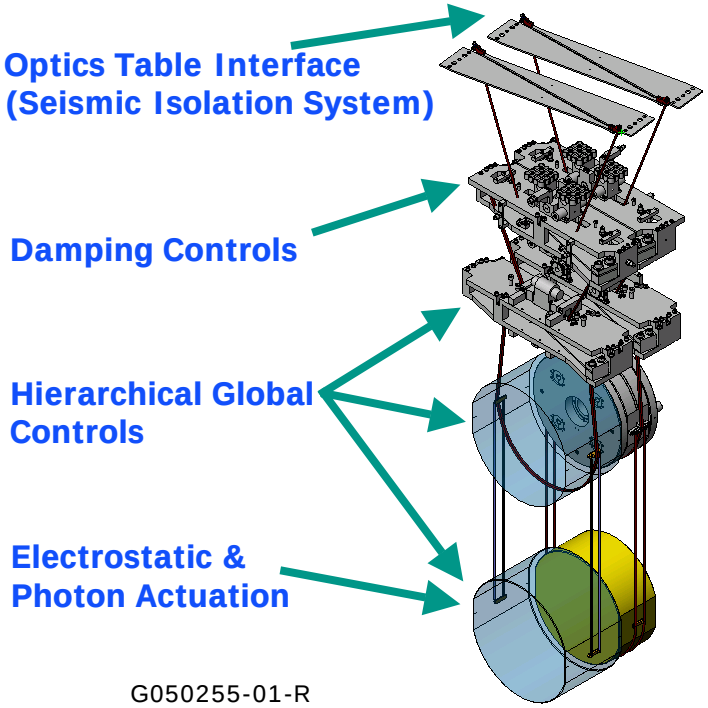


Thermal Noise Suppression (Background)

- Minimize noise from damping controls and global control actuation
- Minimise thermal noise from pendulum modes
  - » Thermally induced motion of the test masses sets the sensitivity limit in the range ~10 — 100 Hz
  - » Required noise level at each of the main optics is 10^{-19} m/√Hz at 10 Hz, falling off at higher frequencies

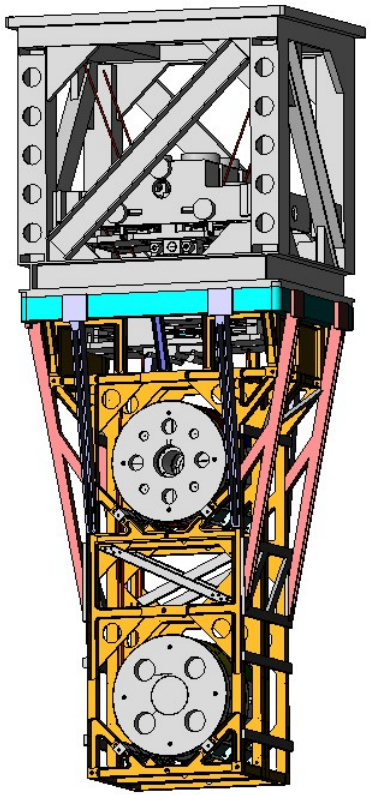






- Choose quadruple pendulum suspensions for the main optics and triple pendulum suspensions for less critical cavity optics
- Create quasi-monolithic pendulums using fused silica ribbons to suspend 40 kg test mass

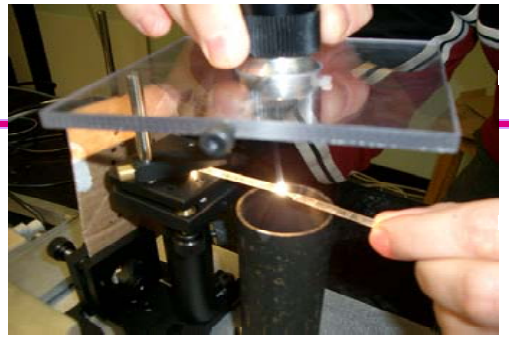
Suspensions Update
(Combined US and UK Effort)



- Test Mass (Quad) Suspension
  - » 'Controls' Prototype
    - – 'Dirty' sub-assembly underway
    - – Design & Fabrication to be completed ~June
    - – Delivery to LASTI planned late summer
  - » 'Noise' Prototype
    - – Concurrent Design by the UK Team (under PPARC funding)
  - » Preliminary Design Reviews
    - – Electronics ~July
    - – Mechanics ~Fall

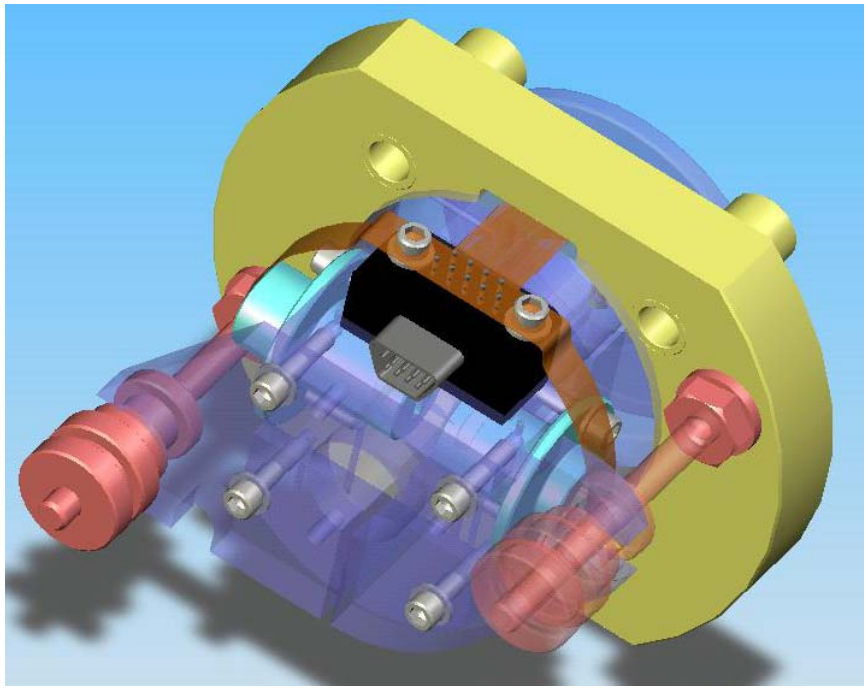
- Mode Cleaner (Triple) Suspension
  - »LASTI Testing of controls prototype completed
  - »Performance as expected
  - »Model-measurement comparison caught some model shortcomings & an as-built difference

Suspensions Update



Welding 3mm silica rod with 9W CO_2 laser

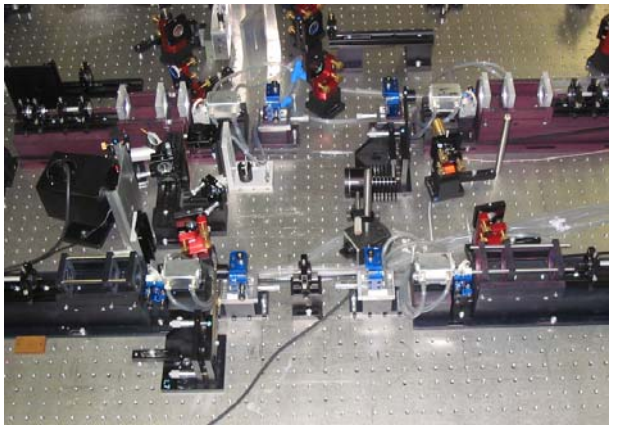
- Silica Fiber/Ribbon Pulling
  - » R&D on computer controlled CO_2 laser system proceeding well
  - » Fibers up to 570 mm long, 184 $\pm$ 5 microns diameter (15 microns dia. repeatability) with 3 GPa breaking stress (factor of safety $\approx$ 4)
  - » Ribbons produced with the beam oscillating across the stock by mirror galvanometers (4 mm x 150 microns typ.)
- Fiber/Ribbon Welding
  - » Fiber & ribbon welding demonstrated
  - » Working to improve welded strength
- Eddy Current Damping
  - » Component design is complete
  - » Optimizatizing location for selected DOFs
- Electrostatics
  - » Mask fabricated on penultimate mass
- Electronics
  - » Optical Sensing & Electro-Magnetic actuator (OSEM) assembly Preliminary design:
    - – Mechanical design complete
    - – Electronics well underway
  - » Damping Controls test stand fabrication & assembly completed at Caltech (dSpace version)



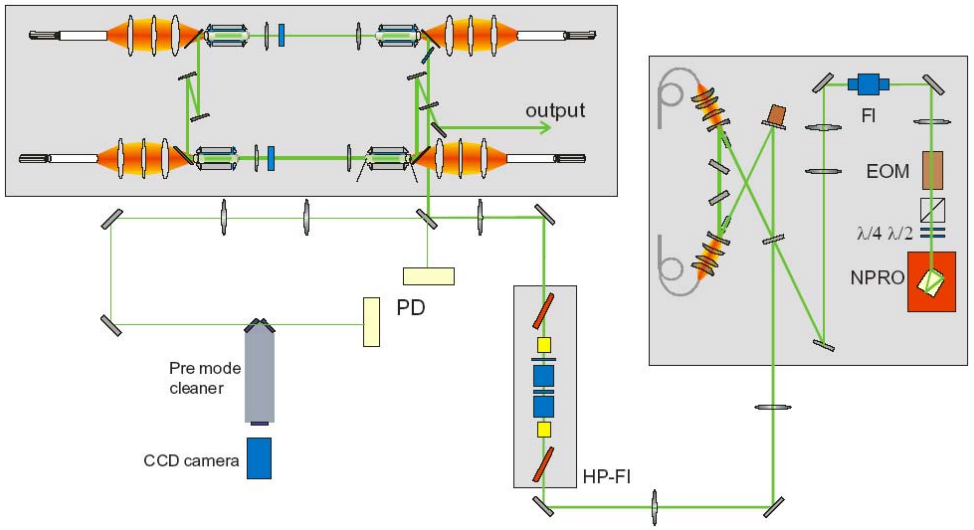
Modified Hybrid OSEM Design

Pre-stabilized Laser
(AEI/MPS & LZH German Effort)

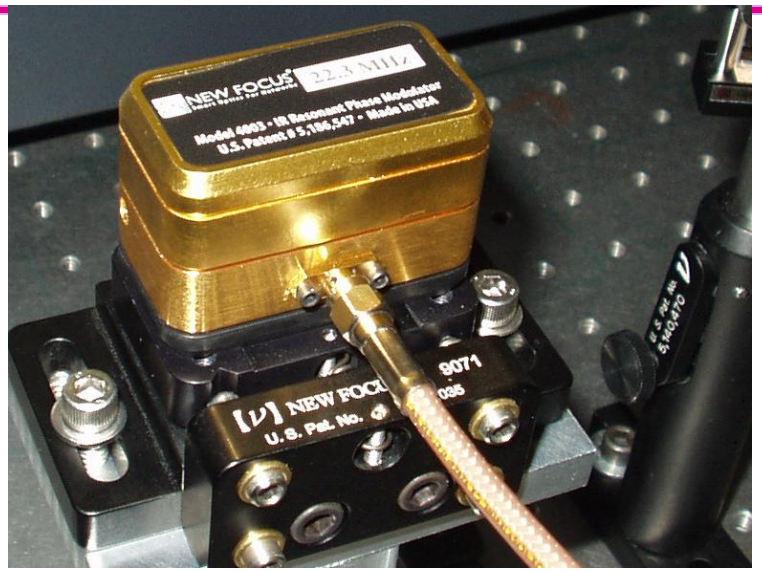
- Injection locking of the 200 W Laser (LZH, AEI)
  - » Automatic: Re-locks 3 stage system in less than 1 sec
  - » Reliable: Durations > 40 min
- Characterizing spatial and temporal behavior
  - » Higher order mode content measured with LIGO-like Pre-Mode Cleaner (PMC)
  - » Spatial profile has donut mode after upgrade of components (100 W to 200 W)
    - – Laser crystal Erbium doping too high
    - – Thermal compensation lenses out of specification (fixed)
- Relative Intensity Noise (RIN) Stabilization
  - » Outer loop power stabilization implemented on GEO600
  - » Mode Cleaner introduces RIN on the beam – effect being studied



●Held Successful Design Requirements and Conceptual Design Review, Mar 2005



Input Optics (IO)
(U of Florida Effort)

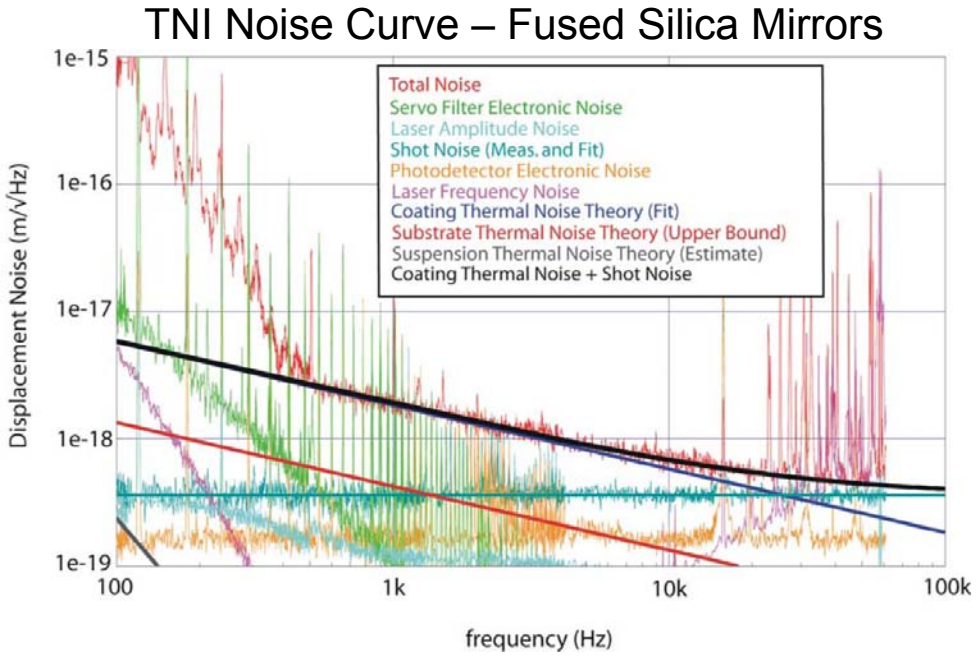


- LLO High Power Laser Facility (HPLF)
  - » Operational (clean room, safety prototcols)
  - » 100 W CW 1064 nm linearly polarized Yb fiber laser is in spec
  - » Reliability problems; since delivery failed 4 times
- Faraday Isolator
  - » 20 mm aperture with thermal lensing & depolarization compensation
  - » 20% thermal lensing of an uncompensated isolator
  - » Total depolarization of -35 dB at 180 W
- Modulation
  - » Received two New Focus EOMs with low absorption RTP crystals
  - » No damage at 85 W for > 400 hrs at irradiances greater than for AL
  - » Mach-Zehnder interferometer being assembled with monolithic mechanical ‘backbone’
- IO Design
  - » Building layout & Components in 3D SolidWorks
  - » Will use Fused Silica for the Adaptive Mode Matching Telescope; Measured Thermal Distortion with Schott OG-515 is too high
  - » Melody Model of the Mode Cleaner indicates that an Absorption Coefficient of 1 ppm can be tolerated

Coatings

(CIT, MIT, Lyon LMA, CSIRO, UG, Stanford Efforts)

- Mechanical Loss Goal: ~10x reduction from 5 10^{-4} to 5 10^{-5} loss angle
  - » Brings coating noise down below substrate Brownian noise
  - » Increases NS-NS 1.4 Ms from ~160 Mpc to ~200 Mpc
- Need to reduce coating thermal absorption inhomogeneity
- Sense is that we can get pretty close with incremental improvements
  - » New results on Tantala doping and single layer materials
  - » New design algorithm for non-periodic, multi-layer dielectric coating decreases thickness of high mechanical loss Tantala

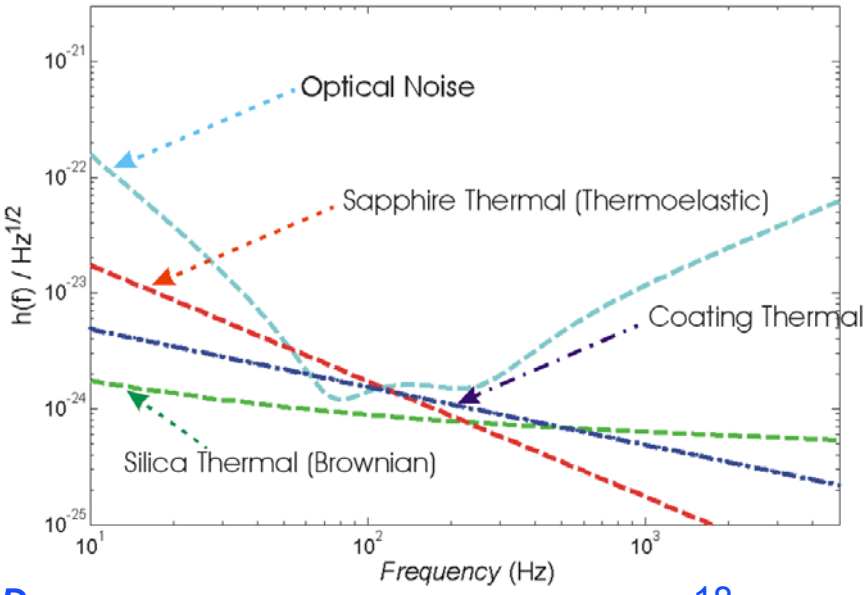


Core Optics

(CIT, MIT, Stanford, UG Efforts)

	Sapphire	Silica
NS-NS 1.4 Ms	191 Mpc	191 Mpc
BH-BH 10 Ms	920 Mpc	1050 Mpc
Pulsar h/√Hz	7 x10^{-24}	12 x10^{-24}
Omega	4.8 x10^{-9}	2.6 x10^{-9}

- Substrate selection = Fused Silica!
  - » Recommendation based on a comparative study of FS & Sapphire
  - » either material could work, but more risks for sapphire
  - » FS better at low frequencies (high mass BH-BH)
  - » Sapphire better at high frequencies (LMXB)
  - » Suspension design intended to be capable of future retrofit to sapphire
  - » Coating loss dominates
    - – limits to ~160 Mpc (NS-NS 1.4 Ms)
- Lab work:
  - » Annealing?
  - » Scatter and absorption characterization of Initial LIGO optics for possible H1 ITM replacement pre-S5
  - » Developing & characterizing:
    - – optical loss for improved cleaning procedures
    - – Required particulate cleanliness levels



Next

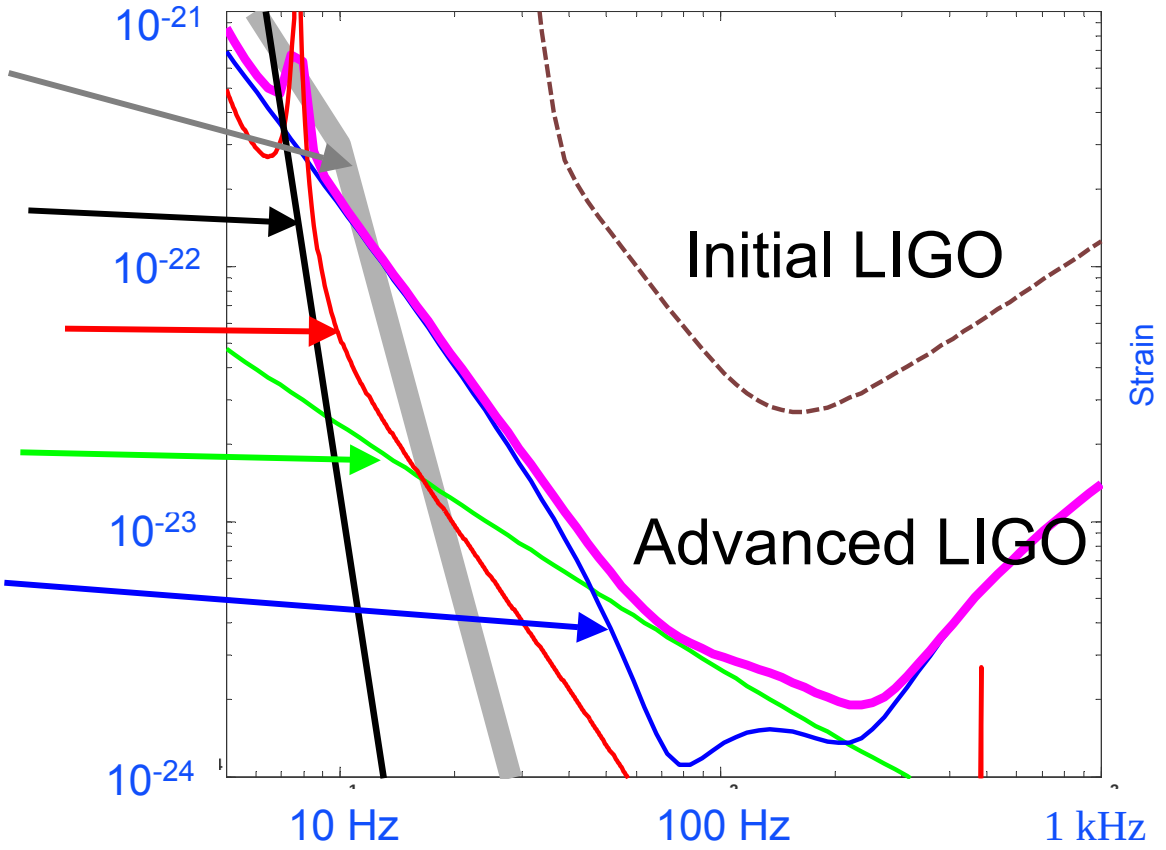
- Seismic Isolation
  - » Critical review of BSC seismic isolation (Feb thru May 2005)
  - » Design changes based on Engineering Test Facility (Stanford) testing
  - » Contracting for final prototype (all of 2005)
  - » Review of HAM approach (mid-2005)
- Suspension
  - » Dynamics & controls prototype quadruple suspension (metal test mass) installed (Aug 2005) in LASTI testbed
  - » “Noise” prototype quadruple suspension installed in LASTI testbed (3Q 2006)
  - » Start Final Design of Triple Suspensions (Mode Cleaner, Recycling Mirrors) informed by LASTI testing (4Q 2005)
- Coating R&D continues for lower mechanical & optical loss
- COC Polishing “pathfinder” in conjunction with Suspension Noise Prototype
- Locking (imminent), exploitation of 40m interferometry testbed (all of 2005+)
- Control & Data Systems, Electronics Infrastructure Conceptual Design
- Continued cost/schedule refinement, linking with Caltech finances, flexible planning for melding with Operations support
- Staffing infusion from observatories into adv. LIGO effort, as Science Run #5 starts (late 2005)

Advanced LIGO RD&D Summary

- RD&D phase plans are being adjusted to accommodate
  - » delayed seismic isolation development
  - » limitations in LIGO operations funding
  - » a stretched development phase
- The SEI Critical Review process is proceeding well
- Fused Silica has been selected as the Test Mass material (over Sapphire)
- ¡The NSF, NSB and the OMB have endorsed the Advanced LIGO Construction project!
  - » MREFC funding start nominally FY08

Projected Adv LIGO Detector Performance

- Newtonian background, estimate for LIGO sites
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Unified quantum noise dominates at most frequencies for full power, broadband tuning



Advanced LIGO's Fabry-Perot Michelson Interferometer is flexible – can tailor to what we learn before and after we bring it on line, to the limits of this topology and fundamental noise limits.