Advanced LIGO Systems Design & Requirements

P Fritschel

LSC Meeting

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Upgrade approach & philosophy

- We don’t know what the initial LIGO detectors will see
  - » Design advanced interferometers for improved broadband performance
- Evaluate performance with specific source detection estimates
  - » Optimizing for neutron-star binary inspirals also gives good broadband performance
- Push the design to the technical break-points
  - » Improve sensitivity where feasible - design not driven solely by known sources

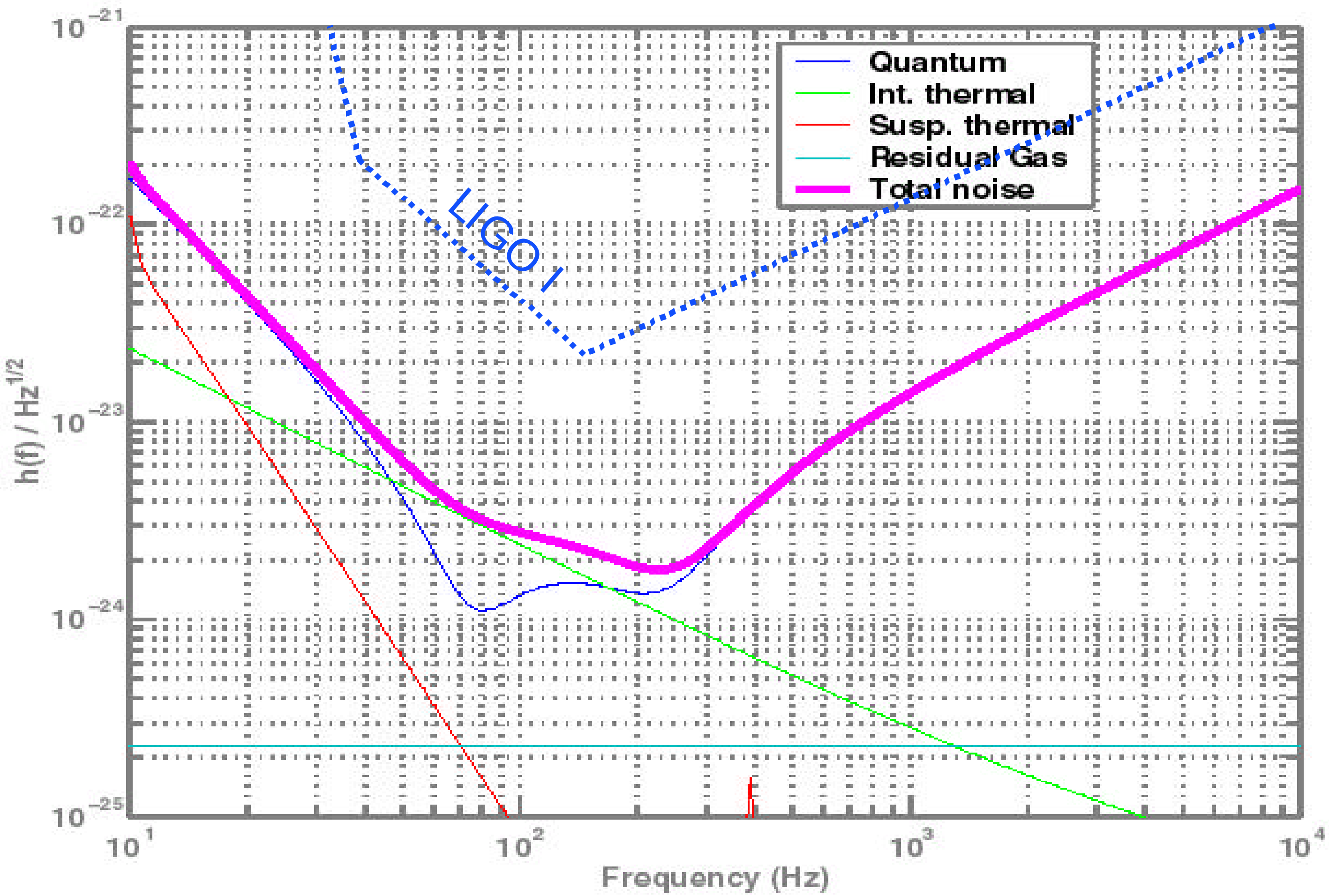
Upgrade approach, cont'd

- Design approach based on a complete interferometer upgrade
  - » More modest improvements may be possible with upgrades of selected subsystem/s, but they would profit less from the large fixed costs of making any hardware improvement
- Two interferometers, the LLO and LHO 4k units, would be upgraded as broadband instruments
- Current proposal for third interferometer (LHO 2k):
  - » increase length to 4 km
  - » implement a narrowband instrument, tunable from ~500 Hz-1 kHz

Estimated strain sensitivity

40 kg sapphire test masses

single interferometer NBI range: 206 Mpc



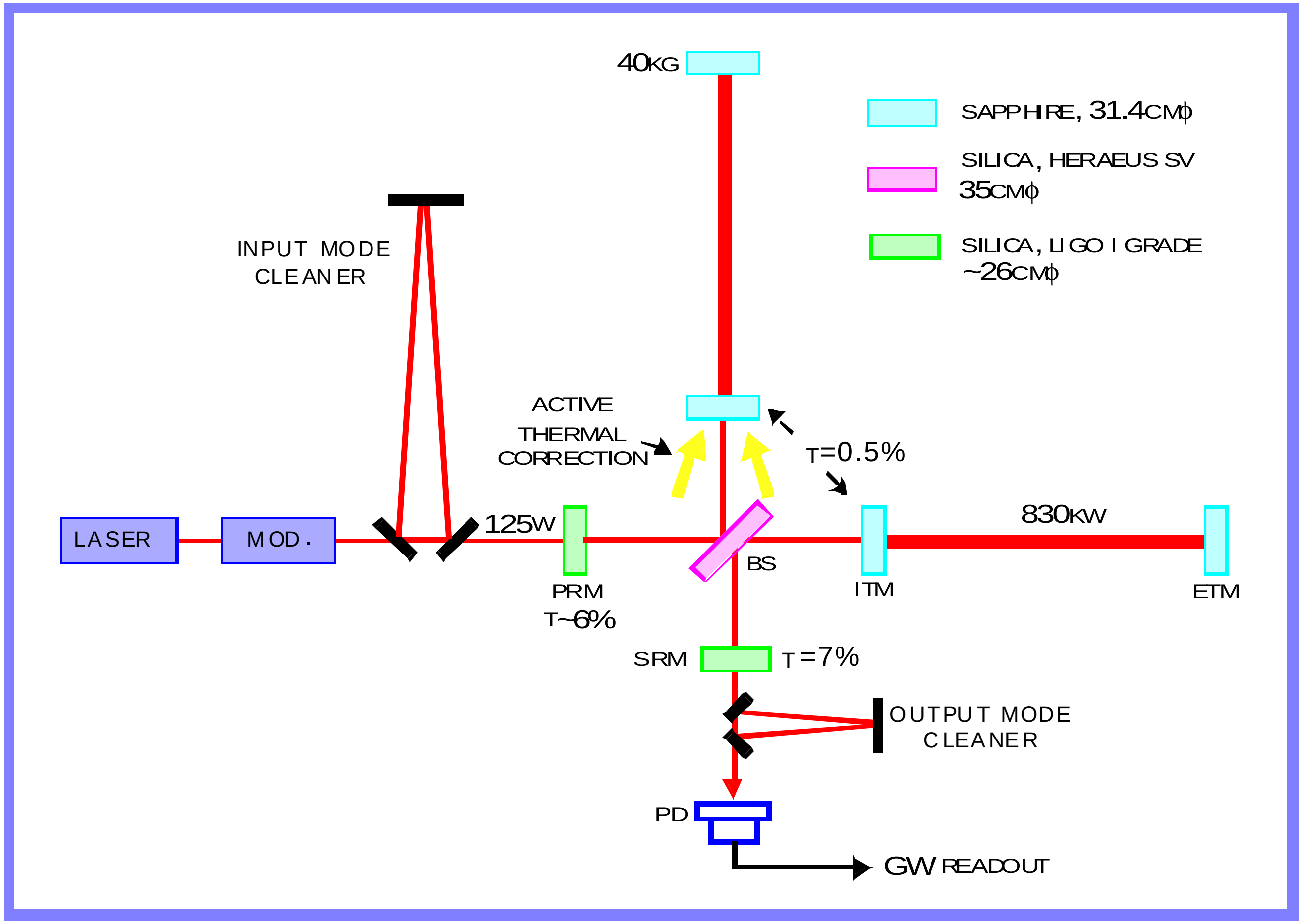
LIGO Top level performance & parameters

Parameter	LIGO I	LIGO II
Equivalent strain noise, minimum	$3x10^{-23}$/rtHz	$2x10^{-24}$/rtHz
Neutron star binary inspiral range	19 Mpc	300 Mpc
Stochastic backgnd sens.	$3x10^{-6}$	$1.5\text{-}5x10^{-9}$
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

System level requirements

- Non-gaussian noise
  - » Difficult to establish quantitative requirements
  - » Subsystems should be designed to avoid potential generation of non-gaussian noise
- Availability – as for initial LIGO:
  - » 90% for a single interferometer (40 hrs min continuous operation)
  - » 85% for two in coincidence
  - » 75% for three in coincidence
- Environmental sensing
  - » Initial PEM system basically adequate, some sensor upgrades possible
- Infrastructure constraints
  - » Designs must fit with existing LIGO facilities, with two possible changes:
    - – Larger diameter mode cleaner tube
    - – mid-station BSCs moved to the ends, for 4km length 3rd ifo
- Data acquisition
  - » Same sample rate and timing requirements as for initial LIGOb
  - » Each subsystem must be designed with appropriate data acquisition channels

System level design – basic layout



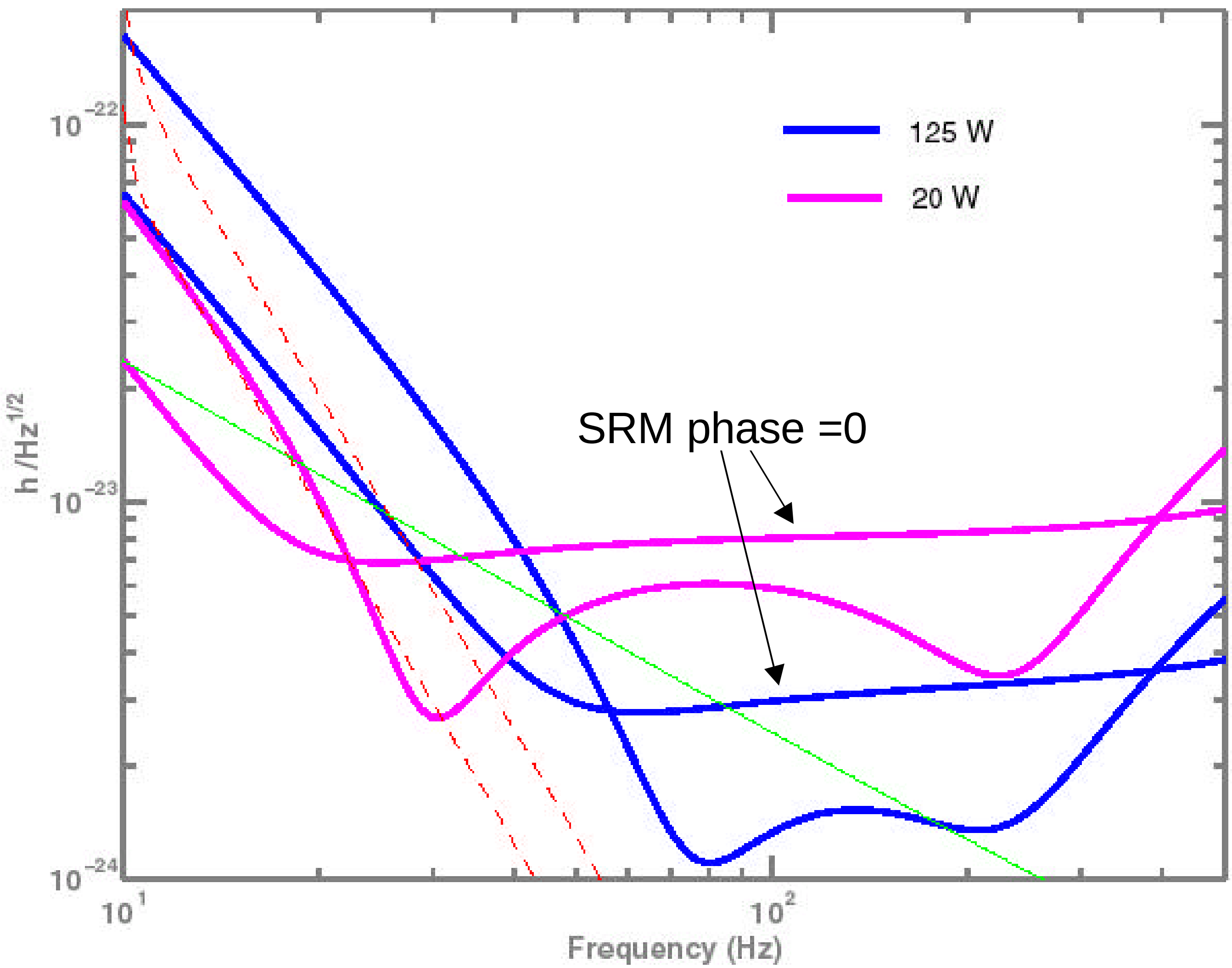
What we've left out

- Internal thermal noise
  - » Flat-topped beams to reduce thermo-elastic noise
  - » Cooling of the test masses
  - » Independent readout of test mass thermal motion
- Quantum noise
  - » Quantum non-demolition techniques
  - » Very high power levels, coupled with all-reflective configurations
- Seismic noise
  - » Independent measurements of gravitational gradient noise

Systems level design: signal recycling

- Provides ability to do some shaping of the response, but principal advantage is in power handling:
  - » Signal recycled interferometer: 200 Mpc NBI range, 2.1 kW beamsplitter power
  - » Non-signal recycled, same input power: 180 Mpc range, 36 kW beamsplitter power
- Limit to signal vs power recycling comes from losses in the signal recycling cavity
  - » Arm cavity finesse of ~1000 probably OK
  - » Arm cavity finesse of ~10,000 probably too high
- Not requiring a tunable or selectable signal recycling mirror transmission
  - » Not necessary for the ‘broadband performance’ goal

Flexibility in quantum noise

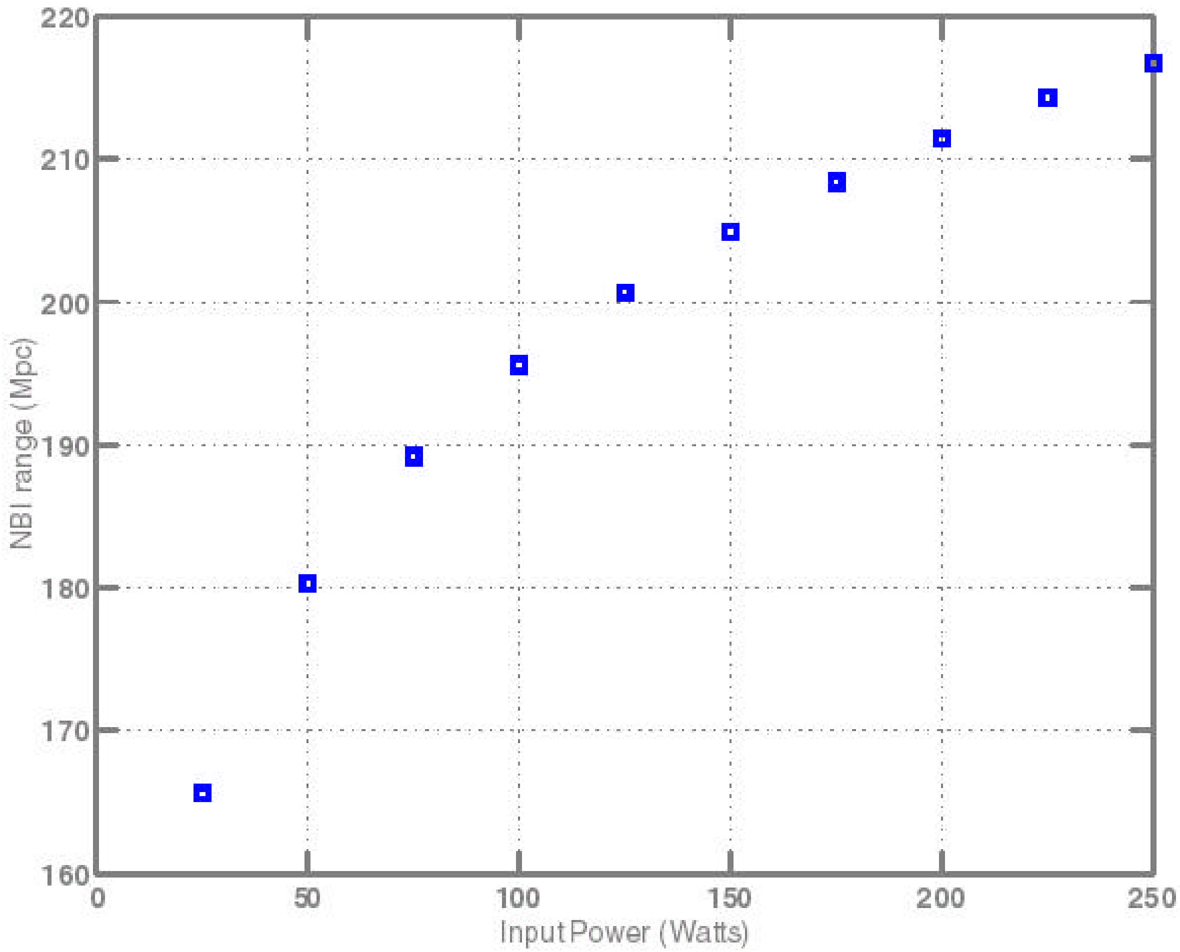


Can gain a factor of ~2 at low (f<40 Hz) and high (f>500Hz) frequencies by positioning the signal recycling mirror at zero phase

More design additions

- Output mode cleaner
  - » Reduce the output power to a manageable level; no need for higher power photodiodes
  - » Avoid unrealistic technical intensity noise requirements if Watts of power were to be detected
  - » Could be a short (~0.5 m) rigid cavity, w/ modest isolation needs … or essentially a copy of the input mode cleaner, depending on the readout scheme adopted
- Active thermal compensation
  - » Thermal loading & distortions almost certainly larger than in initial LIGO, which is close to thermal instability
  - » Required compensation: roughly a factor of 10 in optical path distortion
  - » Two compensation methods:
    - – Radiative ring heater, close to optic
    - – External heating laser beam, scanned over the optic

Input power



40kg sapphire
test masses

180 W from laser

↓

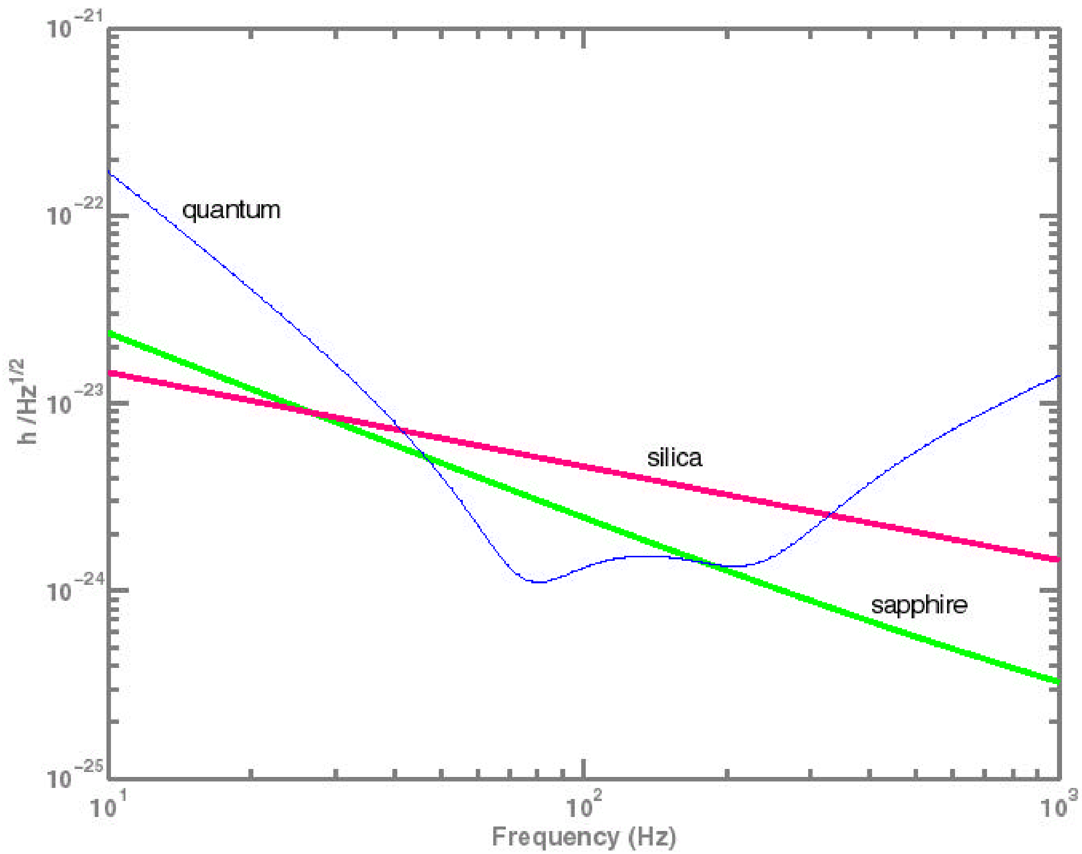
165 W from PSL

↓

125 W from MC

Test mass material: sapphire vs fused silica

- Sapphire is baseline design:
  - » 1.4x larger NBI range
  - » Potential for thermal loading advantage
  - » Still under development:
    - – Size, absorption, homogeneity,scattering
- Silica
  - » Better understood materials properties
  - » Size available, but expensive
- Both suffer from coating losses



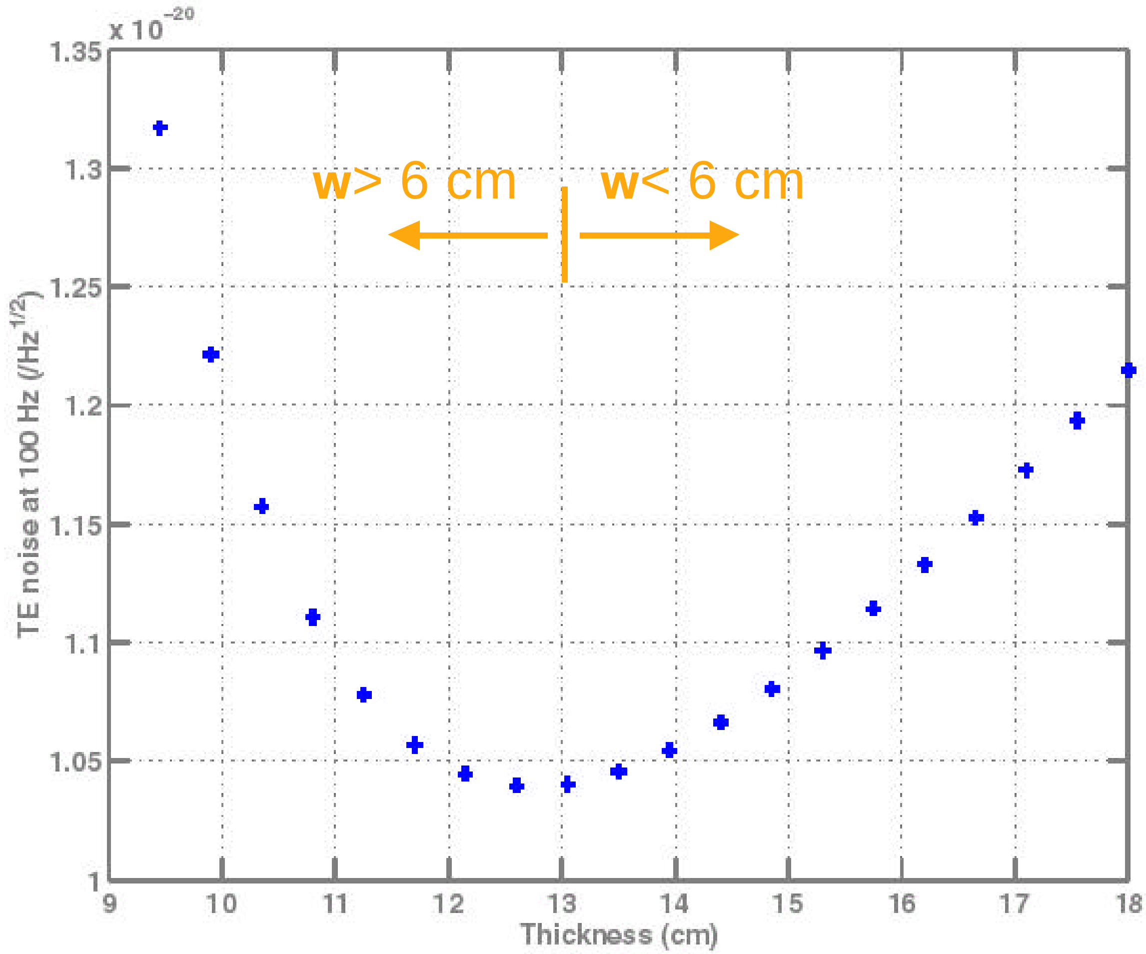
Recent correction to BENCH

- *Error:* Internal noise from bulk mechanical loss not added up for all test masses
  - » Underestimated by a factor of sqrt(2) in h
- Impact:
  - » Sapphire test masses: NBI range reduced from 209 to 206 Mpc
  - » Silica test masses: NBI range reduced from 176 to 142 Mpc
- Coating loss
  - » Lowest coating loss seen: ~3e-5
  - » Sapphire: NBI range reduced to 186 Mpc (10% hit)
  - » Silica: NBI range reduced to 113 Mpc (20% hit)

Test mass & beam size

- Test mass size:
  - » Bigger is better, but 40 kg is a practical maximum for sapphire, in AdLIGO's timescale
- Beam size:
  - » Win quickly with sapphire, $\mathbf{w}^{-3/2}$, more slowly with fused silica, $\mathbf{w}^{-1/2}$ (& as $\mathbf{w}^{-1}$ for coating loss)
- Limits imposed by:
  - » Aperture loss in arm cavities
  - » Polishing challenges: uniformity over a larger area ;very long radii of curvature
  - » Stability of arm cavities in the presence of distortions
- Sapphire
  - » With an upper limit of 15 ppm aperture loss, beam radius of 6.0 cm minimizes thermo-elastic noise, for a 40 kg piece
- Silica
  - » Probably limited more by thermal distortions; using 5.5 cm for now

40 kg sapphire optimization



Aperture loss kept constant at 15 ppm

Seismic wall frequency: 10 Hz

- Specific source detection
  - » Sensitivity to NBIs or stochastic background doesn't significantly change for cutoff frequencies less than 15 Hz
  - » Somewhat more sensitive for intermediate mass BH-BH mergers; still probably no significant loss for any cutoff less than 12-13 Hz
- Technology threshold
  - » Horizontal ground motion (isolated by seismic + suspension) crosses quantum radiation pressure & suspension thermal noise below 10 Hz
  - » Vertical isolation not so large, since last stage of suspension is relatively stiff; couples to beam path at a level of ~0.001
  - » Fiber cross section also driven by minimizing thermal noise: smallest diameter fiber is not the best
  - » By using a dense penultimate mass material, it appears feasible to keep the vertical mode under 10 Hz

GW channel readout: 2 candidates

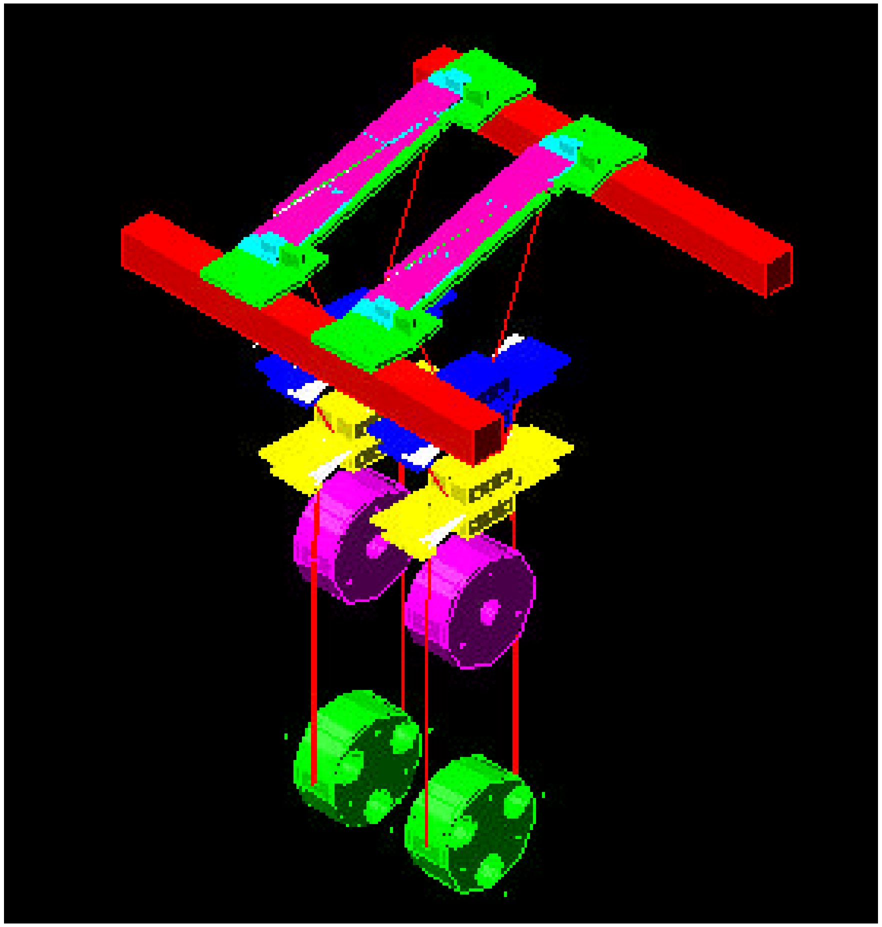
- RF readout, as in initial LIGO
  - » Phase modulate at interferometer input
  - » Arrange parameters for high transmission of RF sidebands (one anyway) to output port
- DC readout
  - » Small offset from carrier dark fringe
  - » GW signal produces linear baseband intensity changes
  - » Advantages compared to rf readout:
    - – Output mode cleaner simpler
    - – Photodetector easier, works at DC
    - – Lower sensitivity to laser AM & FM
    - – Laser/modulator noise at RF frequencies not critical
- Comparison of quantum-limited sensitivity still in progress

System level noise sources: control of fundamental & technical noise

- Quantum noise
  - » Readout scheme: must not significantly compromise ideal sensitivity
- Internal thermal noise
  - » Make beam as big as possible (optimized given sapphire size constraint)
  - » Don't spoil Q of substrate material, BUT …
    - – Mirror coatings and possibly polishing have a significant effect, that we may not be able to mitigate
- Suspension thermal noise
  - » Under control: stress and shape of fiber
  - » Ribbons (10:1 aspect) give about 2x lower noise
    - – improved low-f performance in zero-detuning mode
- Technical noise
  - » Each technical noise source held below 10% of the target strain sensitivity

Ground noise

- Test masses: 10^{-19} m/rtHz at 10 Hz
  - » Strain noise: 5×10^{-23} /rtHz, 30% & 60% of the target for high-power and low-power operation, respectively
  - » Displacement noise for each seismic platform: 2×10^{-13} m/rtHz at 10 Hz
  - » Suspensions to provide the additional required isolation



Summary & Plan

- Systems design: resolution of open issues
  - » Sapphire vs fused silica
    - – Hinges mostly on success of sapphire development
    - – Selection scheduled for mid-20022
  - » Readout scheme
    - – Sensitivity analysis in progress, results are weeks-months away
    - – Tests of dc readout: bench-top, Glasgow, 40m tests
  - » Optics modeling
    - – Need to specify requirements for optics production & active thermal compensation: modeling effort underway with FFT and Melody
  - » Subsystem design requirements reviews being scheduled
    - – Suspensions design review scheduled for 20 September
  - » Need to settle on third interferometer design
- Data analysis
  - » Begin working with A Lazzarini to to scope AdLIGO data analysis