Update on R&D for Advanced LIGO

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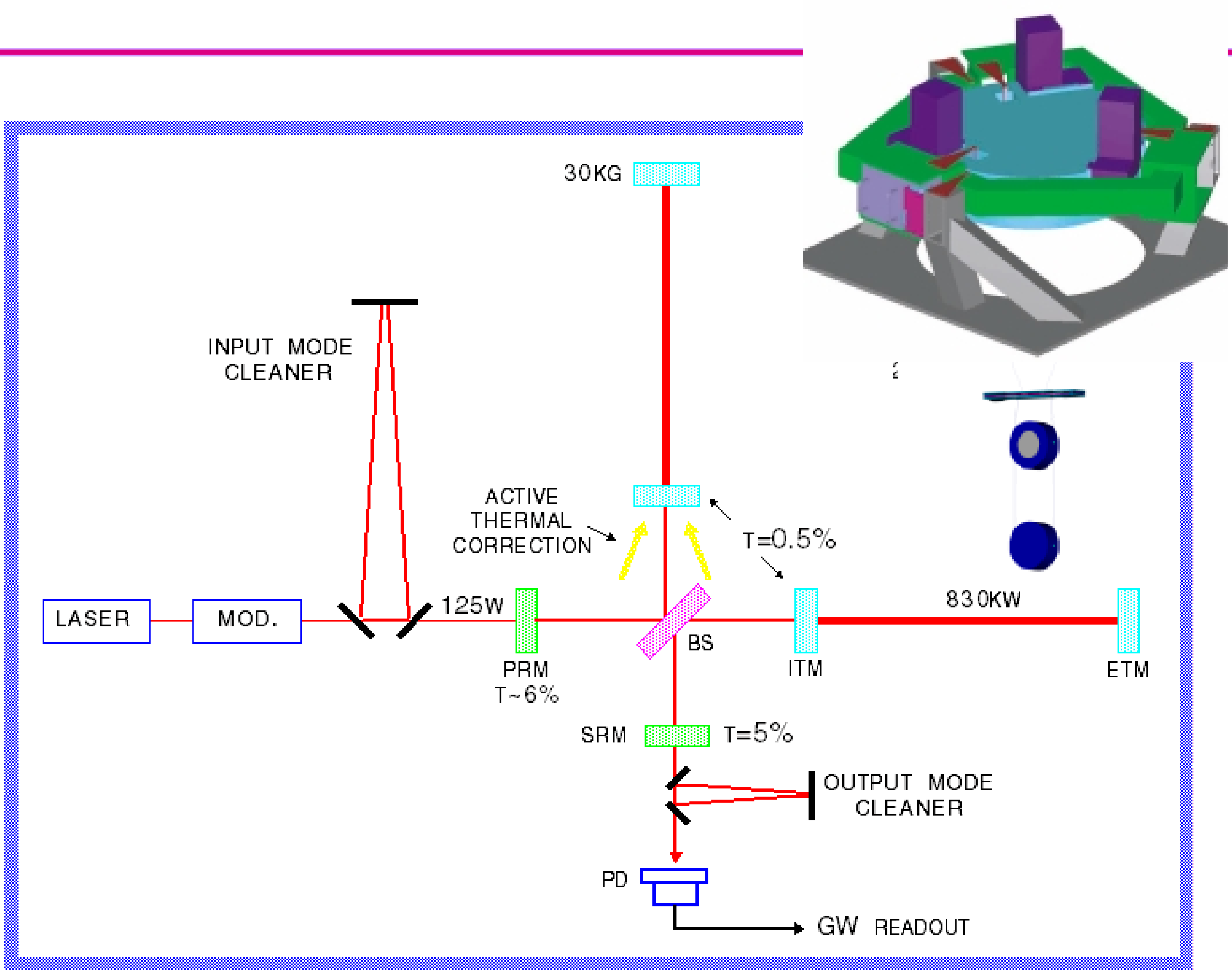
Update

- At June PAC meeting, general overview of motivations and plans given
- Here, we present the incremental progress and highlight concerns which have developed in the interim

Interferometer subsystems

Subsystem	Function	Implementation	Principal challenges
Interferometer Sensing and Control (ISC)	Gravitational Readout; length and angle control of optics	RF modulation/demod techniques, digital real-time control	Lock acquisition, S/N and bandwidth trades
Seismic Isolation (SEI)	Attenuation of environmental forces on test masses	Low-noise sensors, high-gain servo systems	Reduction of test mass velocity due to 0.01-1 Hz input motion
Suspension (SUS)	Establishing 'Free Mass', actuators, seismic isolation	Silica fibers to hold test mass, multiple pendulums	Preserving material thermal noise performance
Pre-stabilized Laser (PSL)	Light for quantum sensing system	Nd:YAG laser, 100-200 W; servo controls	Intensity stabilization: 3e-9 at 10 Hz
Input Optics (IOS)	Spatial stabilization, frequency stabilization	Triangular Fabry-Perot cavity, suspended mirrors	EO modulators, isolators to handle power
Core Optics Components (COC)	Mechanical test mass; Fabry-Perot mirror	40 kg monolithic sapphire (or silica) cylinder, polished and coated	Delivering optical and mechanical promise; Developing sapphire
Auxiliary Optics (AOS)	Couple light out of the interferometer; baffles	Low-aberration telescopes	Thermal lensing compensation

Interferometer subsystems



Advanced Interferometer Sensing & Control (ISC)

- Responsible for the GW sensing and overall control systems
- Addition of signal recycling mirror increases complexity
  - » Permits ‘tuning’ of response to optimize for noise and astrophysical source characteristics
  - » Requires additional sensing and control for length and alignment
- Shift to ‘DC readout’
  - » Rather than RF mod/demod scheme, shift interferometer slightly away from dark fringe; relaxes laser requirements, needs photodiode develop
  - » Buonanno and Chen (Caltech) and Mavalvala and Fritschel (CIT/MIT) working on implications for laser source requirements given the correlations between the photon shot noise and the radiation pressure recently recognized; jury still out on RF/DC decision, but no great urgency.
- System Level Test Facilities:
  - » Controls proof-of-principle (Glasgow)
  - » Controls precision testing (CIT 40m)
  - » High power testing (Gingin)

GEO/Glasgow tests of Sensing/Control

- » First phase at Glasgow SR (only) with high finesse FP cavities to look for basic properties of the LSC developed readout system.
  - – mechanical/optical assembly completed, modulation, photodetectors, phase shifters etc. in place.
  - – Auxiliary locking and final servo electronics near final construction. Initial locking tests soon.
- » Second phase at Glasgow DR with finesse 630 cavities; exhaustive test of readout scheme (sensing matrix etc.) and measurement of some noise-couplings.
  - – new lab including infrastructure (clean room etc.) vacuum system and suspension support structures completed
  - – Installation of suspensions, TMs and PSL underway
  - – Outline design of test readout scheme under evaluation using standard simulation tools.

- ● Progress relative to initial schedule - both phases 2-3 months behind.
- ● Still aim to interface well with current 40m schedule.

40 m RSE Experiment (40m)

- Precision test of selected readout and sensing scheme
  - Employs/tests final control hardware/software
  - Dynamics of acquisition of operating state
  - Frequency response, model validation
- Utilizes unique capability of Caltech 40 meter interferometer --- long arms allow reasonable storage times for light
- Design Requirements Review held in October
  - Objectives, detailed design trades reviewed and approved

40m RSE Experiment: Progress

- Modifications of building, vacuum system, controllers complete
    - Addition of Mode Cleaner vacuum and mechanical system
- Data acquisition, EPICS, Dataviewer, DMT, etc, Environmental monitoring installed and functional
- Pre-stabilized Laser installed and functioning
- Stray light control design complete
- Optics substrates in hand, polishing underway
- All small suspensions complete, large suspensions underway

- Maintaining the schedule

High Power Testing: Gingin Facility

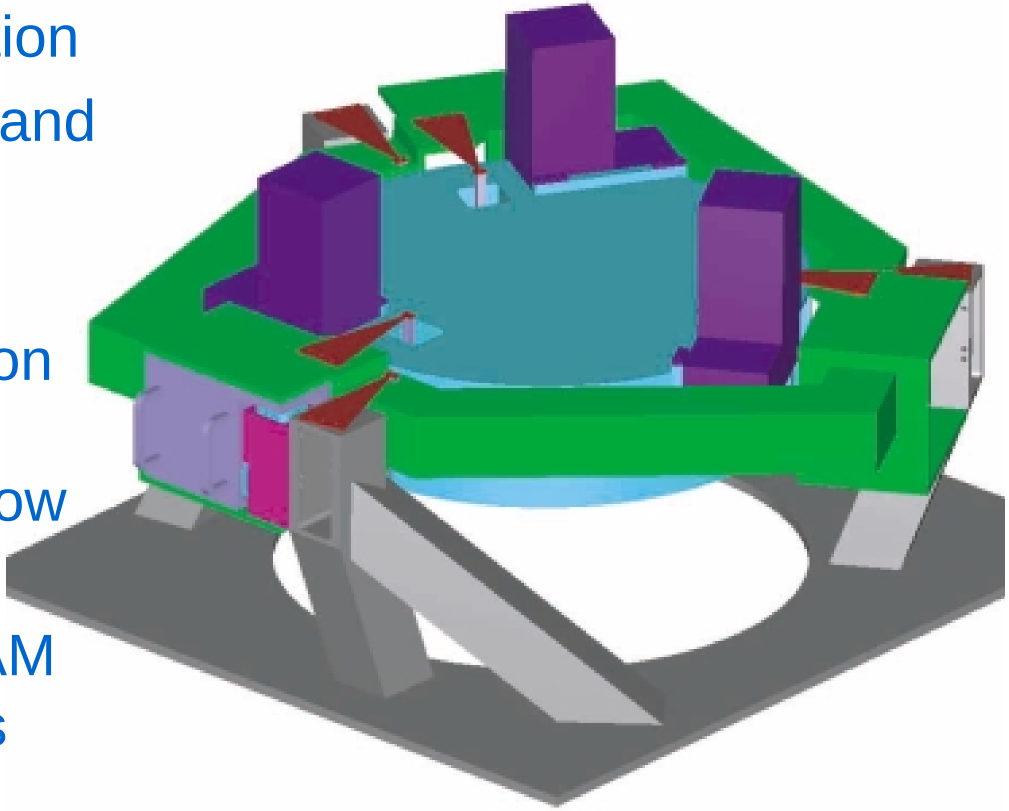
- ACIGA have proposed to develop a high power test facility in support of advanced LIGO at the AIGO Facility at Gingin
  - » Codified in a LIGO Lab/ACIGA MOU
  - » Test high power components (isolators, modulators, scaled thermal compensation system, etc.) in a systems test
  - » Explore high power effects 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)
- ACIGA has just received funding for the program

Active Seismic Isolation R&D (SEI): Requirements

- Render seismic noise a negligible limitation to GW searches
  - Suspension and isolation contribute to attenuation
  - Choose to require a 10 Hz ‘brick wall’
- Reduce or eliminate actuation on test masses
  - Seismic isolation system to reduce RMS/velocity through inertial sensing, and feedback to RMS of <10^{-11} m
  - Acquisition challenge greatly reduced

SEI: Conceptual Design

- Two in-vacuum stages in series, external slow correction
- Each stage carries sensors and actuators for 6 DOF
- Stage resonances ~5 Hz
- High-gain servos bring motion to sensor limit in GW band, reach RMS requirement at low frequencies
- Similar designs for BSC, HAM vacuum chambers; provides optical table for flexibility



Active Seismic Isolation R&D (SEI): Status

- Active Platform Technology Demonstrator:
  - Design completed & into fabrication (next page)
  - Will be integrated into the Stanford Engineering Test Facility (ETF)
  - Serves as a controls-structure interaction test bed
- Prototype system design:
  - HAM and BSC prototype designs to follow the technology demonstrator
  - Will be tested in the LASTI facility
  - Schedule delayed by acceleration of the pre-isolator
- Pre-isolator
  - Hydraulic pre-isolator development has been accelerated for possible deployment in initial LIGO to fix the LLO seismic noise problem
  - Prototype to be tested in LASTI mid-2002
  - Initial LIGO passive SEI stack built in the LASTI BSC
  - Plan to install at LLO ~10/2002

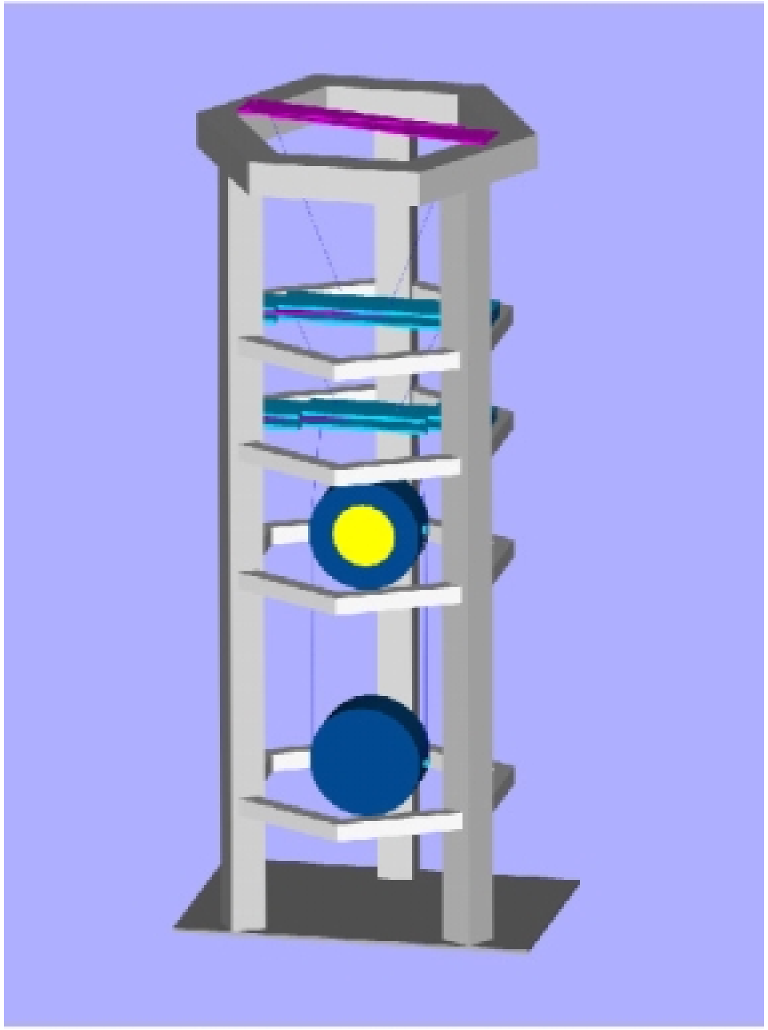
Active Seismic Isolation R&D (SEI)

- ETF Technology Demonstrator:
  - » parts are in fabrication
  - » Initial assembly in Jan

Suspension Research (SUS)

- Adopting a multiple-pendulum approach
  - » Allows best thermal noise performance of suspension and test mass; replacement of steel suspension wires with fused silica
  - » Offers seismic isolation, hierarchy of position and angle actuation
- Close collaboration with GEO (German/UK) GW group
- Complete fused-quartz fiber suspensions completed and functioning in GEO-600 interferometer
- Glasgow-designed Quad prototype delivered to MIT, assembled and ‘experienced’ by Glasgow, Caltech, and MIT team members
- Detailed characterization of modes, damping underway
- Tests of actuation and controls to follow

Quad pendulum prototype



Suspension Research

- Suspension fibers in development
  - Refinement of fabrication facilities at Caltech and Glasgow
  - 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
  - Complementary measurements of material properties at Caltech
  - May allow very low thermal noise with comfortable dimensions
- Attachment of fibers to test masses
  - Hydroxy-catalysis bonding of dissimilar materials is issue
  - Silica-sapphire tested, looks workable
  - silica-leadglass (for intermediate mass) to be explored
- Significant design work: simpler ‘triple’ suspensions, thinking about caging etc.

Stochastic noise system tests: LASTI

- Full-scale tests of Seismic Isolation and Test Mass Suspension.
  - » Takes place in the LIGO Advanced System Test Interferometer (LASTI) at MIT: LIGO-like vacuum system.
  - » Allows system testing, interfaces, installation practice.
  - » Characterization of non-stationary noise, thermal noise.
- ‘Blue piers’ and support structures in place
- Initial LIGO Test Mass isolation system installed (to support hydraulics tests – a significant detour)
- Pre-stabilized Laser installed and in testing
- Data acquisition, Diagnostics Test Tool, etc. functioning and in use
- Test suspensions for first laser-controls testing in installation

- Team focussed on the hydraulic pre-isolator development and test

Thermal Noise Interferometer (TNI)

- Direct measurement of thermal noise, at LIGO Caltech
  - » Test of models, materials parameters
  - » Search for excesses (non-stationary?) above anticipated noise floor
- In-vacuum suspended mirror prototype, specialized to task
  - » Optics on common isolated table, ~1cm arm lengths
- Complete system functional, ‘locked’
  - » Initial noise performance (~5e-18 m/rHz, 1 kHz) not bad
  - » Work on increasing locked time, locking ease, and noise performance underway

Core Optics

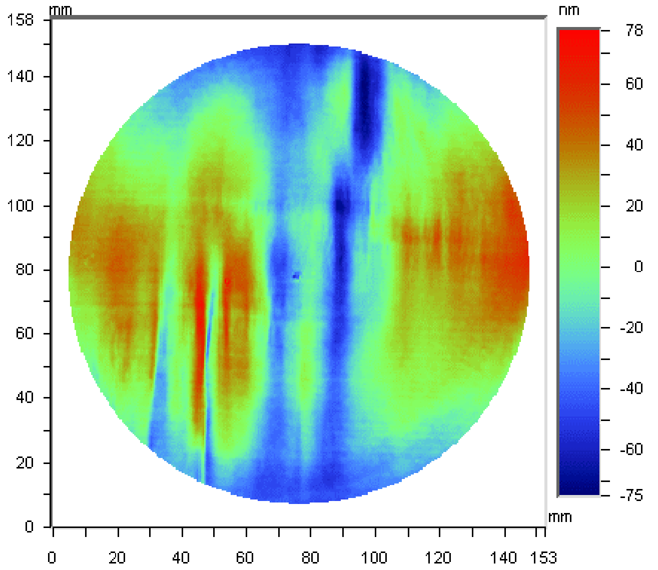
- Must serve both optical and mechanical requirements
- Two possible substrate materials:
  - » Fused silica, familiar from initial LIGO and to the optics fabrication houses
  - » Crystalline sapphire, new in our sizes and our requirements for fabrication of substrates, polishing, and coating
    - – Low internal mechanical losses → lower thermal noise at most frequencies than for fused silica
    - – High thermal conductivity → smaller distortions due to light absorption
- Optical coatings
  - » Thermal noise issues – later slide, but note that we believe the greater Young's modulus of sapphire makes coating losses significantly less important
- …and must be able to assemble the system (attachments)

R&D: Core Optics
Material Development Status

- 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
  - » Additional measurement from modification of thermal compensation setup, good agreement with other values, puts the technology in our hands for more measurements if desired
- 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



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Pupil: 100.0 %
PV: 152.5563 nm
RMS: 27.0963 nm

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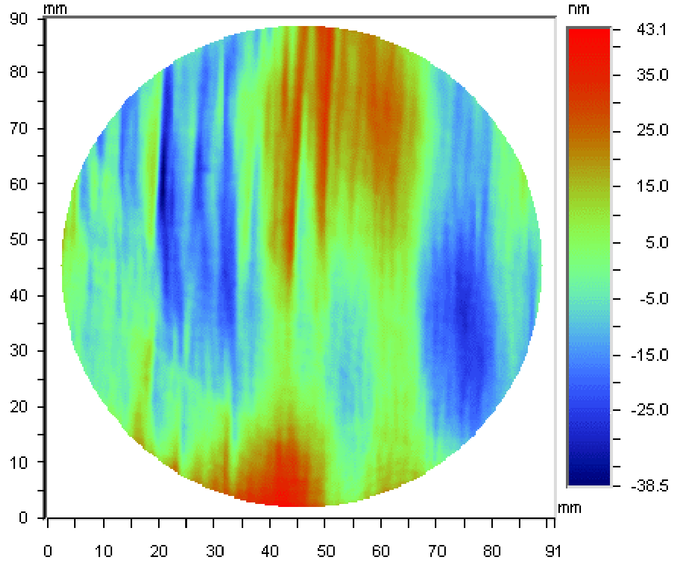

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RMS: 13.2016 nm

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Masks:

R&D: Core Optics
Material Development Status

- Effort to reduce bulk absorption (Stanford, Southern University, CS, SIOM, Caltech)
- LIGO requirement is <10 ppm/cm
- Recent annealing efforts are encouraging
  - » CSI: High temp. anneal in air appears to have an inward and outward diffusion wave; core values are ~45 ppm/cm and dip to 10ppm/cm. Absorption in the wings is in the hundred ppm range.
  - » 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, and with no wings.
  - » Higher temp furnace being commissioned at Stanford

R&D: Core Optics
Sapphire Polishing

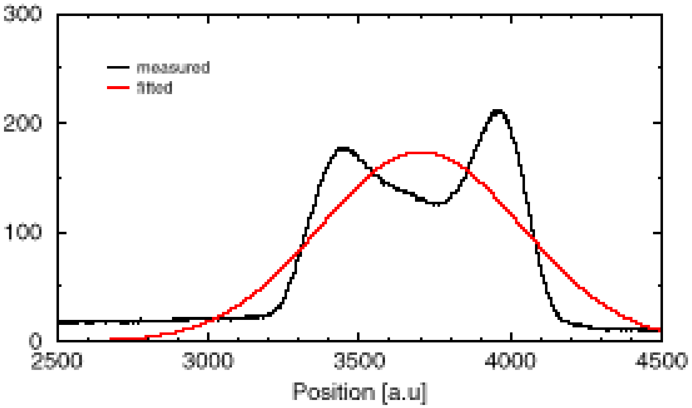
- Demonstration of super polish of sapphire by CSIRO (150mm diameter, m-axis)
  - » Effectively met requirements
- Optical Homogeniety compensation
  - » Need 5 to 10 x reduction of inhomogeneity
    - – Need may be reduced by better material properties, as noted
  - » Computer controlled ‘spot’ polish by Goodrich (formerly HDOS)
    - – Going slowly, some confusing interim results, may not deliver in a timely way
  - » Ion beam etching, fluid stream polish, compensating coating by CSIRO

R&D: Optics
Coating Research

- Two issues to work:
    - Mechanical losses of optical coatings leading to high thermal noise
    - Optical absorption in coating leading to heating and deformation
- Two coating houses involved – maybe multiple sources at last!
- SMA/Lyon (France)
    - Developed to handle VIRGO coatings
    - Capable of Adv LIGO-sized substrates
    - Significant skilled optics group, interested in ‘collaborative’ effort
    - Pursuing a series of coating runs designed to illuminate the variables, and possibly fixes, for mechanical losses
    - Mechanical Q testing by Stanford, Syracuse and MIT
- MLD (Oregon)
    - Spinoff of fathers of the field of low-loss coatings
    - Could modify for Adv LIGO-sized substrates, not trivial
    - Pursuing a series of coating runs targeting optical losses
- Just getting started in both endeavors

Input Optics R&D Issues & Status

- Advanced LIGO will operate at 180W CW powers -- presents some “challenges”:
  - » Thermal Lensing --> Modal Degradation
  - » Thermally induced birefringence
    - – Faraday Isolator (FI): loss of isolation
    - – Electro-Optic Modulation (EOM): spurious amplitude modulation
  - » Damage
  - » Other (nonlinear) effects (SHG, PR)



5 x 5 x 40 mm $LiNbO_3$ EOM - thermal lensing is:
i) severe
ii) position dependent

- Research Program:
  - » Modulator Development:
    - – RTA material performance (should be better than KTP)
    - – Mach Zehnder topology for modulation as an alternative
  - » Modulator Status
    - – RTA shows no evdience of thermal lensing or damage at 50W input power
    - – LiNbO3 shows severe lensing and even damage
    - – RTA-based EOMs currently being fabricated by Quantum technologies
      - transverse modulation
      - temperature stabilized

Input Optics
R&D Issues & Status

- Isolator Development:
  - Full FI system test (TCFI, EOT)
  - Possible thermal compensation (-dn/dT materials)
- Isolator Status:
  - 45 dB isolation demonstrated at 80 W using compensated 2 crystal design
  - thermal lensing compensation using negative dn/dT FK51 glass after TGG gives 98-99% TEM_00 mode recovery (from 50% without)
- Telescope Development:
  - in-situ mode matching adjustment

R&D: Optics
Thermal Compensation

- Thermal lensing forces polished-in curvature bias on initial LIGO core optics for cavity stability at operating temperature
- LIGO II will have ~20X greater laser power, ~3X tighter net figure requirements
  - » higher order (nonspherical) distortions significant; prepolished bias, dynamic refocusing not adequate to recover performance
  - » possible bootstrap problem on cold start
- Test mass & coating material changes may not be adequate
  - » SiO_2 has low k_{th} , high dn/dT, but low bulk absorption
  - » Al_2O_3 has higher k_{th} , moderate dn/dT, but high bulk absorption (so far...)
  - » coating improvements still speculative

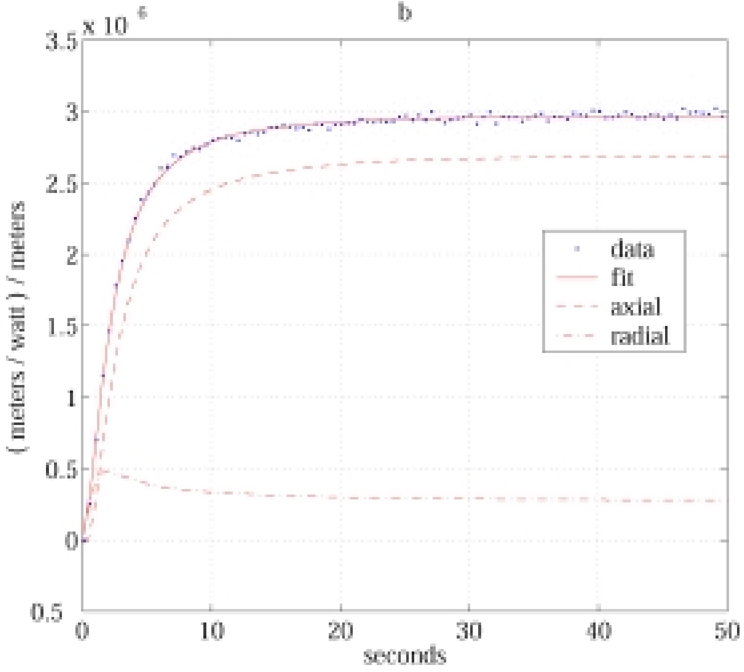
R&D: Thermal Compensation

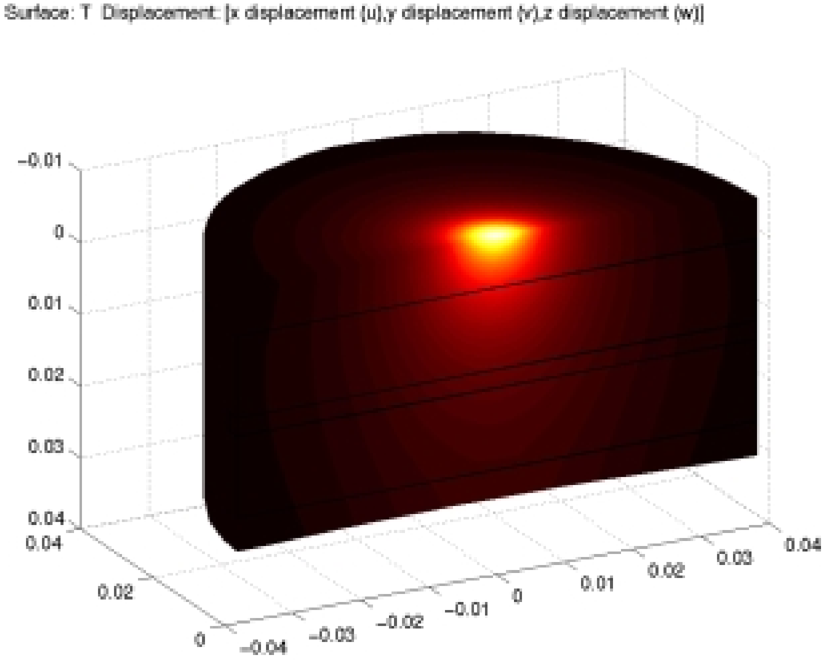
- In Lab, concentrated on getting sapphire setup working and collection of thermophysical parameters
  - » Ready to characterize sapphire along various axes, then do ‘raster’ compensation for details and asymmetries
- In Analysis, built a matlab-based 3D model to find the thermal lensing and thermoelastic deformation in cylindrical optics with beam heating at non-normal incidence (heating in the coatings and in the bulk)
  - » To use in Melody for the beamsplitter (and mode cleaner optics), and will give me a better idea on how lensing in the beamsplitter effects thermal compensation

R&D: Thermal Compensation

Temporal evolution of deformation, and

fit to measured absorption

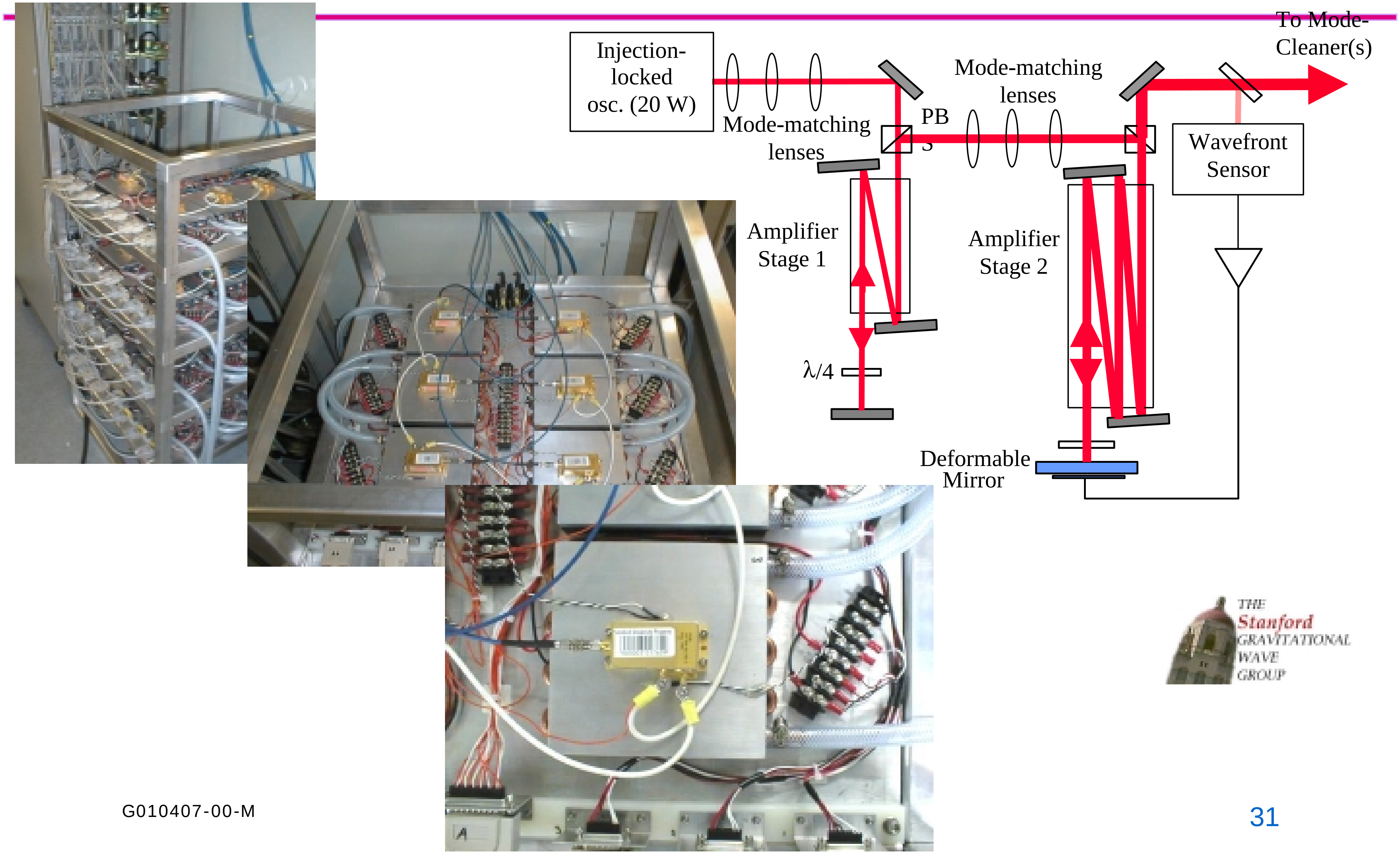




R&D: High Power Laser

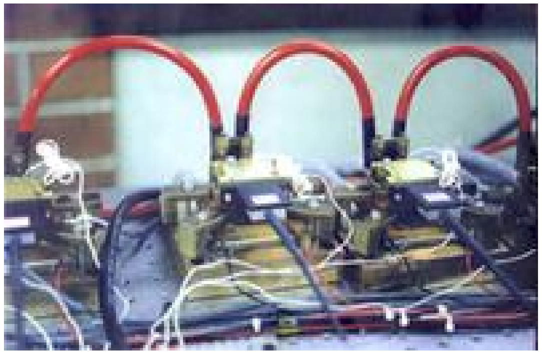
- High power required to reach interferometer design sensitivity
  - » ~180 W for Sapphire, ~80 W for fused silica
- Multiple sites in ‘friendly competition’ for baseline approach
  - » MOPA slab (Stanford)
    - – uses proven technology but expensive due to the large number of pump diodes required
  - » stable-unstable slab oscillator (Adelaide)
    - – typically the approach adopted for high power lasers, but not much experience with highly stabilized laser systems
  - » rod systems (Hannover)
    - – uses proven technology but might suffer from thermal management problems
- LZH Hannover to carry subsystem through design, test, probably also fabrication
- In a phase of testing multiple concepts

R&D: High Power Laser Stanford MOPA Design



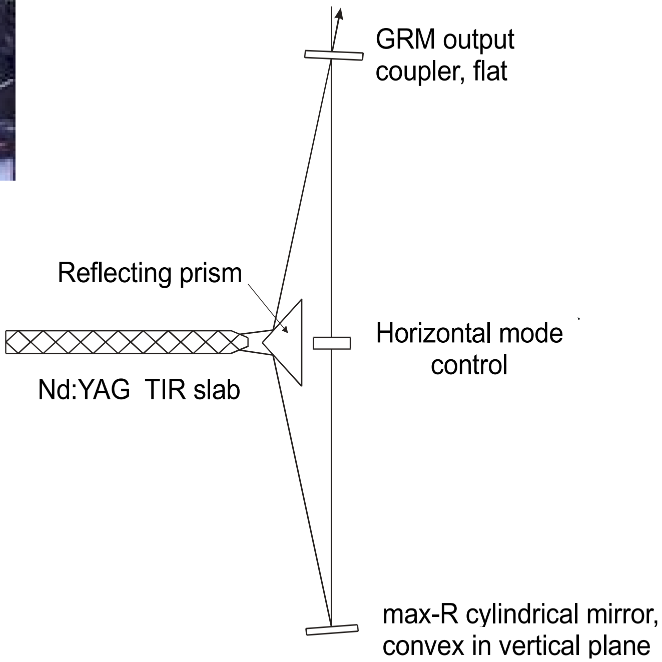
THE Stanford GRAVITATIONAL WAVE GROUP

R&D: High Power Laser Adelaide Configuration



Two in a series of linked pump diode-laser heads.

100W Laser Configuration

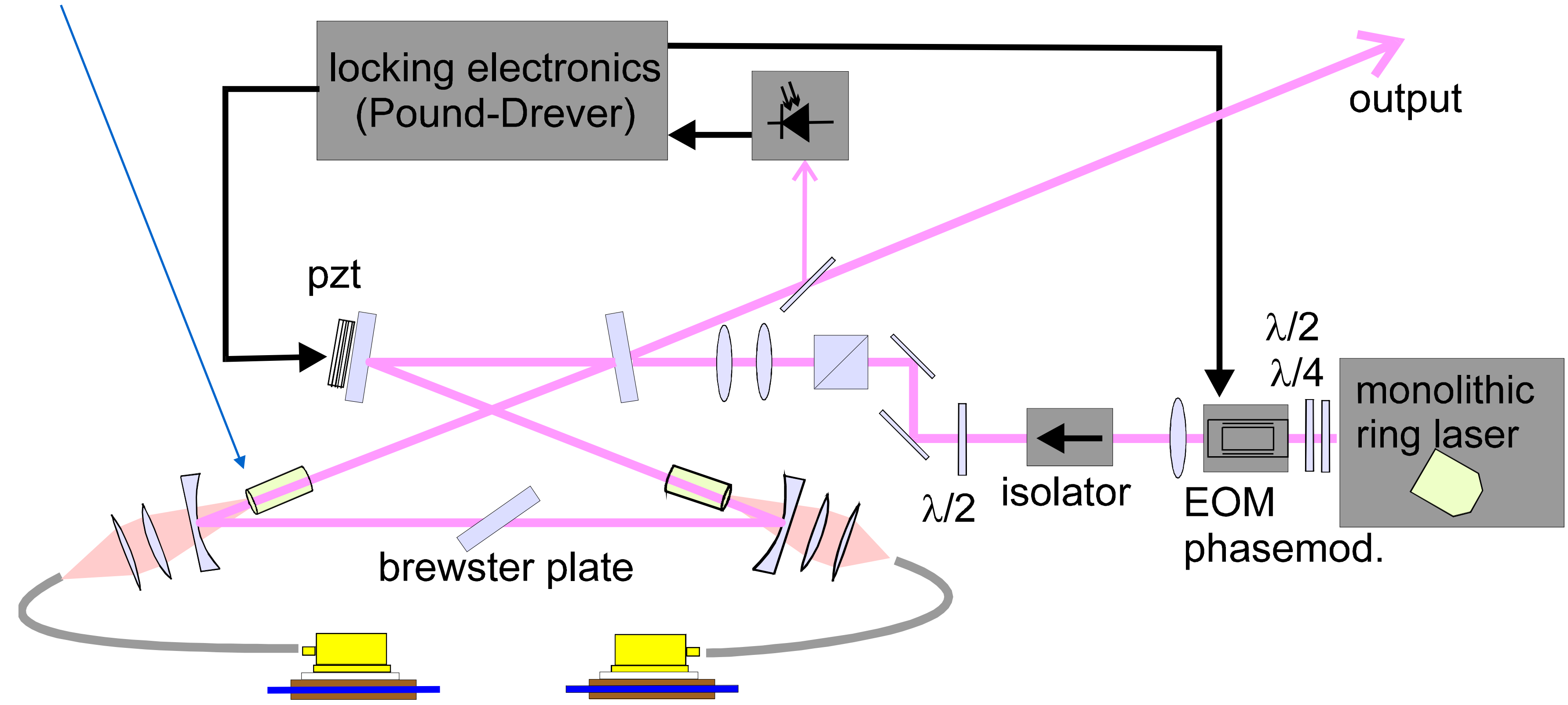


- slab is side-pumped by 520W of fibre-coupled diode lasers
- resonator is stable in the zig-zag (horizontal) direction, unstable in the vertical direction

Adelaide University **ACIGA**

R&D: High Power Laser Hannover Configuration

Nd:YAG or Nd:YVO$_4$ rods



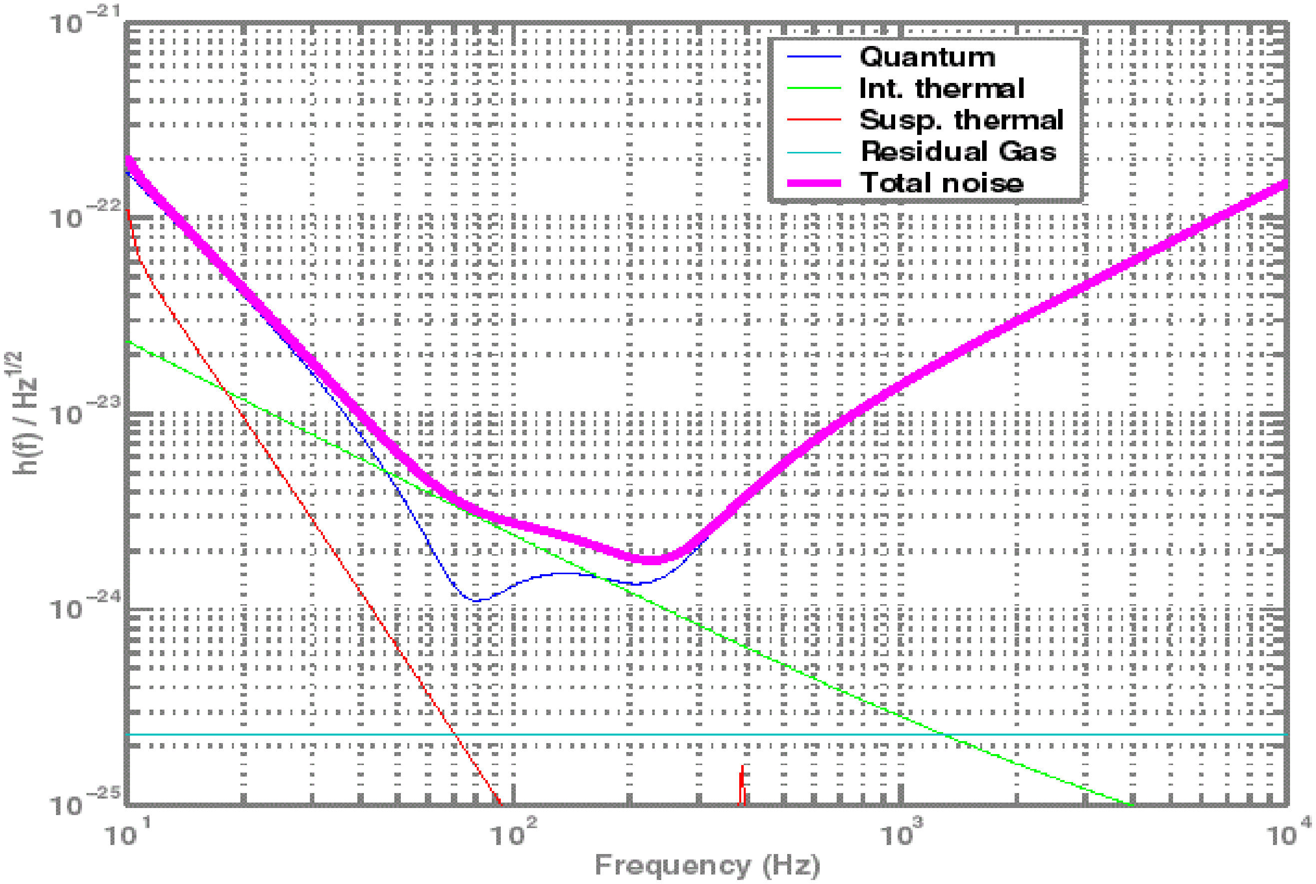
temperatur stabilized fibre coupled laser diodes

High power Laser: Recent progress

- Adelaide:
  - » Observation of saturation of slope at 250-300 W pump power
  - » Collection of experiments performed to find problem – fiber coupling to medium was suspect
  - » Will now make interferometer to look at distortion *in situ*
- LZH Hannover
  - » Gearing up for high-power tests – laser diodes ordered, mounting and heat sinks in fabrication, etc.
  - » 20W Nd:YVO4 (Niobium-Vanadate) injection locked laser is close to delivery to the VIRGO project
- Stanford
  - » Looking for means to achieve needed ~15-20 W pump power
  - » LIGO Lab considering funding Lightwave to upgrade an existing LIGO I style ~10W laser to a 20W MO for Stanford's PA

System Issues

- System Design Requirements Review held in July
  - » Top-level requirements and trades described
  - » Initial Optical layout shown
  - » Environmental inputs assembled



System trades

- Test mass material – silica or sapphire
  - Influences frequency of best performance, best power, suspension designs, thermal compensation needs
  - Discussed above, in many contexts
  - Better understanding of ‘coating thermal noise’ encourages selection of sapphire
- Test mass size and beam size
  - Influences thermal noise, motion of mass due to photon ‘buffeting’, polishing requirements, power budget, ability to acquire materials
  - Closing in on 40kg test masses, 32 cm diameter

System Trades

- Low frequency suspension ‘bounce’ mode
  - » Influences position of ~10 Hz peak
  - » Could observe below this frequency (as well as above)
  - » Influences suspension design (and ability to fit suspension in available space), local damping noise requirements, all electronics noise requirements
  - » not a seismic noise issue
  - » Source predictions canvassed; technical study in process
  - » New fiber ideas give more design flexibility
- Gravitational wave readout – RF or DC
  - » Simpler laser requirements in most domains if DC
  - » May not give as good quantum noise – subtle issue
  - » Can presently pursue both without significant penalty
  - » Will be resolved in a timely way by calculation, small-scale prototype tests

Summary

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

- …but manpower stressed to support R&D and initial LIGO satisfactorily