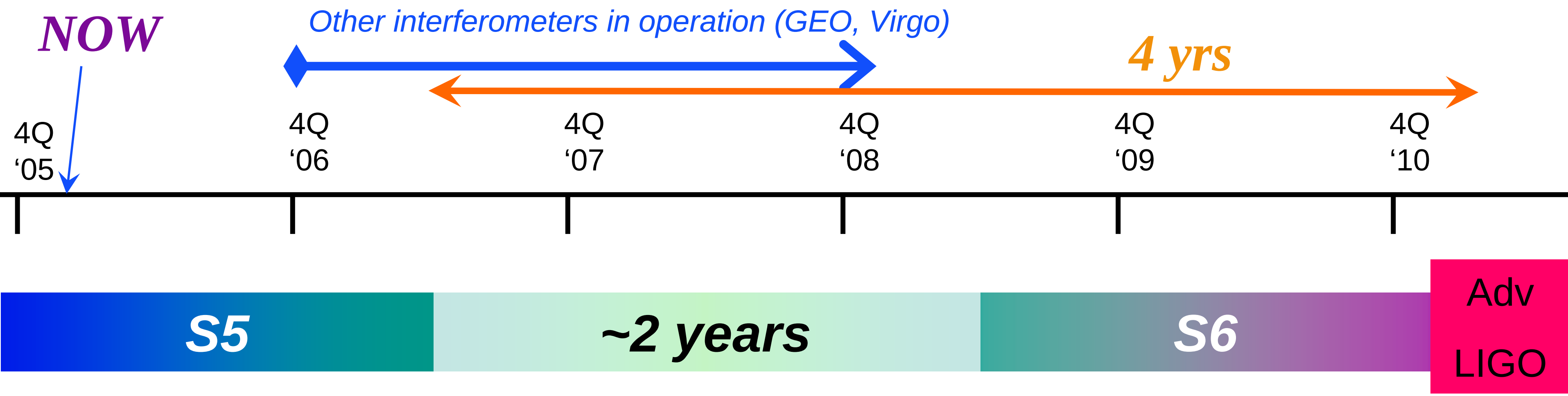
Advanced LIGO
Technical progress and update

GWADW 2006 - VESF meeting
May 27- June 2, 2005

Osamu Miyakawa
Caltech

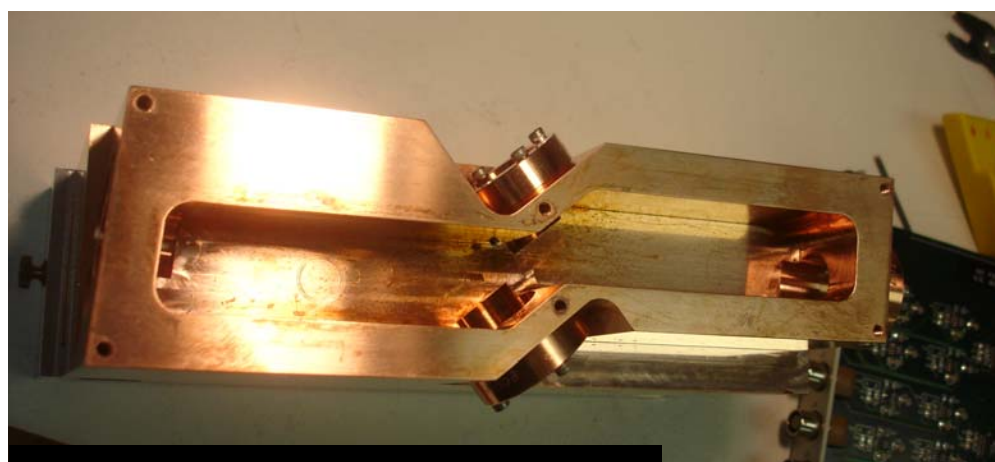
The next several years



- **Between now and AdvLIGO, there is some time to learn and improve and detect gravity waves…**
  - **~Few years of hardware improvements + ~1 ½ year of observations.**
  - **Factor of ~2-2.5 in noise, factor of ~5-10 in event rate.**
  - **Better to spend debuggin time before AdvLIGO**
  - ***AdvLIGO is a HUGE step in terms of interferometry!***

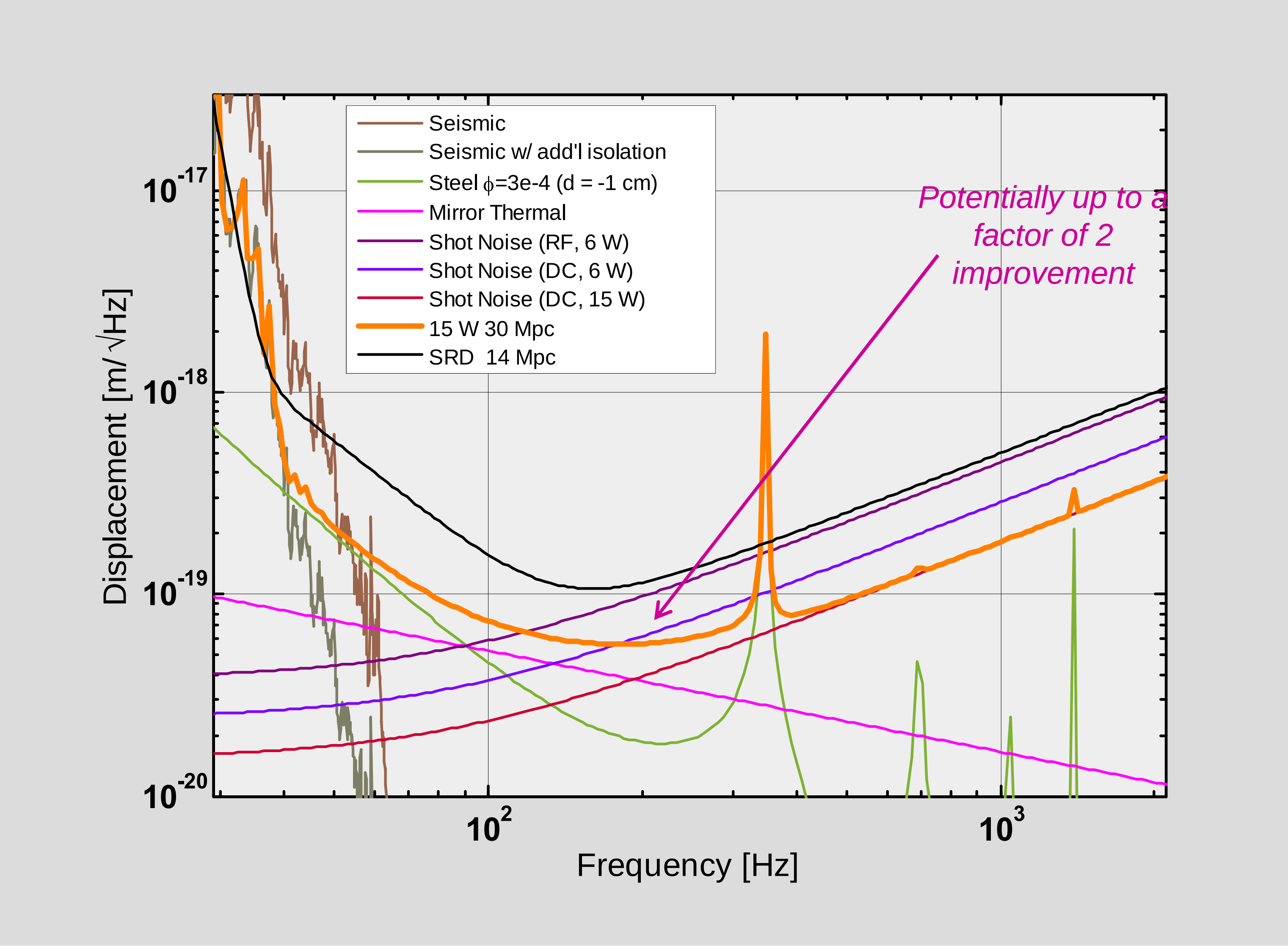
Baseline materials of initial LIGO upgrade

1. Higher power laser ~30W
   » Laser-Zentrum Hanover (LZH) AdLIGO technology
2. High Power Input Optics (Modulators/Isolators)
   » University Florida AdLIGO technology
3. Output mode cleaner
   » In-vacuum implementation
   » DC Gravity Wave detection as in AdvLIGO (RF fallback)
   » Removes the junk light
   » ~100 mW of light for DC readout
4. Suspension thermal noise improvement
5. Miscellaneous …



OMC at Caltech 40m

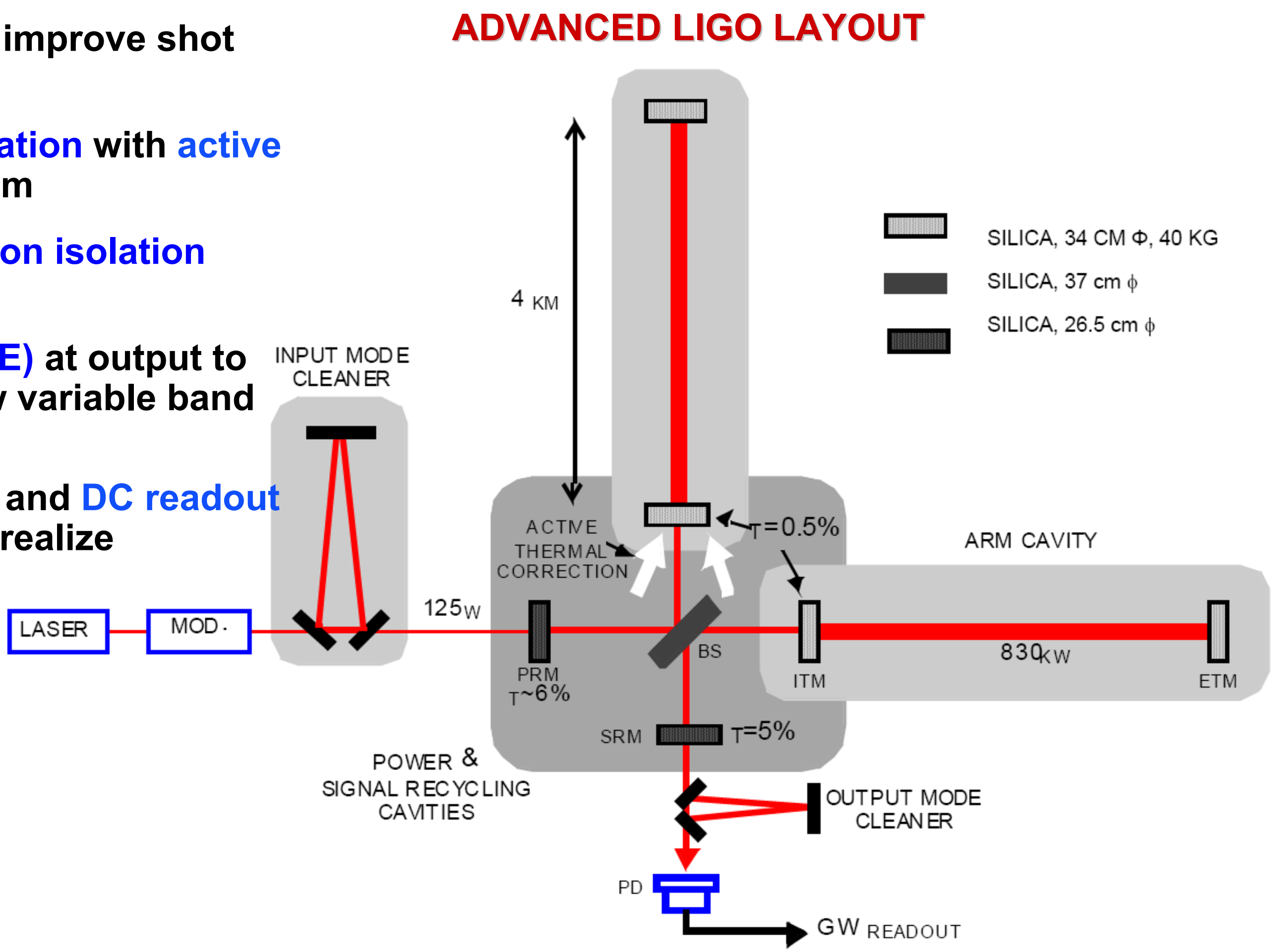
Fundamental noise sources for an improved detector



Advanced LIGO Detector Improvements

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

- **Increase laser power ~20x to improve shot noise limits**
- **Replace passive seismic isolation with active controlled multi-staged system**
- **Increase number of suspension isolation steps**
- **Add GW signal recycling (RSE) at output to increase sensitivity and allow variable band frequency tuning.**
- **Employ output mode cleaner and DC readout to be free from RF noise and realize homodyne detection**



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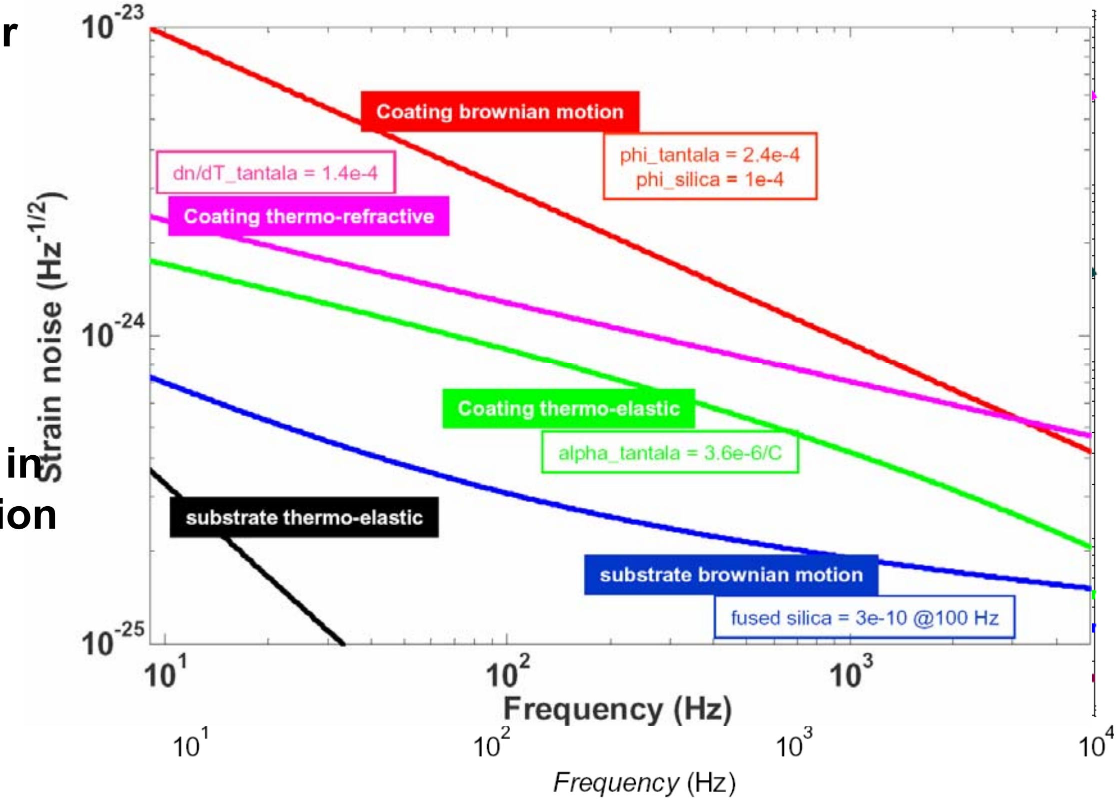
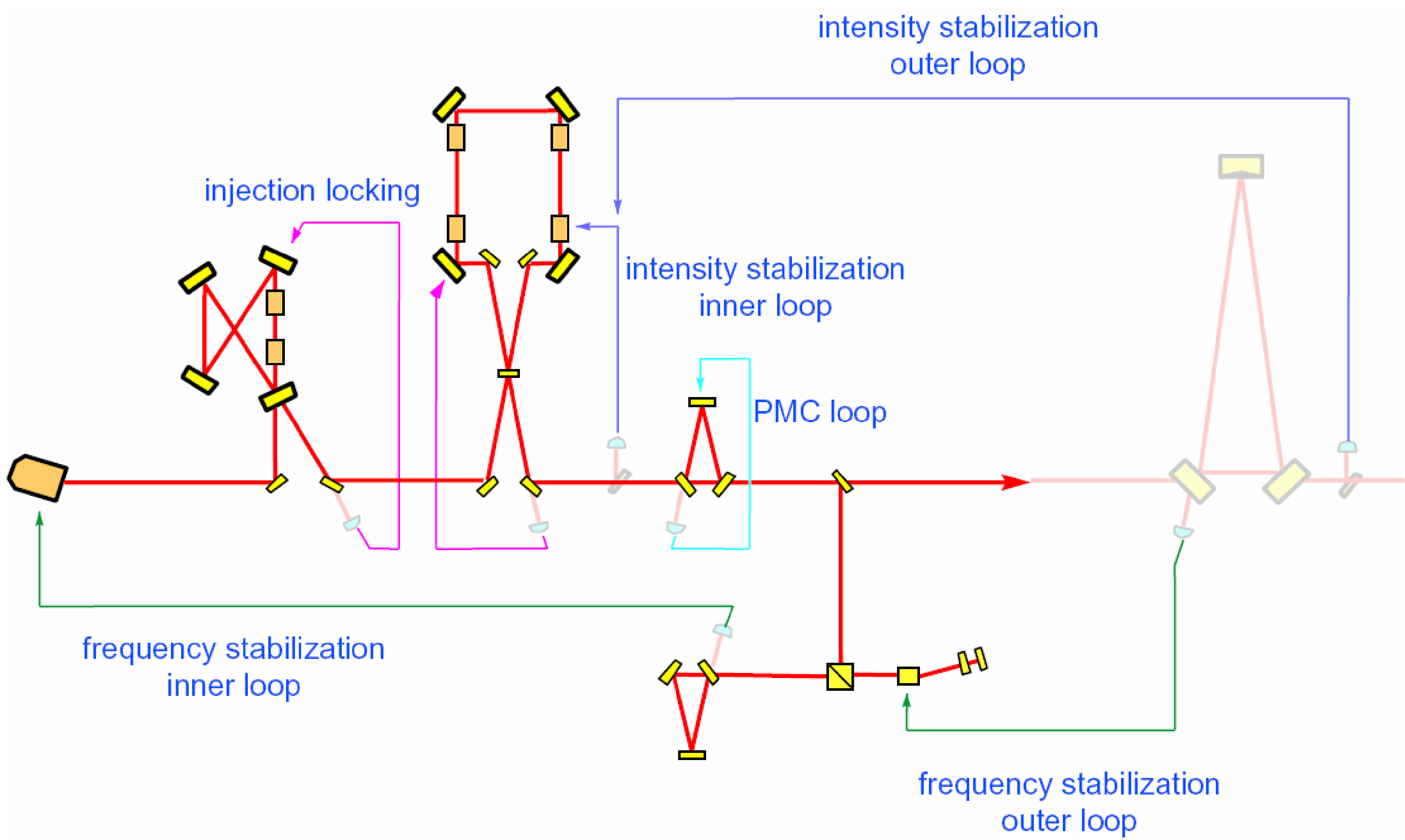
Adv LIGO Detector Performance

- Factor of 10 better amplitude sensitivity, factor of 4 lower frequency bound, factor of ~1000 greater volume and thus event rate
- Low-frequency limited by suspension thermal noise, gravity gradients
- Mid-band performance limited by coating thermal noise
- Performance at other frequencies limited by quantum noise (shot, or photon pressure)
- Most curves available through a combination of signal recycling mirror tuning (sub-wavelength motions) and changes in laser power determined by the astrophysics
- 'Pulsar' tuning requires a change in signal recycling mirror transmission – several weeks to several days (practice) of reconfiguration



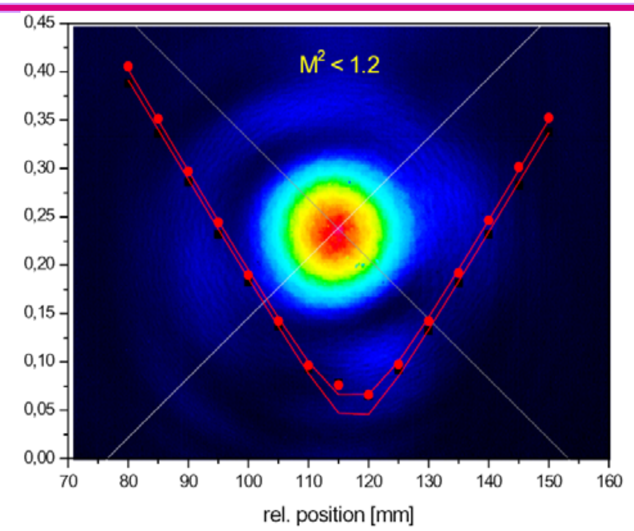
Pre-Stabilized Laser

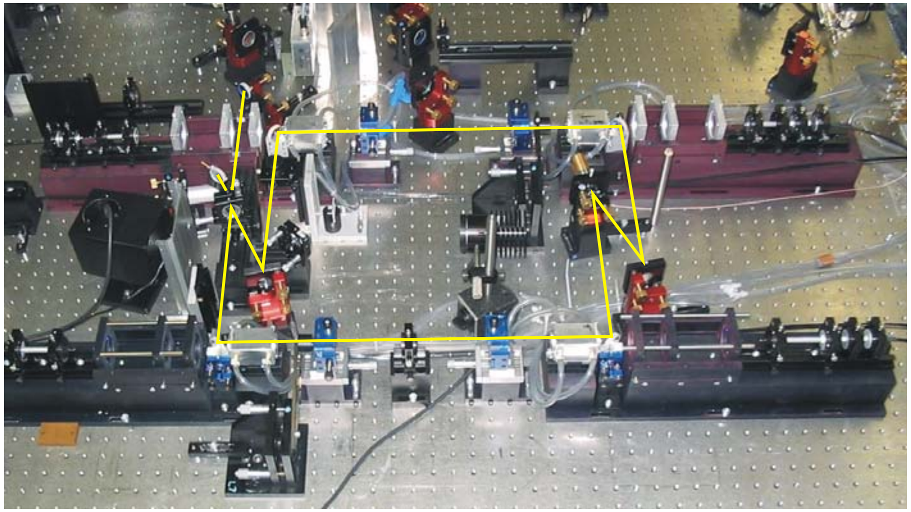


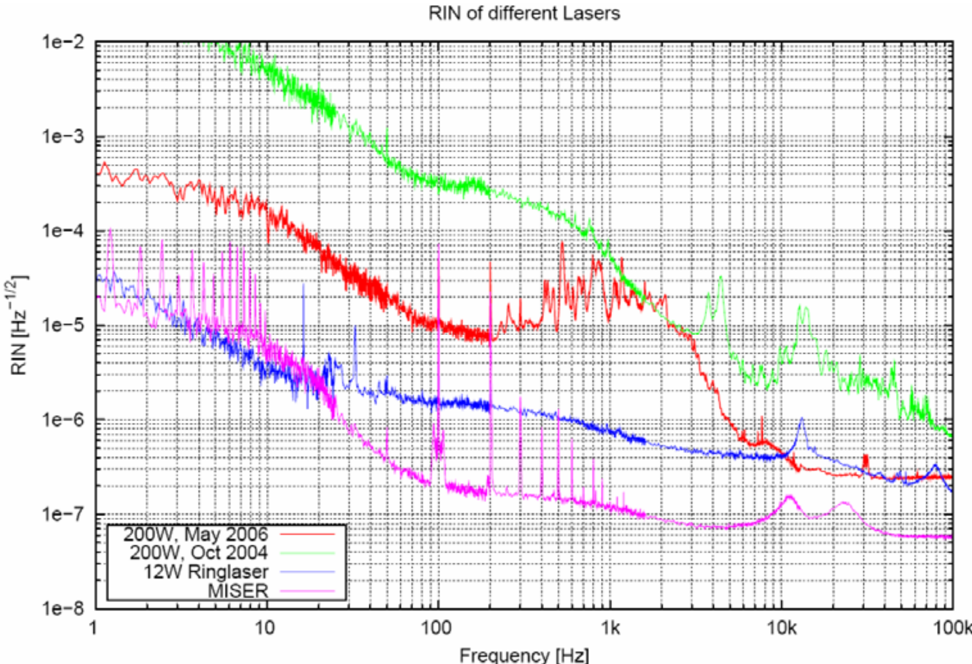
Pre-Stabilized Laser

Max-Planck Institute Hannover, Laser Zentrum Hannover and CIT

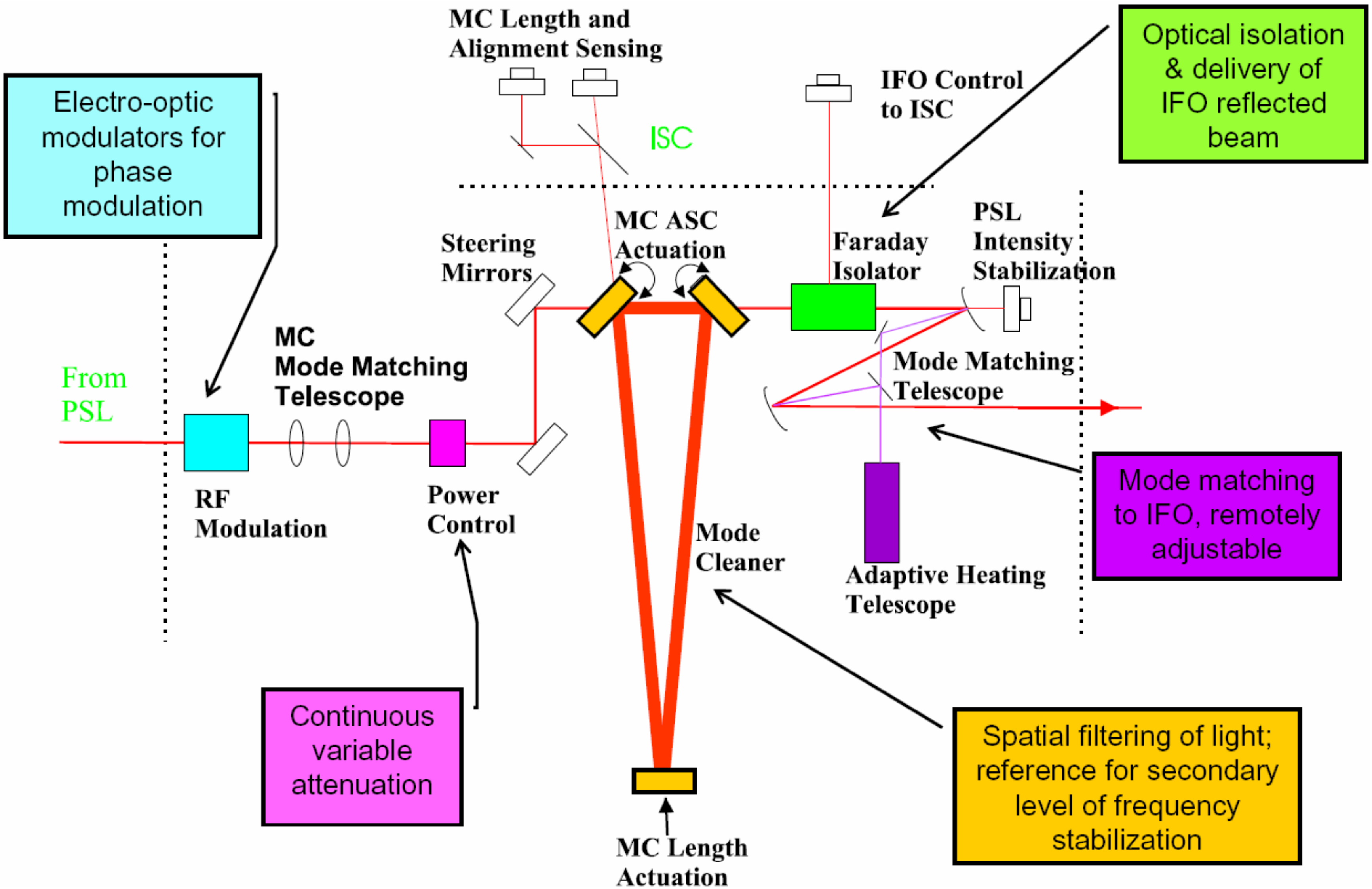
- 180W output power
- Transfer engineering model to MIT test interferometer (LASTI)
- Plans forming to supply this 30W source in an AdL 'early delivery' for initial LIGO update
- Frequency noise requirement achieved (LIGO)
- RIN = 3*10-9 / sqrt(Hz) above 20Hz (in table top experiment)







Input Optics



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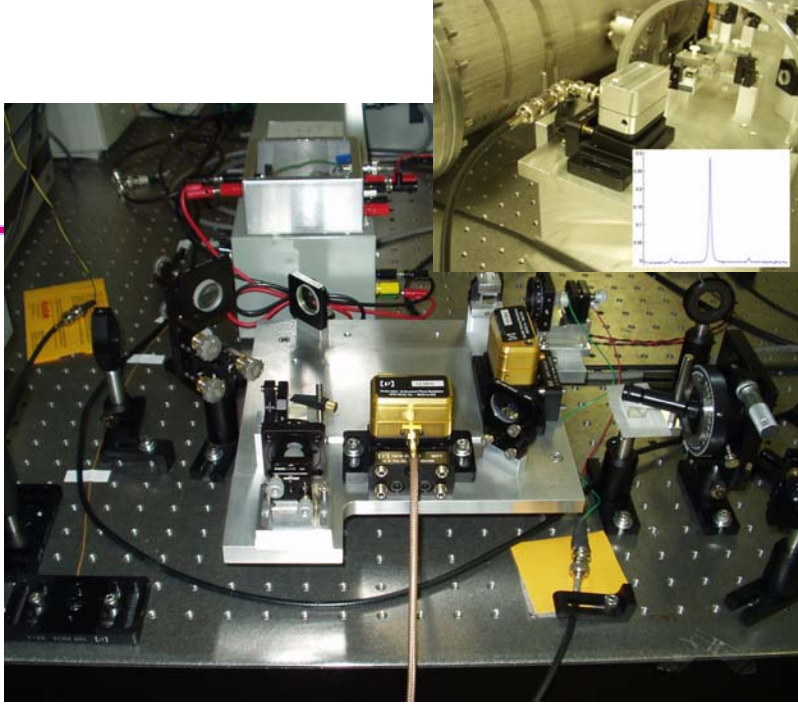
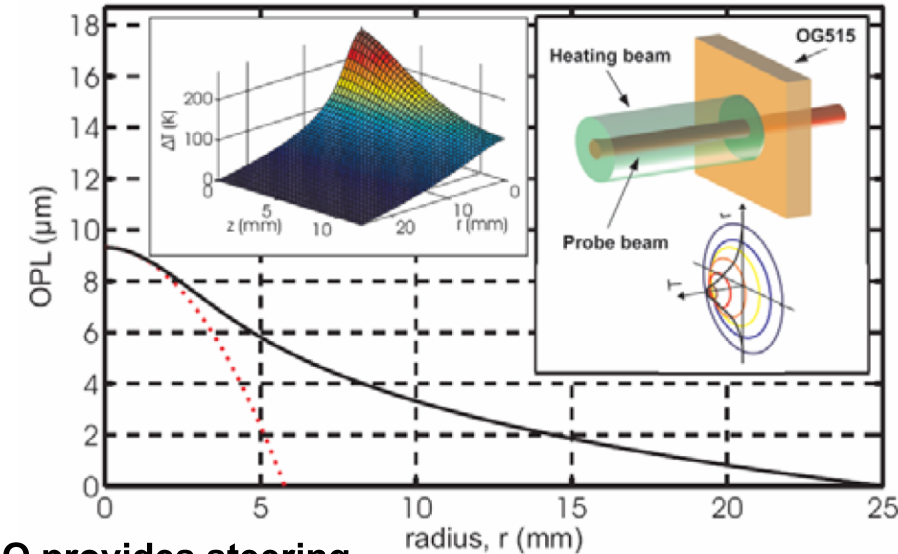
Input Optics

Subsystem at University Florida

- **Modulation**
  - » Rubidium titanyl phosphate (RTP) EOMs extensively tested for high power operation (initial LIGO upgrade)
  - » MZ prototype
    - – Requirement of phase and frequency noise ΔL ~ 6x10-13 m/rHz in 20–80 Hz band not too difficult to meet
  - » Also looking at complex (AM/PM) modulation
- **Adjustable power control into the IFO using waveplate on stepper stage**
  - » ΔP ~ 75mW for P = 90W on input power
  - » ΔP ~ 350W for P = 400kW on arm cavity power
- **Mode Cleaner**
  - » Thermal modeling with Melody
    - – Current intracavity intensity: ~ 45 kW/cm^2
    - – AdvLIGO intracavity intensity: ~ 200 kW/cm^2
- **Faraday Isolator (initial LIGO upgrade)**
  - » In excess of 40dB at 100W loading with novel compensated design
- **Mode Matching telescope**
  - » Suspended three mirror design same as initial LIGO provides steering
  - » Laser adaptive telescope based on controlled thermal lens using auxiliary laser of two mirrors





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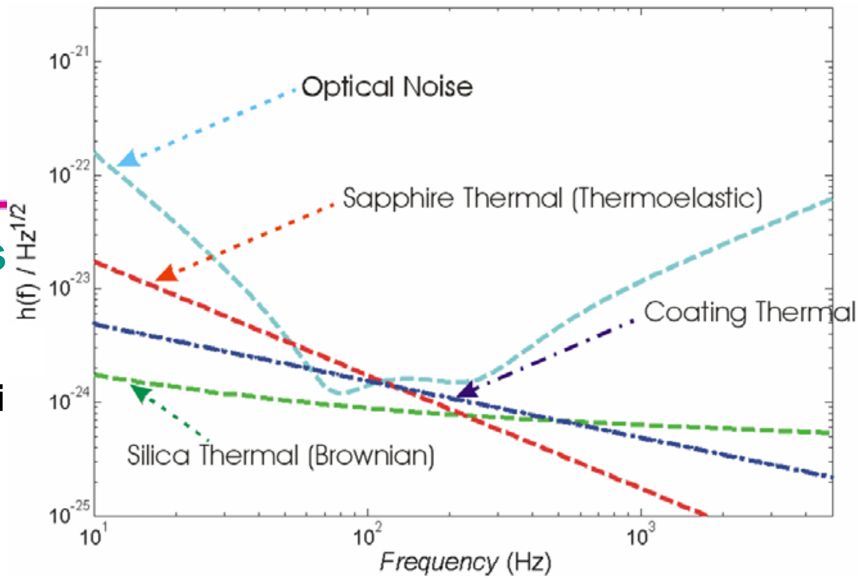
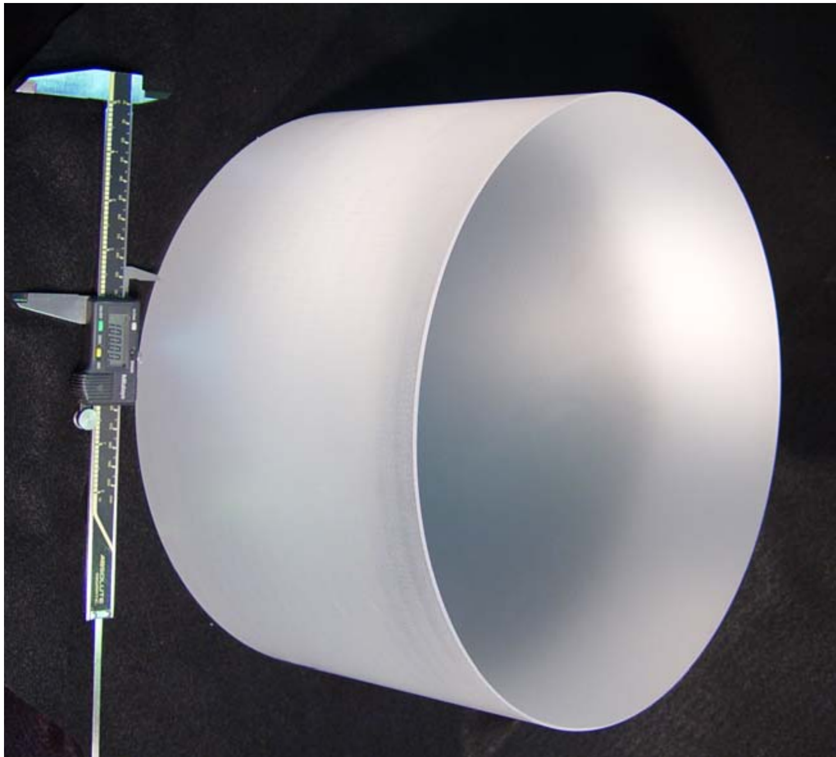
Core Optics

Combined CIT, MIT, Stanford, Glasgow efforts

- **Substrate selection = Fused Silica!**
  - » Either material could work, but more risks for sapphi
  - » FS better at low frequencies (high mass BH-BH)
  - » Sapphire better at high frequencies (LMXB)
- **First actual substrates received – Hereaus 311, contributed by UK**
  - » 40 kg, 34cm x 20cm, fused silica
- **Polishing**
  - » Low micro-roughness (< 1 angstrom-rms)
  - » Low residual figure distortion (< 1 nm-rmsover central 120mm diameter)
  - » Accurate matching of radii-of-curvature
  - » Surfaces for attachment of suspension fibers
- **Dielectric coatings**
  - » Low absorption (0.5 ppmor smaller)
  - » Low scatter
  - » Low mechanical loss (< 2e-4)
  - » Silica/titania-doped tantala coating for input and end test masses, Silica/tantala coating for other optics





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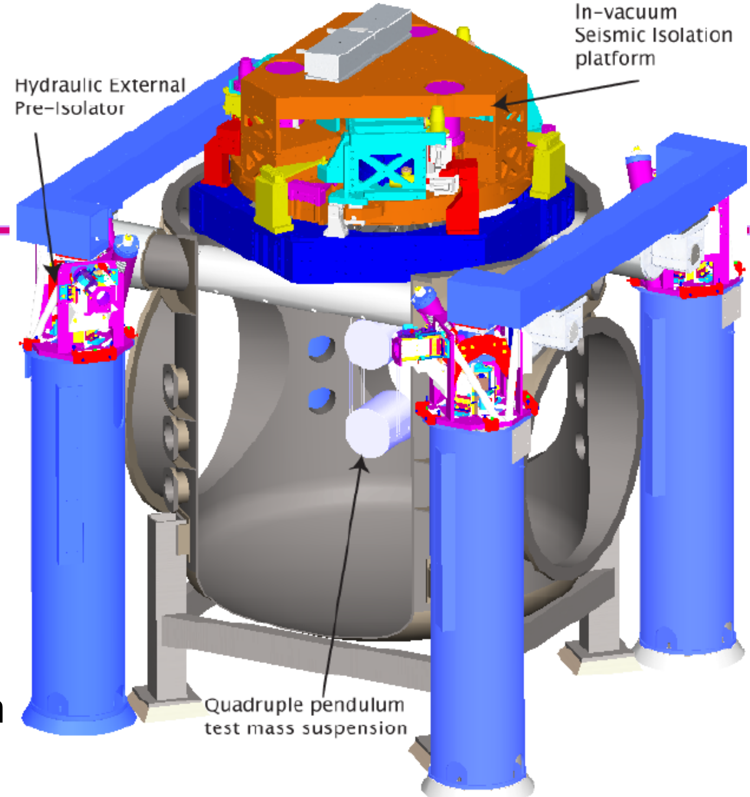
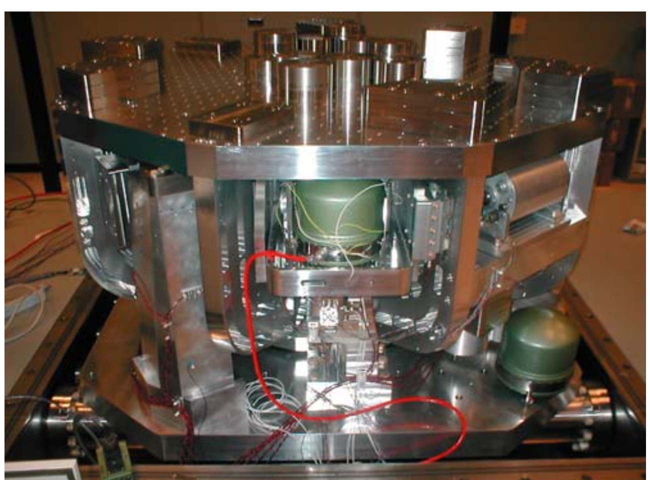
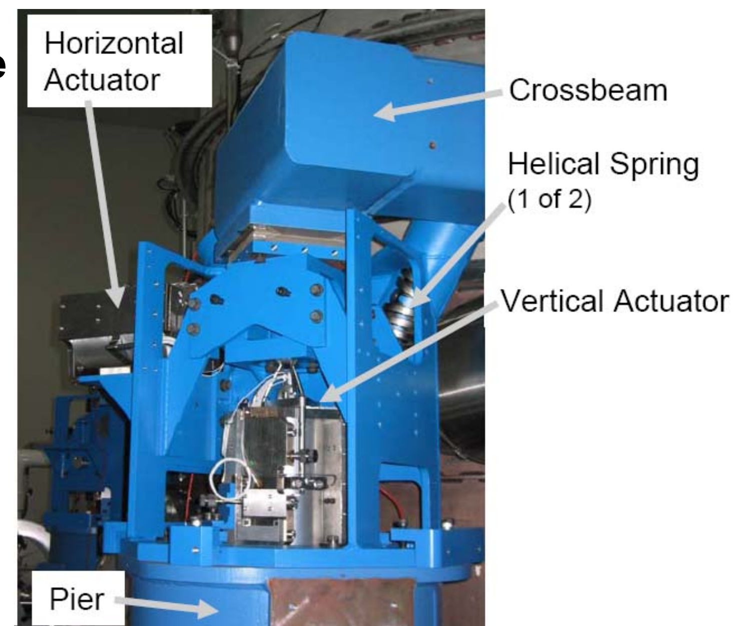
Seismic Isolation

- HEPI already deployed in LLO (before S4 run), and has met isolation performance expectations
- BSC Chamber design
  - » Full Scale Prototype is being assembled at LASTI
  - » Installation & Test this year with Quadruple Pendulum Suspension Prototype
- HAM Chamber design
  - » Single Stage Internal Seismic Isolation (ISI) System under study along with relaxed requirements
  - » Prototype HAM SAS (low-natural-frequency isolator) to be fabricated, tested in Sept as possible variant





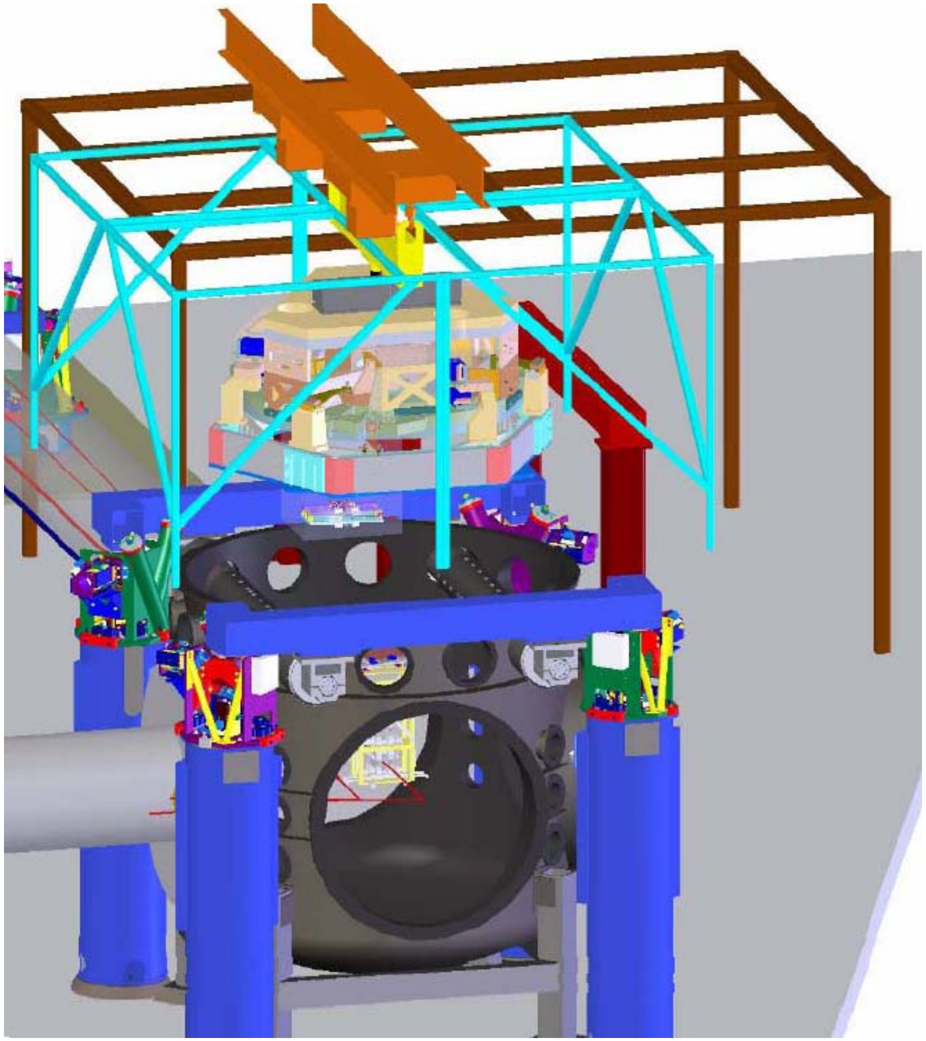


Suspensions

Suspension design based on GEO600 triple

- "Controls" prototype (all- metal) constructed at Caltech and delivered in Feb 2006 to LASTI
  - » Mass catcher or 'cage' from UK (PPARC funded)
  - » Spring design, mass design from Caltech
  - » Some initial tests, then to be installed in BSC chamber
- Interferometry using AdL suspensions
  - » Two mode-cleaner triple suspensions set up as short cavity
  - » For controls testing
- "Noise" prototype (full monolithic silica assembly)- development underway in UK,
  - » delivery to LASTI early 2007

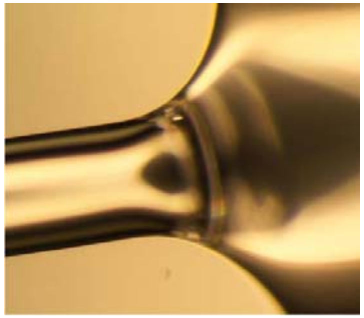
BSC “Cartridge”Insertion into BSC Chamber @LASTI



Suspensions: Silica Fibers

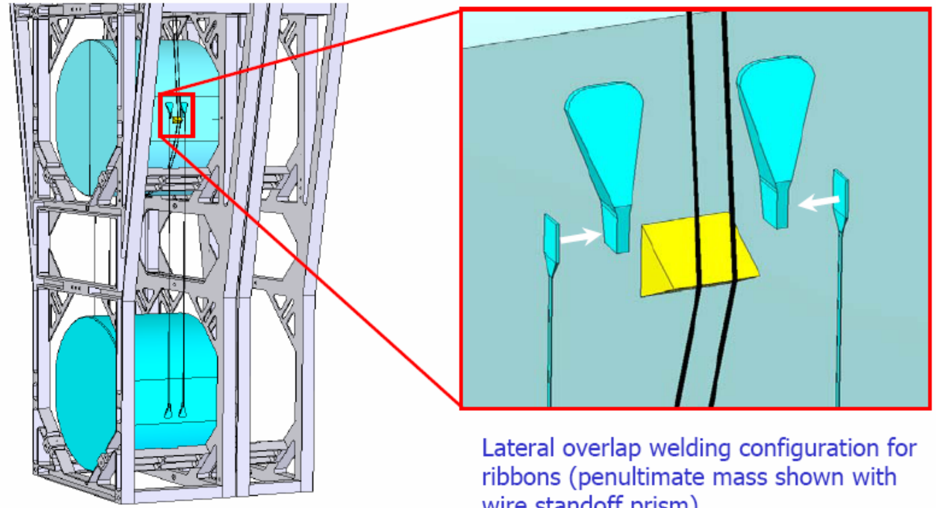
Lead by University of Glasgow

- Ribbon pulling and welding
  - » R&D on computer controlled CO_2 laser system proceeding well
  - » Fibers up to 570 mm long, 184 ±5 microns diameter
  - » 3 GPabreaking stress (factor of safety ≈4)
- Silicate bonding and ear development



Welding silica rod with 9W CO_2 laser

Fiber pulling fixture

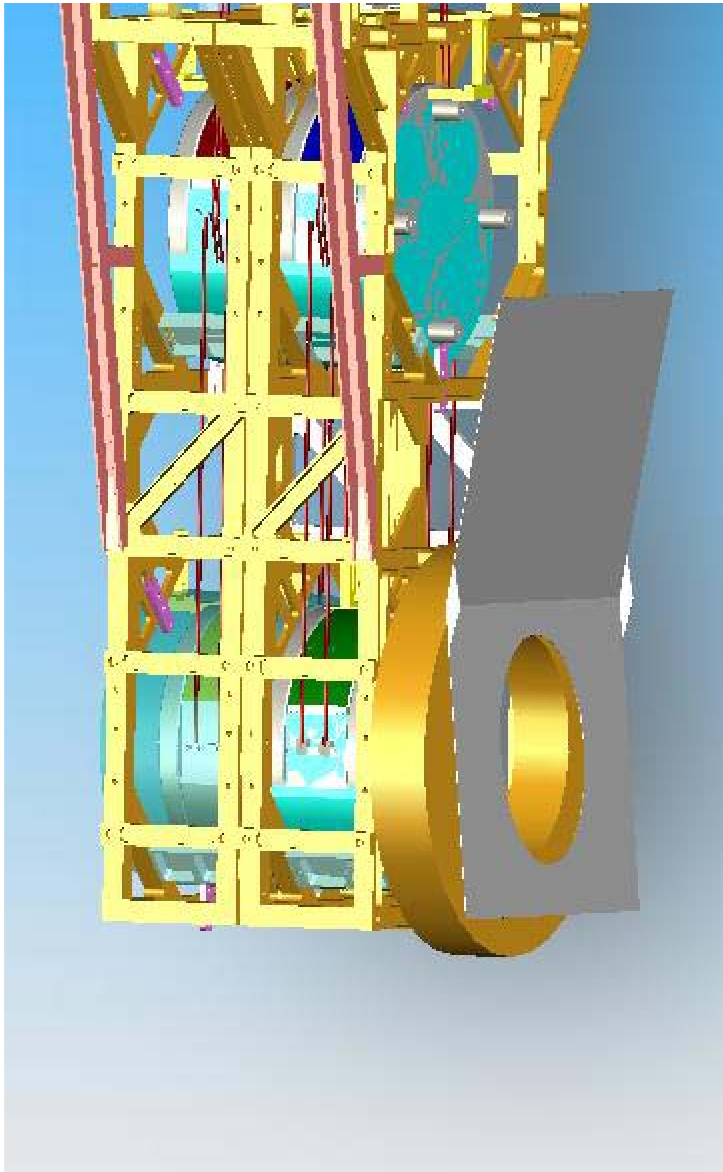


Monolithic stage in lower structure / mass catcher assembly

Lateral overlap welding configuration for ribbons (penultimate mass shown with wire standoff prism)

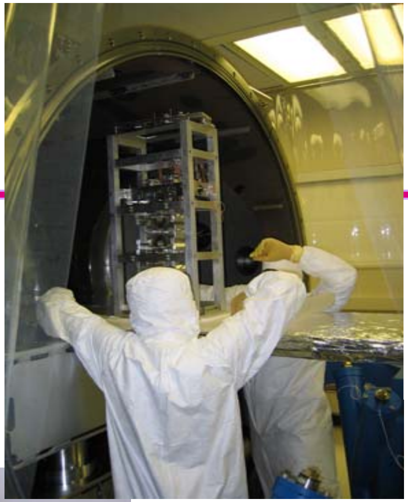
Auxiliary Optics

- **Initial Alignment System**
  - » Surveying support for proper installation of components
- **Photon calibrators**
  - » Calibration tool using photon pressure of a modulated laser beam
- **Viewports**
  - » For beams entering and exiting vacuum
- **Optical levers**
  - » Orientation monitors of each suspended optic, relative to the floor
- **In-vacuum stray light control**
  - » Baffles and beam dumps for diffuse scattering and ghost beams
- **Beam reducing telescopes**
  - » For pick-off beams and the output beam
- **Thermal compensation system**
  - » Senses thermal distortions of core optics and corrects by adding compensating heat



System Testing

LASTI (Triple Suspension in a HAM Chamber)



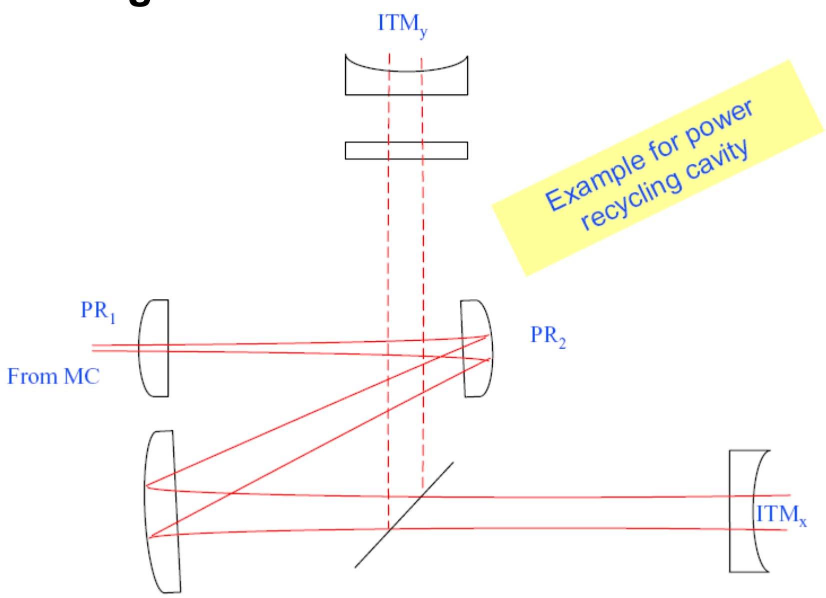
- Two major LIGO prototype test facilities:
  - » LIGO Advanced System Test Interferometer (LASTI) @MIT
    - – full scale tests of seismic isolation, suspensions, laser, mode cleaner
  - » 40m Interferometer @Caltech (see talk of Osamu this evening)
    - – sensing/controls tests of readout, engineering model for data acquisition, software
- Support from LSC testbeds
  - » Gingin Facility @Gingin, Australia
    - – thermal compensation
    - – parametric instability (see talk of Ju Li on Thursday)
  - » 10m Interferometer @U of Glasgow – readout
  - » Engineering Test Facility (ETF) @Stanford – seismic isolation
  - » Thermal Noise Interferometer @CIT
  - » GEO600 @Hanover, Germany – much more than a prototype! (test of the quasi-monolithic fused silica suspension)
- Initial LIGO
  - » Hydraulic External Pre-Isolator (HEPI)
  - » Thermal Compensation System
  - » High power modulators & isolators
  - » Output mode cleaner & DC readout

Gingin Facility

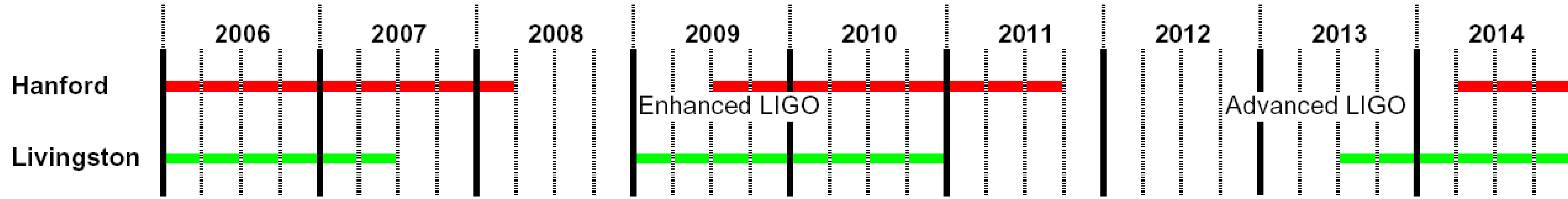
40 M Lab

Other Advanced R&D

- Unstable optical spring when the SRC is detuned
  - » Length control system will provide wideband feedback (~200 Hz) to stabilize (unstable mode at 50-60 Hz for nominal tuning)
- Angular instability due to radiation torque in study
- E2E Adv. LIGO modeling well underway (Hiro and Monica's talk on Thursday)
- LF-LF RF modulation (9-180MHz -> 25-45MHz?) in study
- Mode-Stable recycling cavity in study
  - » RCs are at the edge of stability, include focusing elements in the RCs to achieve a significant Gouy phase shift
- Seismic Platform Interferometer
  - » Reducing low frequency seismic motions by another factor of 10-100x could Make lock acquisition much simpler
- Optical spring (Thomas's talk on Sunday)
- Flat top beams (Marco's talk on Sunday)
- Injection of squeezed vacuum



Advanced LIGO Development Schedule



- Initial LIGO S5 run to reach goal of one year of integrated data in mid-2007
- Advanced LIGO funding at start of FY2008; fabrication, assembly, and stand-alone testing of detector components
- Needs NSB approval of budget, schedule
  - » Cost close to that proposed in 2003 plus inflation (199M plus UK, German contributions)
- Thorough 'Baseline Review' of these elements May 31 – June 2 at MIT
- Enhancements to be installed, commissioned progressively at Hanford, Livingston; first running in early 2009
- Science runs with enhancements starting in early 2009, running to beginning-mid 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