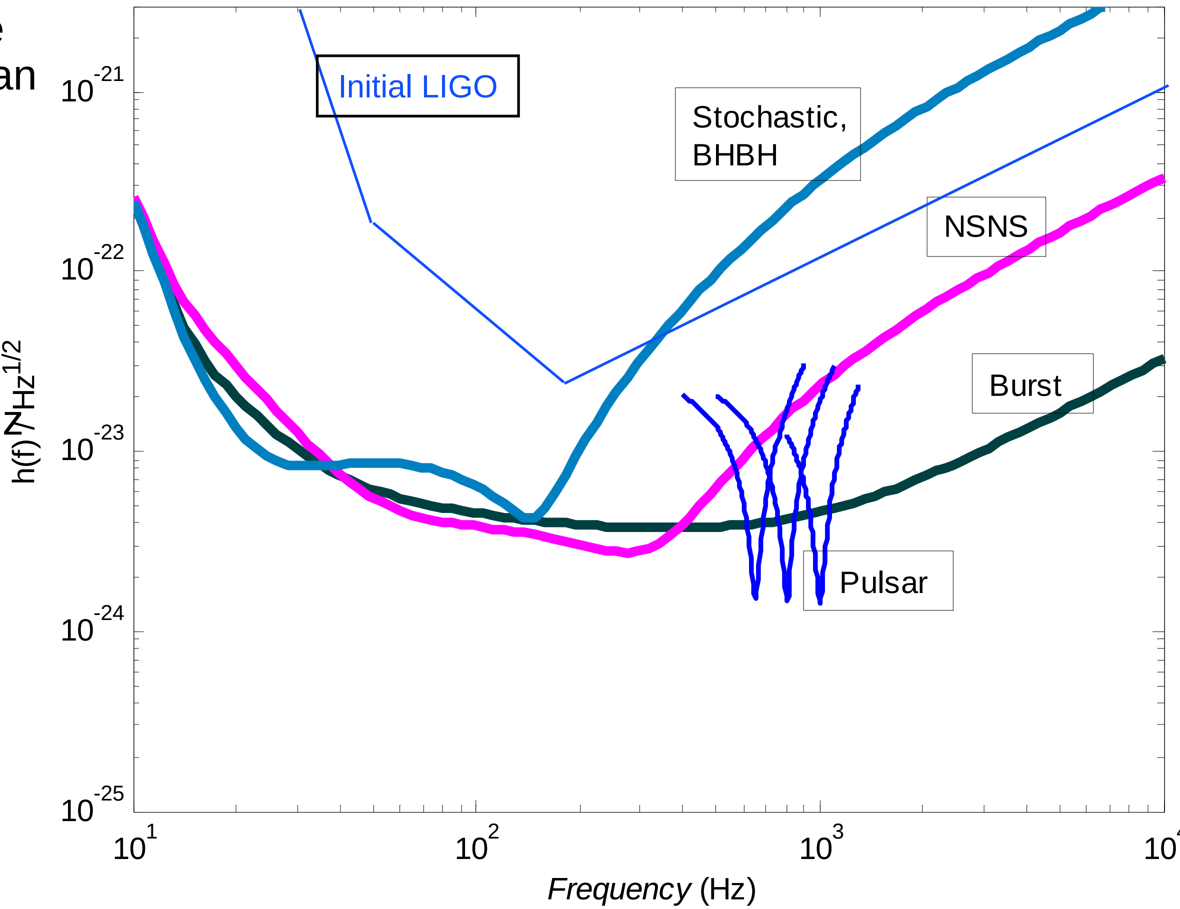
Advanced LIGO R&D

NSF Review of the LIGO Laboratory
23 October 2006

David Shoemaker

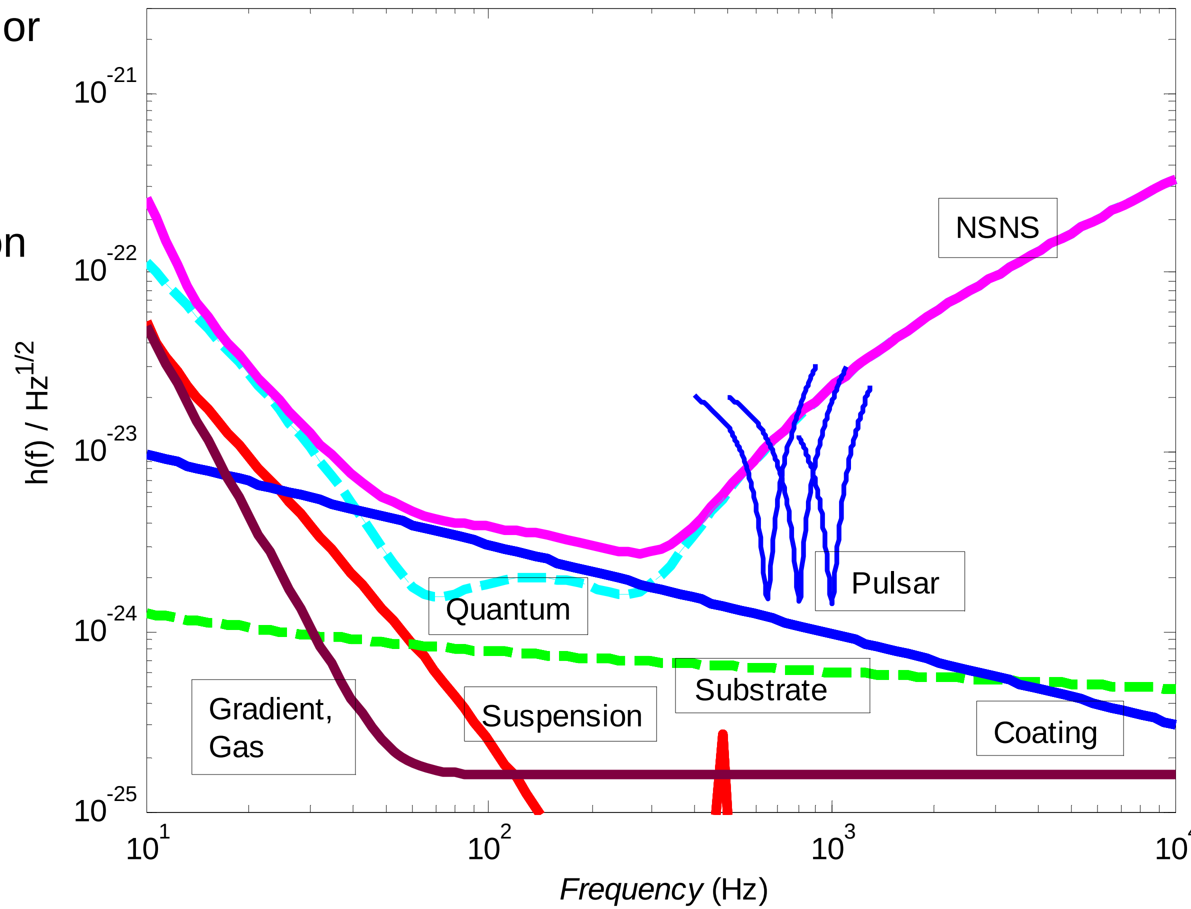
Advanced LIGO: Sensitivity

- LIGO conceived as an infrastructure to support a series of improving detectors
- Advanced LIGO is the Lab/LSC proposal for the major upgrade to follow initial LIGO
- Replacement of all three interferometers; change to 4km length for LHO #2; re-use of vacuum and laboratory infrastructure
- As for Initial LIGO, we specify the sensitivity of Advanced LIGO by an RMS sensitivity: 10^{-22} h_{RMS} in a 100 Hz band
  - » A factor of 10 improvement over Initial LIGO
- Anticipated performance is better than above (as in Initial LIGO) – roughly 3×10^{-23} h_{RMS} in a 100 Hz band, around 250 Hz, tuned for NSNS inspirals
- Flexibility of tuning will allow a range of responses, and the configuration of the three-interferometer system should be determined by the astrophysics we are chasing

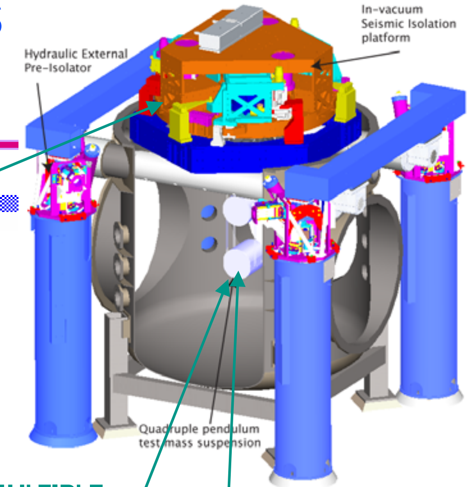


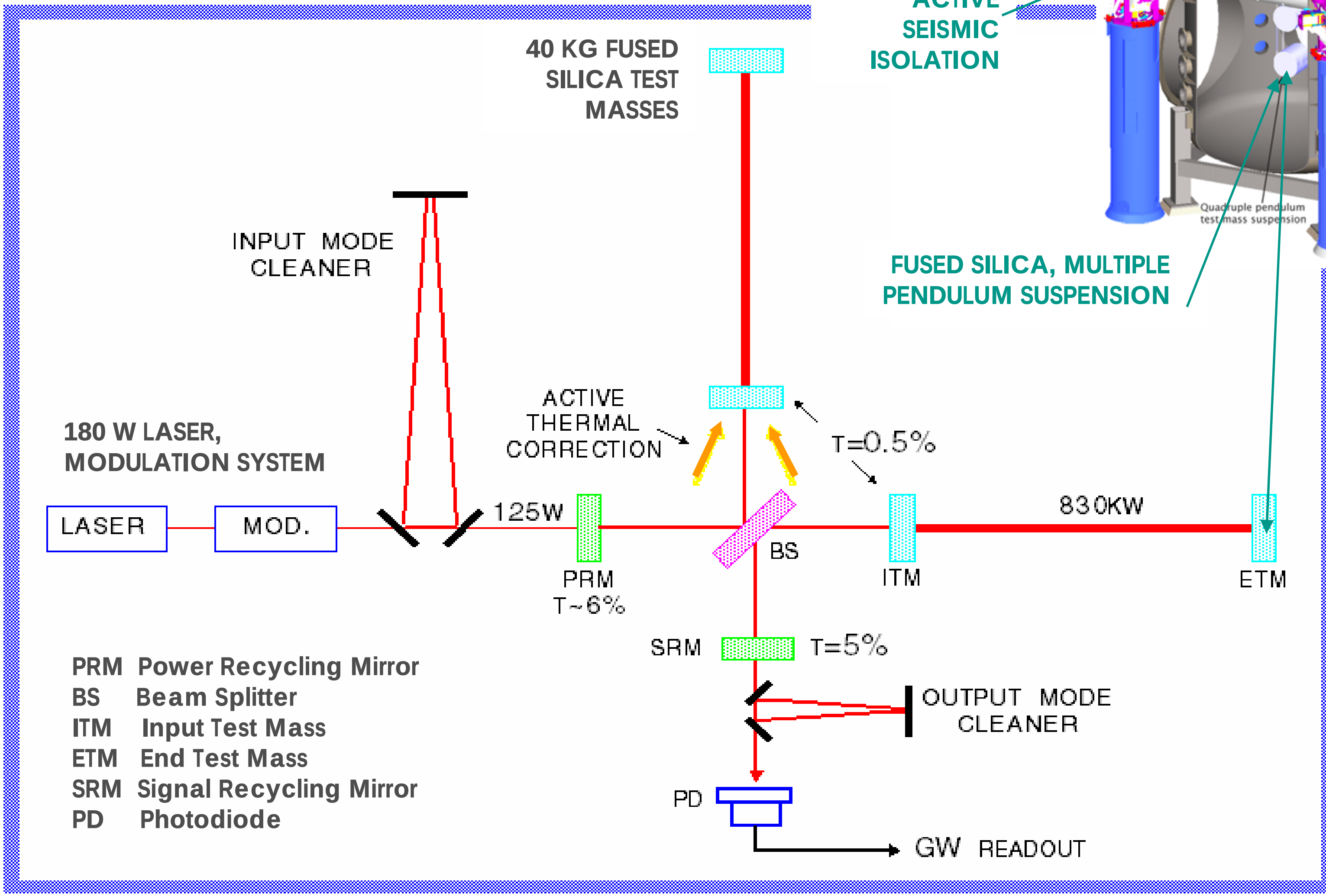
More on sensitivity

- Mid-band performance limited by Coating thermal noise – a clear opportunity for further development, but present coating satisfactory
- Low-frequency performance limited by suspension thermal noise, gravity gradients
- Performance at other frequencies limited by quantum noise (shot, or photon pressure); have chosen maximum practical laser power
- Most curves available on short time scale through a combination of signal recycling mirror tuning (sub-wavelength motions) and changes in laser power
- To change to 'Pulsar' tuning requires a change in signal recycling mirror transmission – several weeks to several days (practice) of reconfiguration (but then seconds to change center frequency)



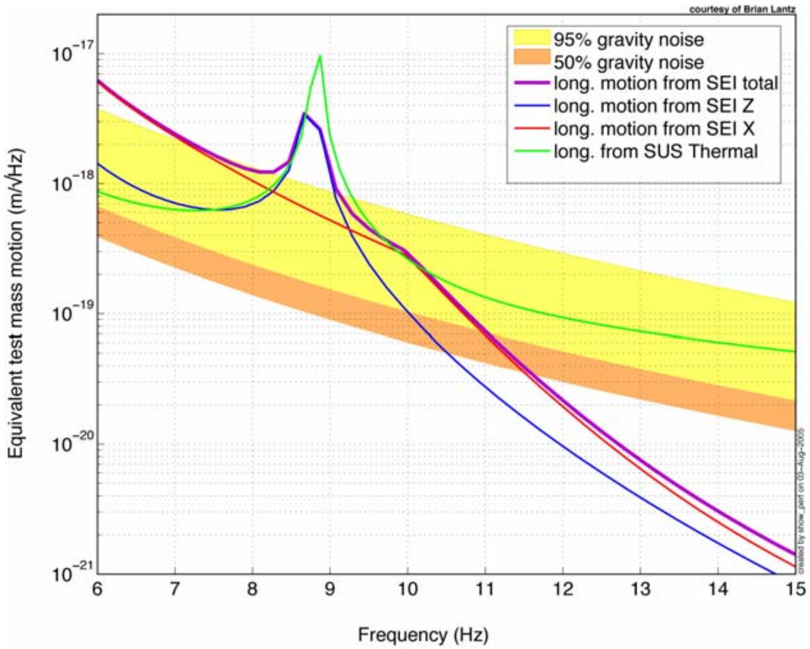
Advanced LIGO Design Features

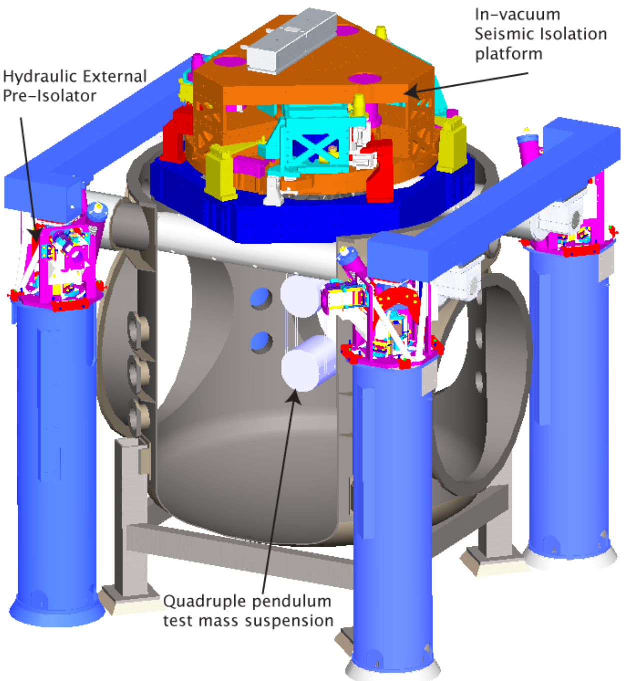




Seismic Isolation: Multi-Stage Solution

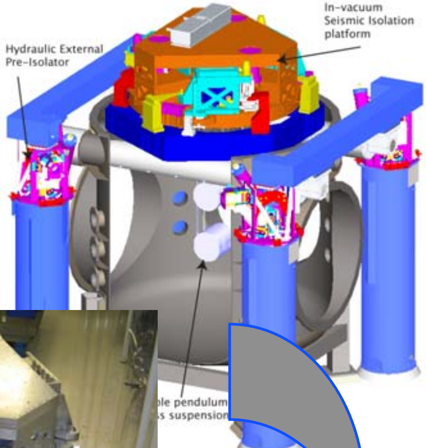
- Render seismic noise a negligible limitation to GW searches
  - » Both suspension and isolation systems contribute to attenuation
  - » Newtonian background will dominate for frequencies less than ~15 Hz
- Reduce actuation forces on test masses



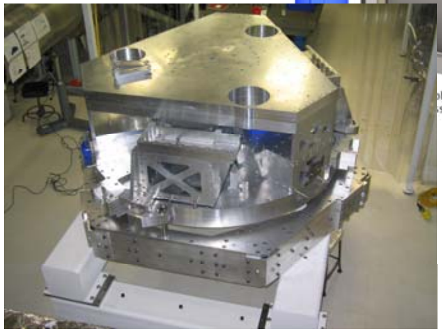


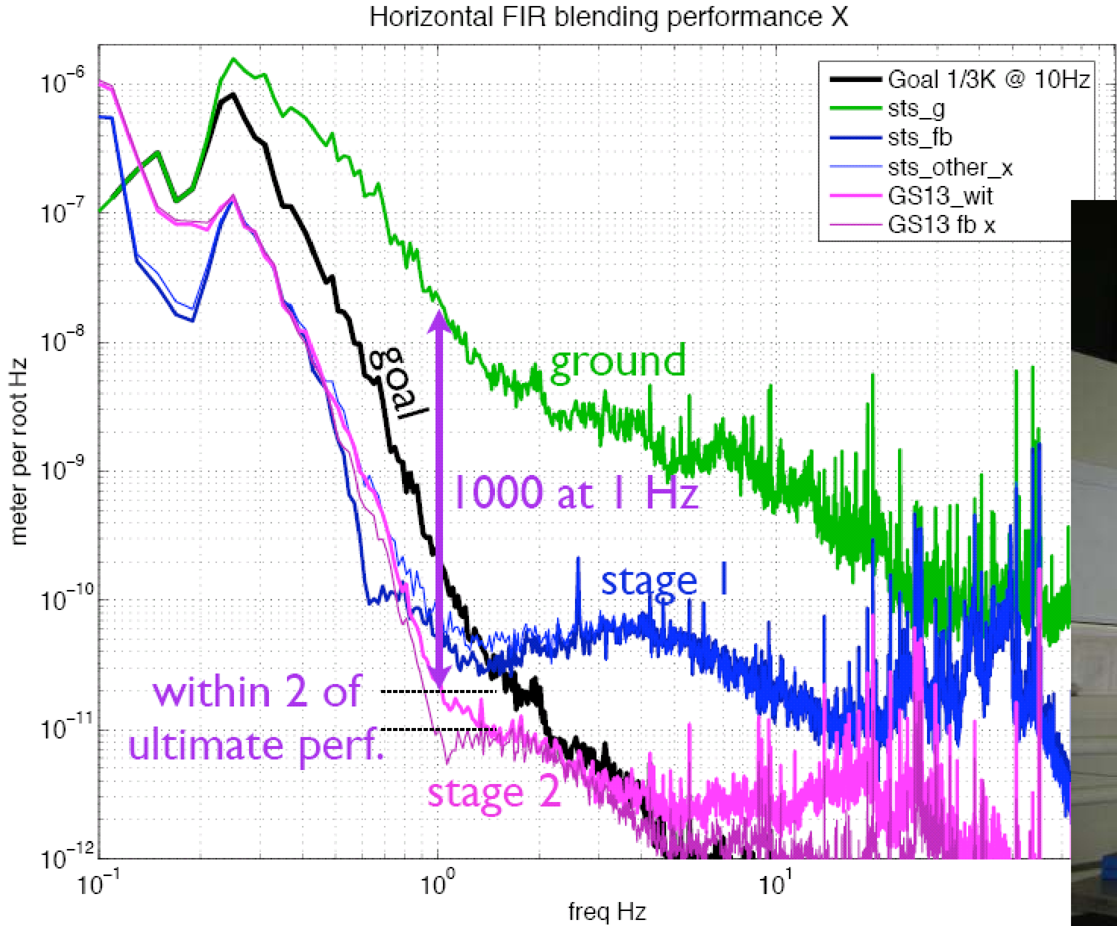
- Active isolation approach:
  - » 3 stages of 6 degree-of-freedom each
  - » *Hydraulic External Pre-Isolation (HEPI), implemented at LLO now
  - » Two Active Stages of Internal Seismic Isolation
- Increase number of passive isolation stages in suspensions
  - » From single suspensions in initial LIGO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

Seismic Isolation for the Test Mass Chamb



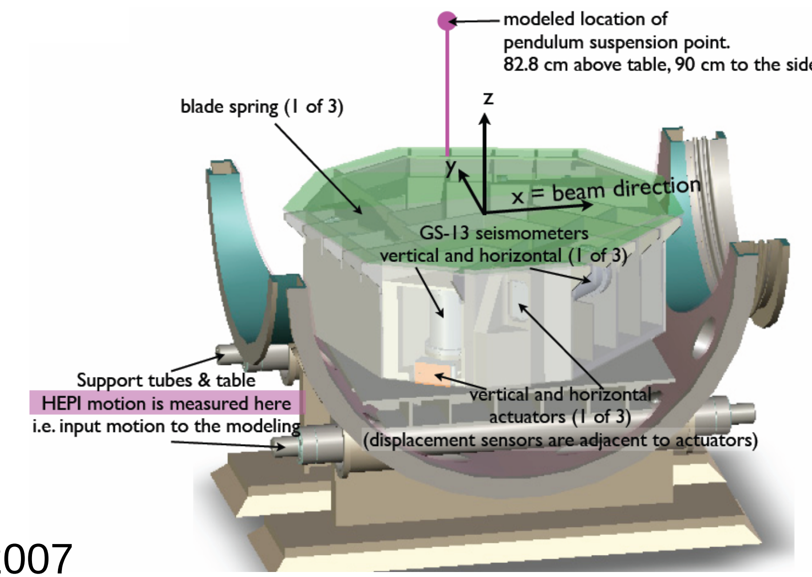
- Proof-of-principle prototype shows good results (Stanford test facility)
- Full Scale Prototype fabricated, assembled, and now in modal testing (MIT test facility)

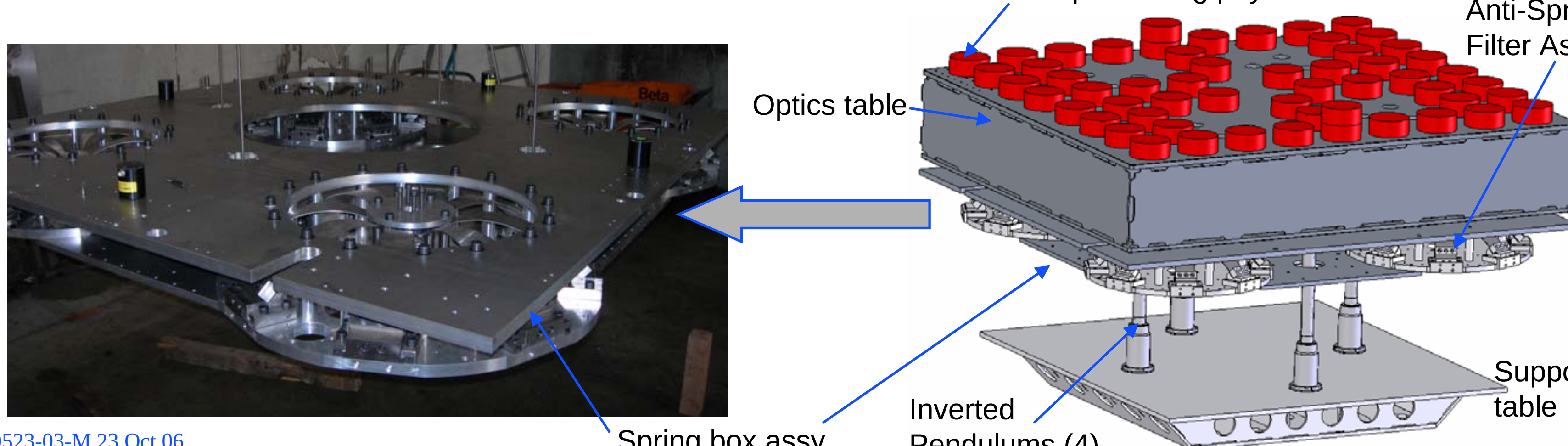




Seismic Isolation for the Multi-purpose Optics Chamber - Progress

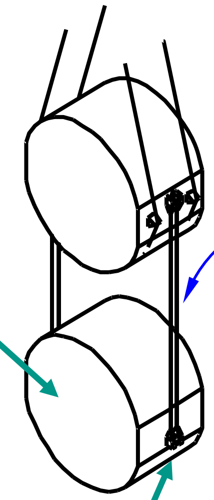
- Relaxed Seismic requirements established
- Baseline 'active' design approach
  - » Optimized (now single stage internal to vacuum system)
  - » Prototype conceptual design completed; bid package for detailed design just sent out
- Alternative 'passive' approach
  - » Prototype fabrication expected to be completed in November
  - » MIT testbed Experimental Results due by 4/2007
- Decision & AdL Prototype fabrication start 4/2007

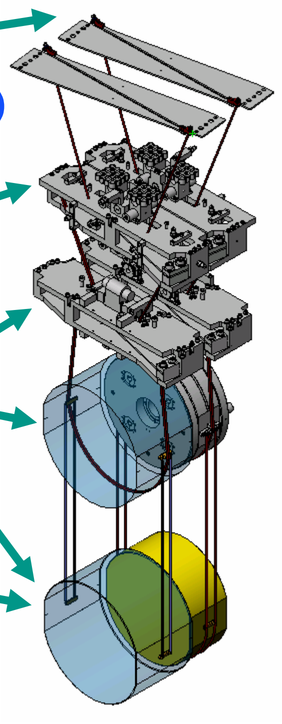


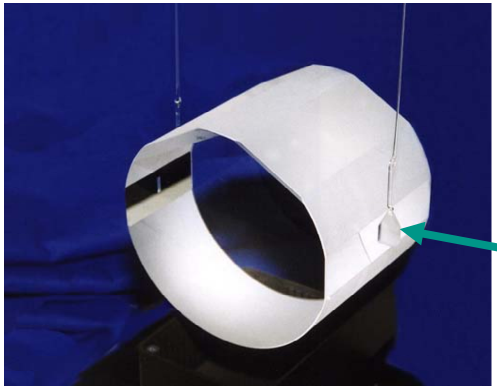


Test Mass Suspension

- Must deliver passive seismic isolation
- Minimize noise from damping controls and global control actuation
- Minimize 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





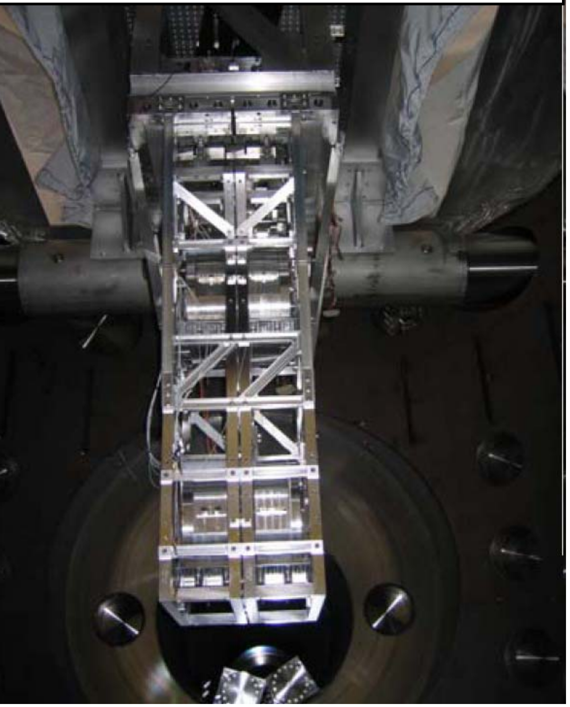


- Create quasi-monolithic pendulums using fused silica ribbons to suspend 40 kg test mass
- Choose quadruple pendulum suspensions for the main optics and triple pendulum suspensions for less critical cavity optics
- Combined UK-US effort; UK contribution to AdL

advancedligo

Suspensions – Progress

Quad Suspension in LASTI BSC Chamber

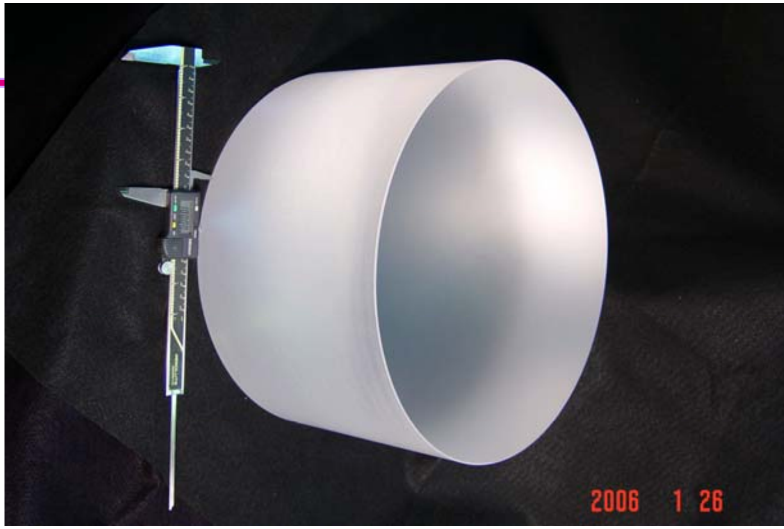


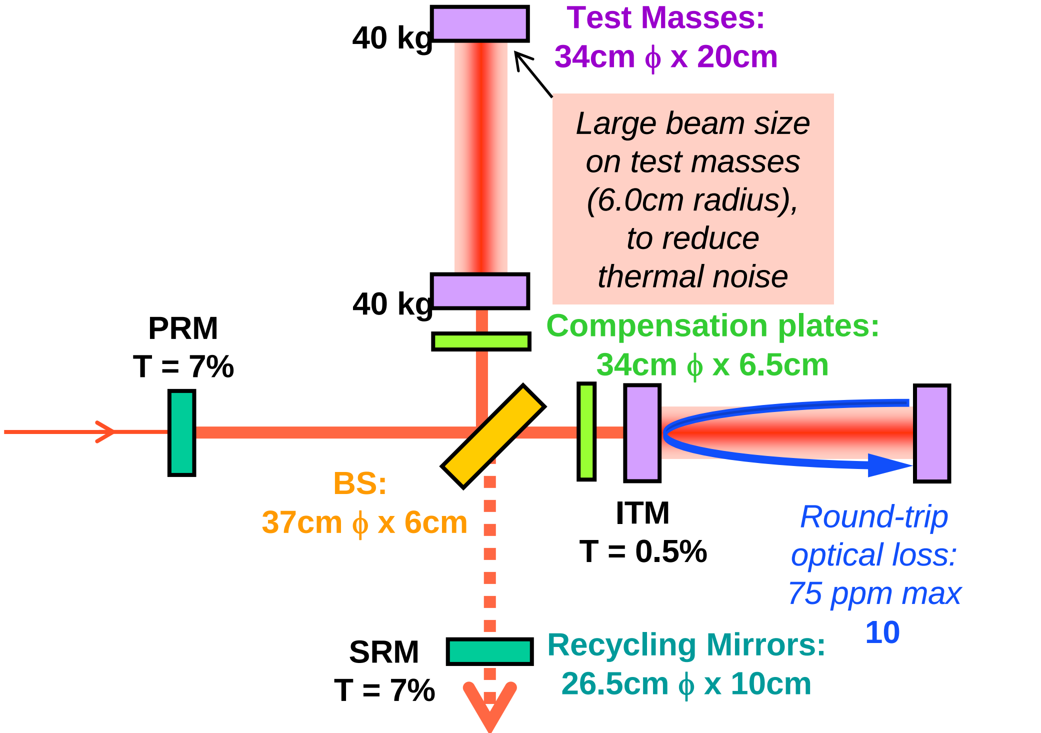
- Test Mass (Quad) Suspension
  - » 'Controls' Prototype installed at MIT Testbed, in test
  - » Design for the "Noise" prototype (silica fibers) progressing well (UK) –procurements placed
- Mode Cleaner (Triple) Suspension
  - » A second 'controls'-testing metal-fiber prototype fabricated, installed in MIT Testbed;
  - » Two placed face-to-face to form optical cavity for controls testing; excellent match to model – PhD thesis

- •Silica Fiber/Ribbon Pulling on computer controlled CO_2 laser system
  - •Fibers up to 570 mm long, 184 $\pm$ 5 microns diameter
  - •(15 microns dia. repeatability)
  - •3 GPa breaking stress (factor of safety $\approx$ 4)
- •Fiber/Ribbon Welding
  - •Fiber & ribbon welding demonstrated
  - •Working to improve welded strength
- •Motion Limiters ('earthquake stops')
  - •Fused silica contact tips, improved adjustment capability

Core Optics Components

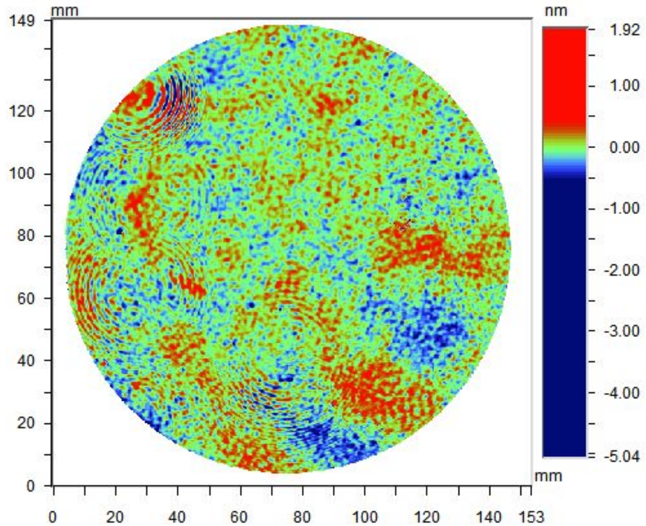
- Test masses serve also as mirrors for interferometry
- The 'core' of the experiment
- For Advanced LIGO, some changes:
  - » Heavier to resist photon 'buffeting'
  - » Larger optical surface and reduced mechanical loss in optical coatings to reduce thermal noise
  - » Reduced mechanical loss in suspension method
  - » Lower optical absorption in substrate and surface
  - » Aggressive thermal focus compensation





Core Optics Components – Progress

‘orange peel’ residual polishing error
In an Initial LIGO Core Optic (0.18 nm rms)



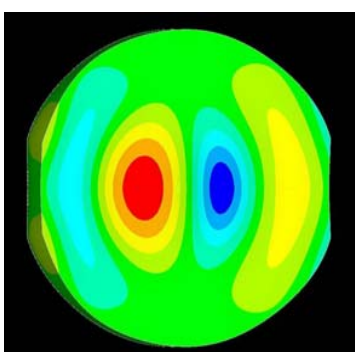
- Optics Figure
  - » Analysis of Radius-of-Curvature sensitivity
    - – FFT Optical Analysis code development nearing completion
    - – Will define ROC tolerance for nearly de-generate (baseline) and stable (alternative) recycling cavities for ‘Pathfinder’ effort
    - – *Continued grad-student effort to explore ‘Flat-Top’ beams for post-AdL interferometers

- Preparing ‘Pathfinder’ procurement specifications/bid-package to qualify polishing sources on larger optics
    - – Low micro-roughness (< 1 angstrom-rms)
    - – Low figure distortion (< 1 nm-rms over central 120mm diameter)
    - – Accurate matching of radii-of-curvature
    - – Surfaces for attachment of suspension fibers
- Have actual AdL substrates for the pathfinder, thanks to UK capital contribution

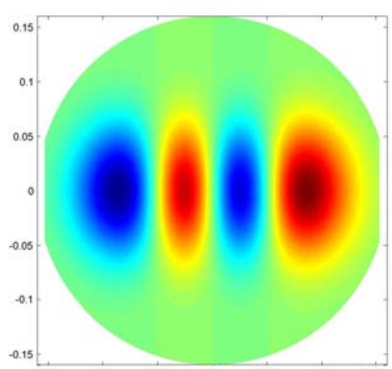
Core Optics Components – Progress

- Parametric Instability a focus of research this year
- Transfer of power from one optical mode to another via a test mass resonance, with potential for runaway excitation of resonances
- Recent studies with explicit spatial numerical simulations indicate only ~6 modes are susceptible – manageable number
- Studying experimentally solutions for damping selected mechanical modes, modeling thermal tuning of optical system to control resonances

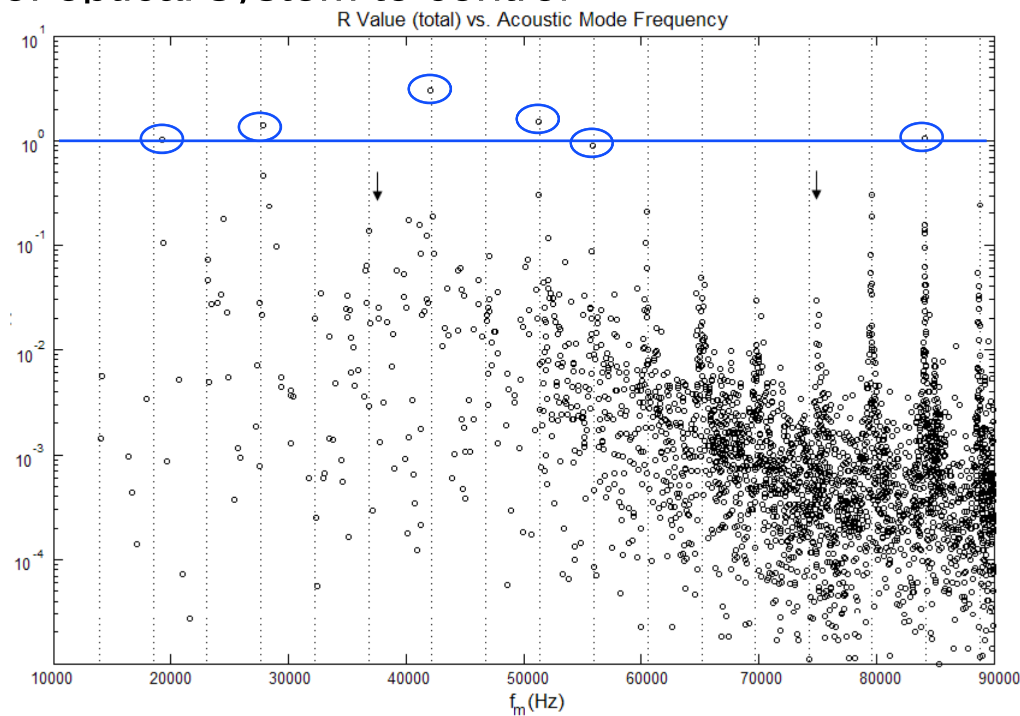
Mechanical mode
47.27 kHz



Optical mode



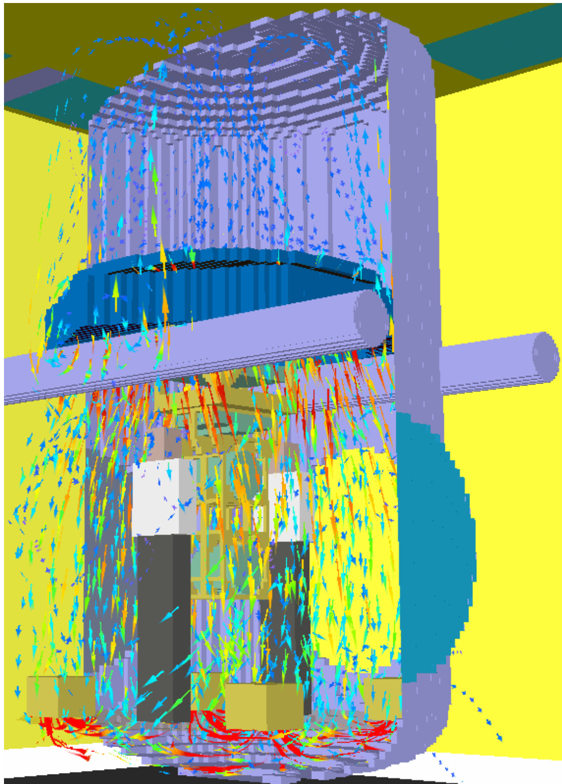
Overlap: 0.8



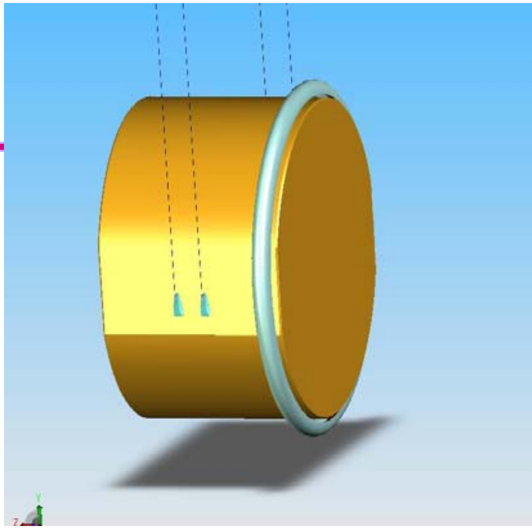
Core Optics Components – Progress

- Dielectric coatings
  - » *Have a coating which would allow us to meet AdL requirements – but improvements would mean better astrophysical reach
  - » Continuing development of coatings
    - – Silica/Silica-doped titania shows reduced mechanical loss, but not likely as good as Silica/titania-doped tantala for optical properties
      - Very high Q's, but anticipated lower Young's modulus
      - Plan to directly measure Young's modulus with a nanoindenter
      - The lower index of titania vs tantala requires thicker coatings
    - – Silica/Silica-doped tantala coatings are being tested currently
    - – Vendor/collaborators working on minimizing loss in Silica/titania-doped tantala
- Scatter requires improvement over Initial LIGO levels
  - » Indications of basic process problems – working with Vendors
  - » Exploring improved particulate cleanliness techniques/requirements
  - » Models of airflow during installation 'as is' and with addition of air showers
- Electrostatic charging
  - » Work at MSU, Trinity, Glasgow with self-built and commercial equipment
  - » Commercial Kelvin probe acquisition in process
  - » Charging under study as possible low-frequency source in initial LIGO

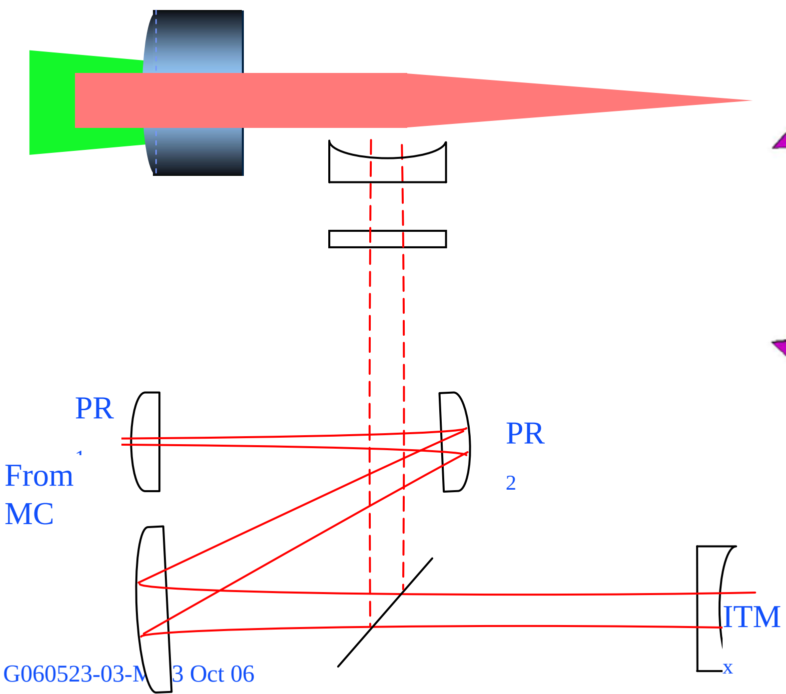
Airflow Studies for Clean Installations

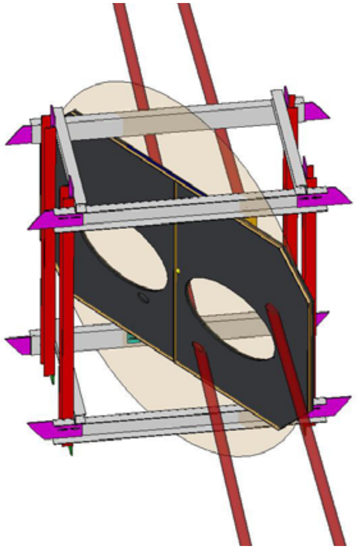


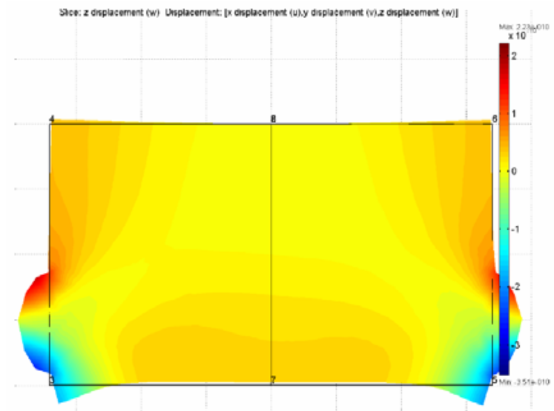
Auxiliary Optics

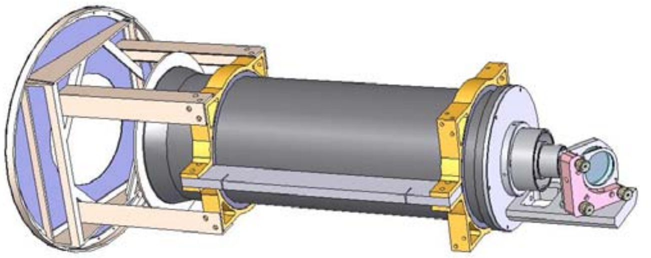


- Thermal focus Compensation design proceeding; some simplifications identified, notion of –dn/dT compensation plate
- Thermal compensation testing on the quad to be incorporated into the LASTI program
- Working through layout issues, baffling, output coupling telescopes, etc.



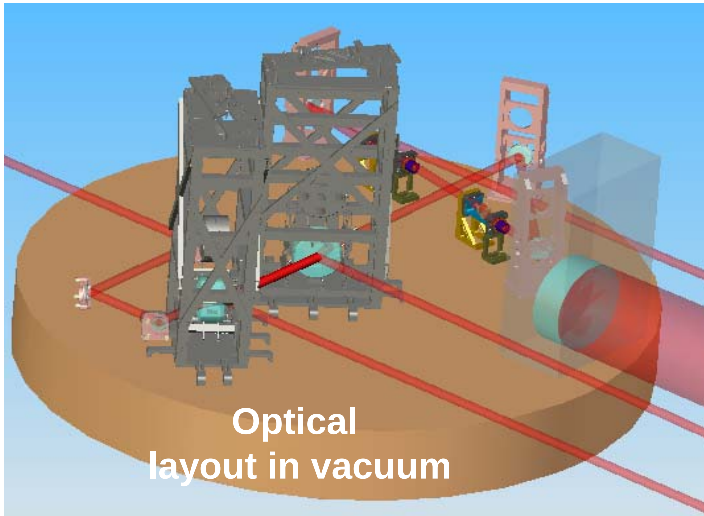






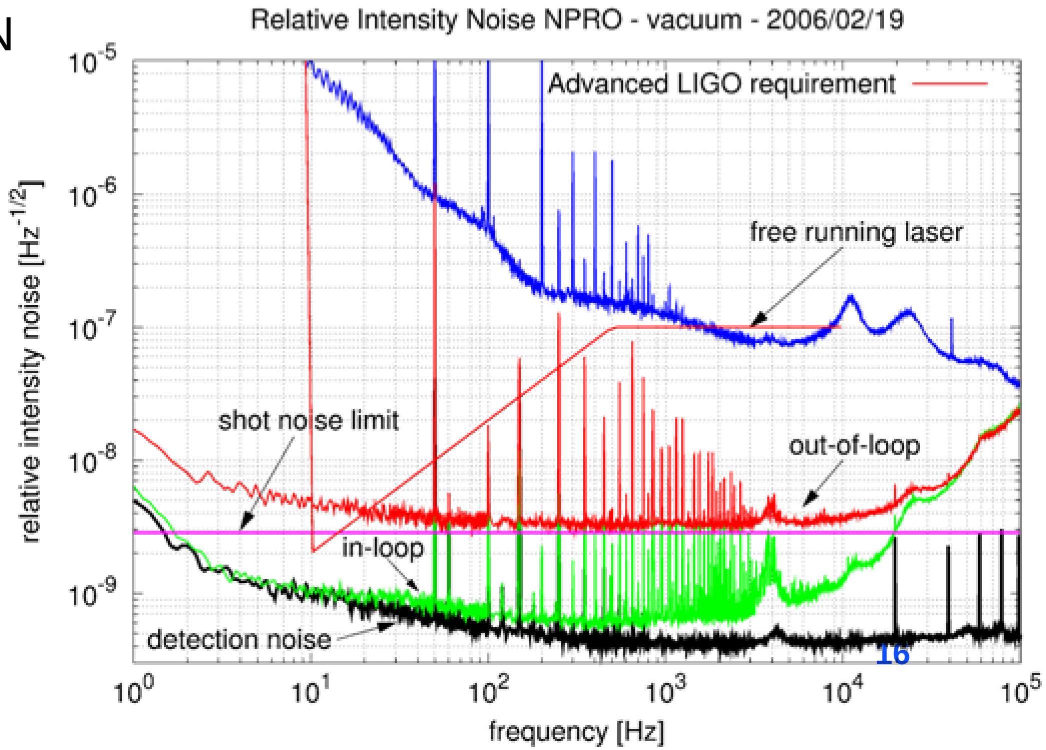
Input Optics

- Handled by our colleagues at University of Florida (as in initial LIGO)
- Conditions and filters the input light
- Applies RF modulation for auxiliary length detection (see Interferometer sensing and control later)
- Matches between the mm-size laser beam and the 10-cm size interferometer beam
- Formal progress on design – layout, design reviews
  - » Participation in discussions of changes in system layout
  - » Reduction of finesse of Mode Cleaner cavity given experience to date
- Very significant advances in Faraday Isolators and Modulators (Enhancements) – Advanced LIGO components in fabrication and soon to be exercised in situ!



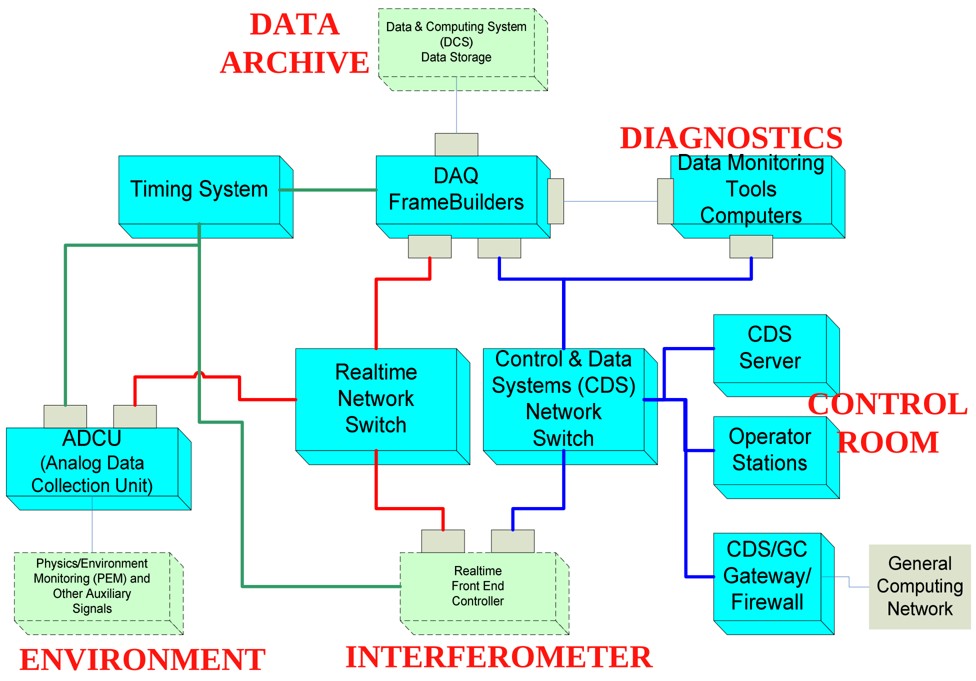
Pre-Stabilized Laser

- Topology very similar to initial LIGO, but with significant increase (20x) in power; PSL contributed by Hannover Max Planck group
- Some requirements relaxed – frequency noise, for example – and some stiffer – intensity fluctuations (2e-9 Relative Intensity Noise @10 Hz)
- Progress this year on new front-end laser (Enhancements)
  - » Wonderful opportunity to exercise this design in situ
- Progress in achieving required RIN
  - » 3e-9 at 20 Hz
  - » Meets requirements almost everywhere;
  - » Requirement is set at 1/10 of other noise sources



Control & Data System

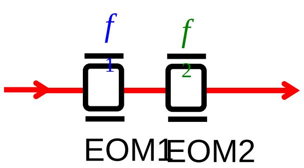
- Prototype PCI-X System
  - » Completed Installation at LASTI for Suspension Testing
  - » Balance of infrastructure & seismic support installation is in-process

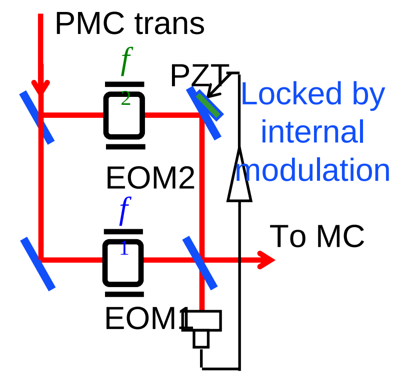


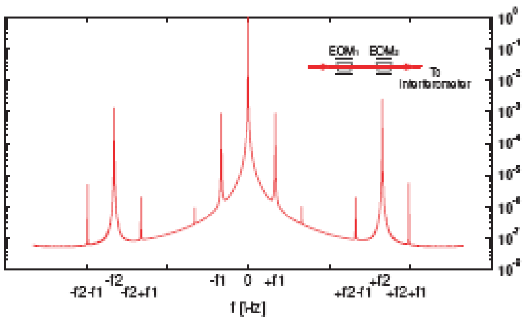
- New Realtime Network Topology
  - » Star fabric vs Serial loop
  - » Deterministic GigE/PCIe from ADC/DAC I/O chassis to computers
- PCIe and custom ADC/DAC I/O
- Multi-CPU computers
  - » Arbitrary Waveform Generator (AWG) and Test Point Manager (TPM) built in
  - » EPICS interface via CPU memory instead of networked
- Supports higher infrastructure data rates (to 128 kHz)
- Realtime Linux Testing
  - » Previous systems use vxWorks
  - » Move away from Solaris for Framebuilders and operator stations
- New Timing System tests
- Generation of realtime code from Matlab model files
  - » LASTI quad & HEPI systems have code automatically generated from Matlab model files

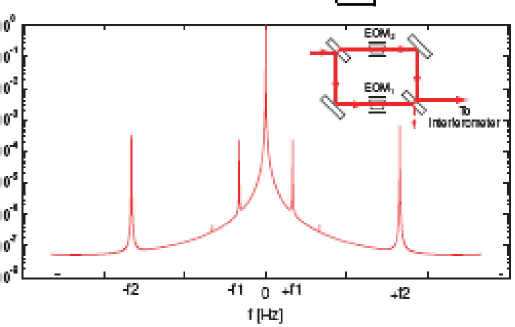
Interferometer sensing and Control

- Significant differences from initial LIGO –
  - » Signal recycling cavity: additional degrees of freedom
  - » DC readout: shift from dark fringe to see baseband intensity changes (Enhancements)
  - » Output Mode Cleaner (Enhancements)
  - » Higher power: photon pressure a big factor in longitudinal and angular control systems
- 40m demonstration of control systems, exploration of dynamics
  - » Already successfully demonstrated locking, agreement with modeling, of signal recycled interferometer
  - » *Modulation system to avoid sidebands-on-sidebands successfully implemented
  - » This year building up DC readout, just completed last week
- Modeling, exploration of stable recycling cavities,
- *Seismic platform interferometers in planning to aid in locking









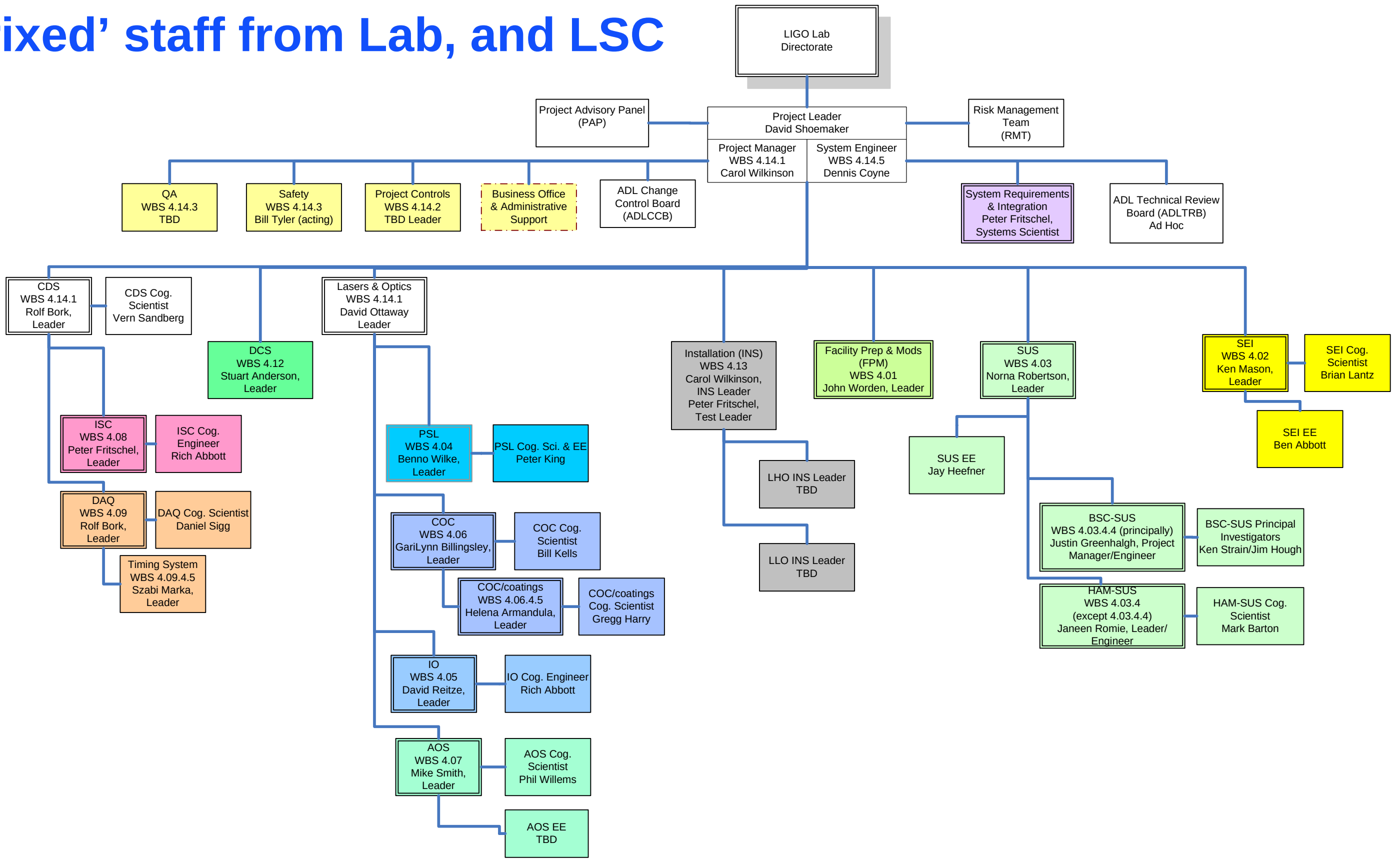
Advanced LIGO in context

Black: Operations (R&RA); Blue Project (MREFC)

- Advanced LIGO R&D well advanced, heading toward Final Design phases for each subsystem
- Initial LIGO S5 run to reach goal of one year of integrated data in Fall 2007
- Advanced LIGO funding at start of FY2008; fabrication, assembly, and stand-alone testing of detector components
- Advanced LIGO R&D ramps down end FY2008
- Initial LIGO Enhancements to be installed, commissioned progressively at Livingston, Hanford
- Science runs with Enhancements starting in early 2009, running to early 2011
- Advanced LIGO starts decommissioning initial LIGO instruments in early 2011, installing new detector components from stockpile
- First Advanced LIGO interferometer accepted in early 2013, second and third in mid-2014. Project completes!
- Commissioning of instruments, engineering runs starting in 2014

Advanced LIGO Organization

- Reports to Lab Director
- Has its own advisory, change control, risk control mechanisms
- 'Matrixed' staff from Lab, and LSC



Advanced LIGO Project Organization

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Advanced LIGO

- Development program delivering completed subsystem designs
  - Nice progress on many fronts in the Lab and across the LSC
  - Some puzzles remain, but nothing that feels scary
- Based on a great deal of initial LIGO experience
  - Technical: no longer the first time to design, fabricate, and bring to operation a 4km-baseline gravitational-wave detector
  - Organizational: Now in context of Laboratory/LSC; plans take advantage of these resources
- Cost, Schedule, Risk tools in place and well exercised
  - Stability in Project cost per scope reassuring
- The design is flexible, development nearing completion, significant prototyping underway, the teams are working well –

The astrophysics will be great.