Advanced LIGO Systems Design & Interferometer Sensing & Optics

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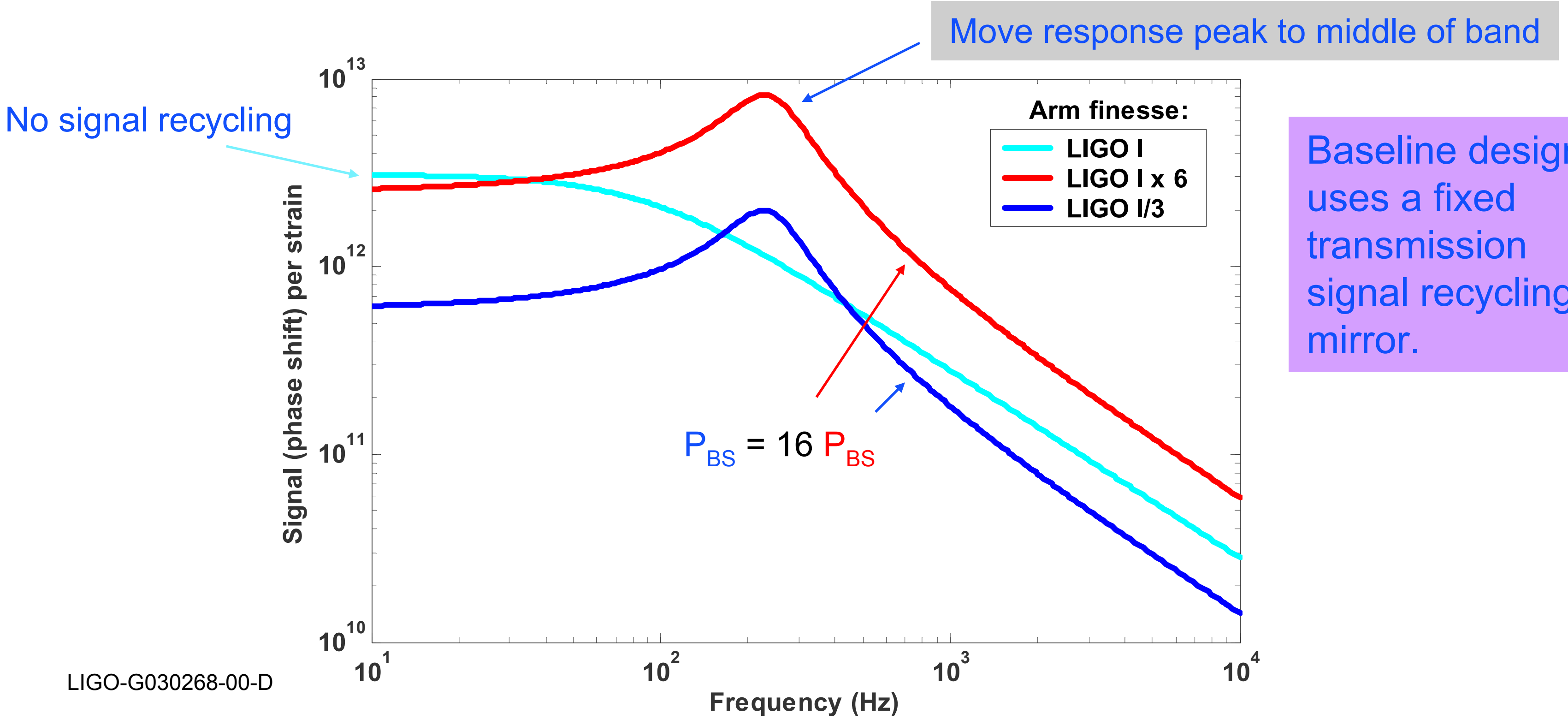
Upgrade approach: arriving at the present design

- 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
- 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

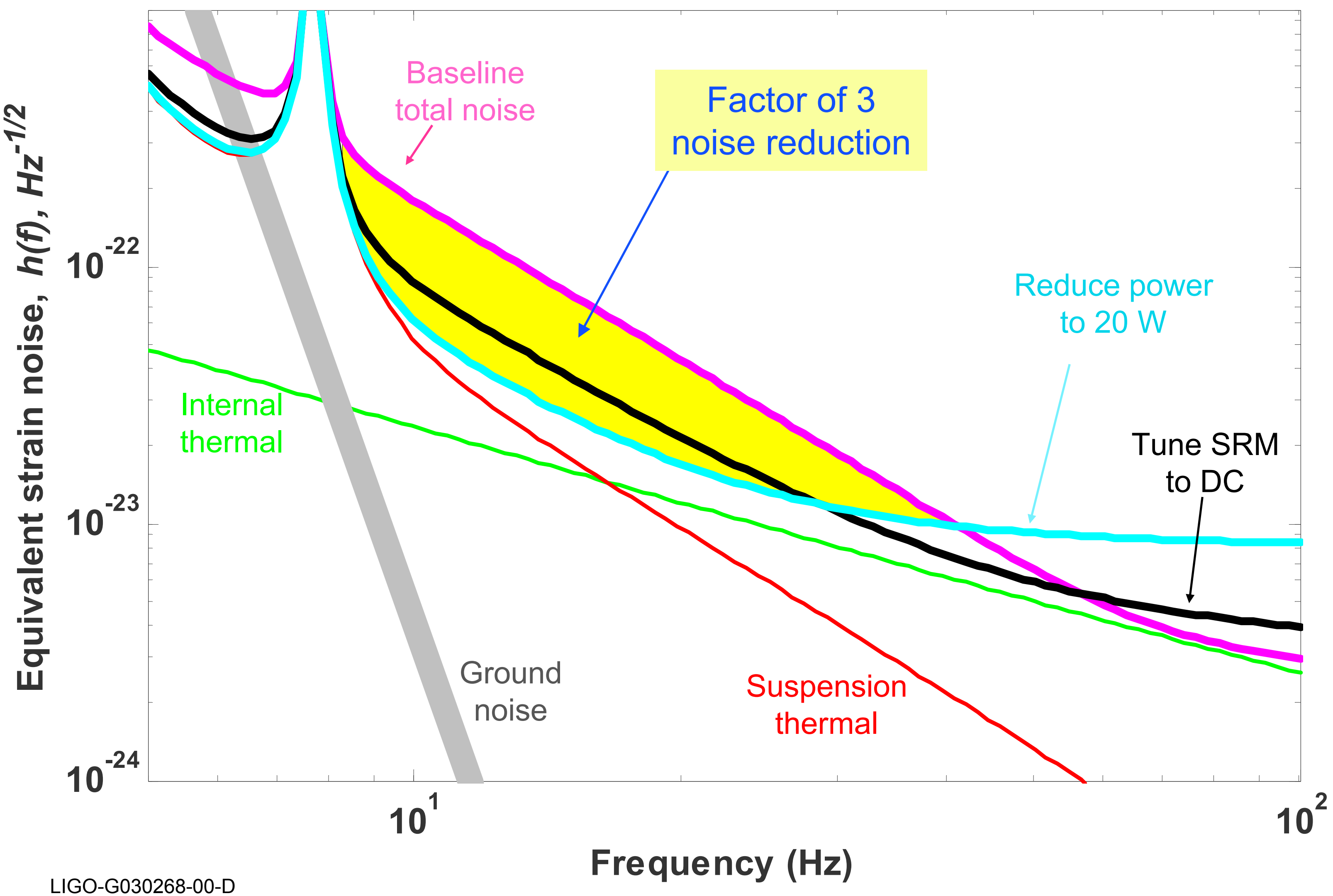
Advantages of Signal Recycling

- ☐ Provides ability to do some shaping of the response, but principal advantage is in power handling:
  - Signal recycled: 200 Mpc NBI range, 2.1 kW beamsplitter power
  - Non-signal recycled, same P_{in}: 180 Mpc range, 36 kW BS power
- ☐ Reduces 'junk light' at anti-symmetric output (factor of ~10)



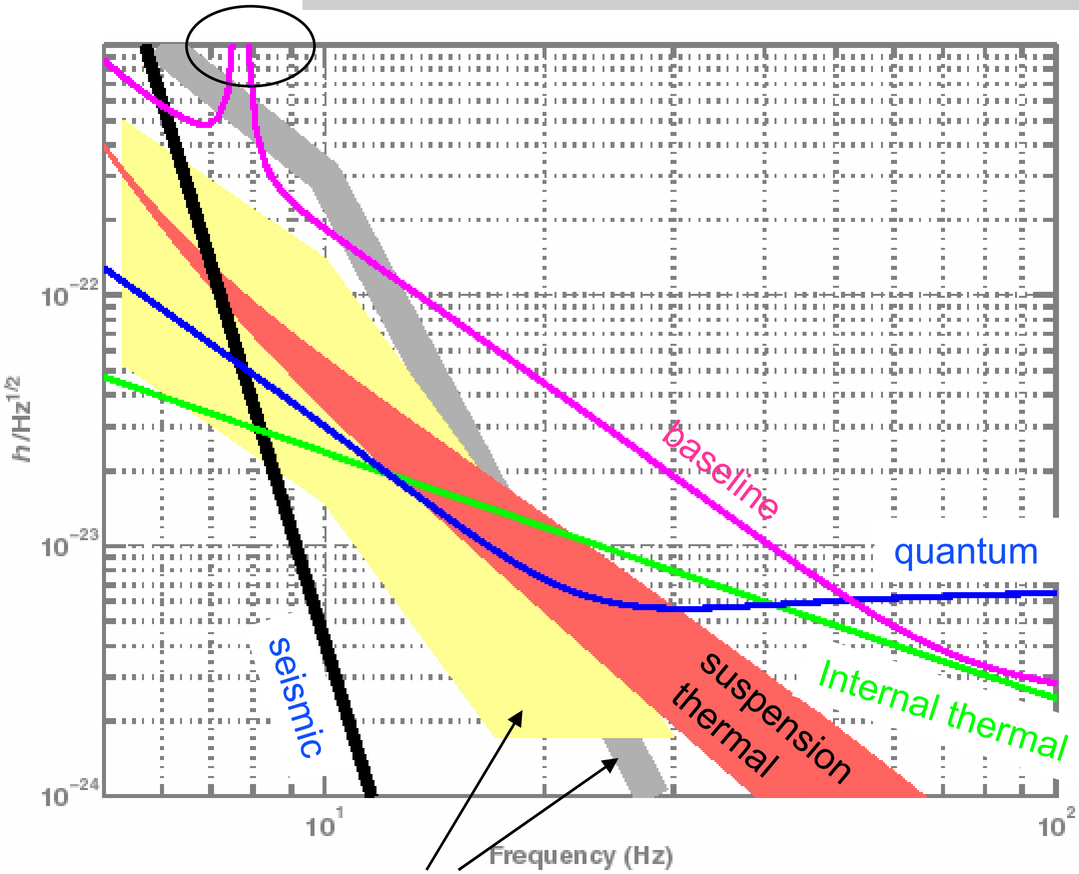
Baseline design uses a fixed transmission signal recycling mirror.

Low frequency mode



Seismic wall frequency

- vertical mode of the suspension's last stage is relatively high: ~10 Hz
- trade-off between horizontal thermal noise and vertical stiffness
- variable cross-section fiber may allow 'dual optimization'
- may be possible to remove vertical mode signal from data w/ signal processing
- gravity gradient noise may dominate below 15 Hz anyway

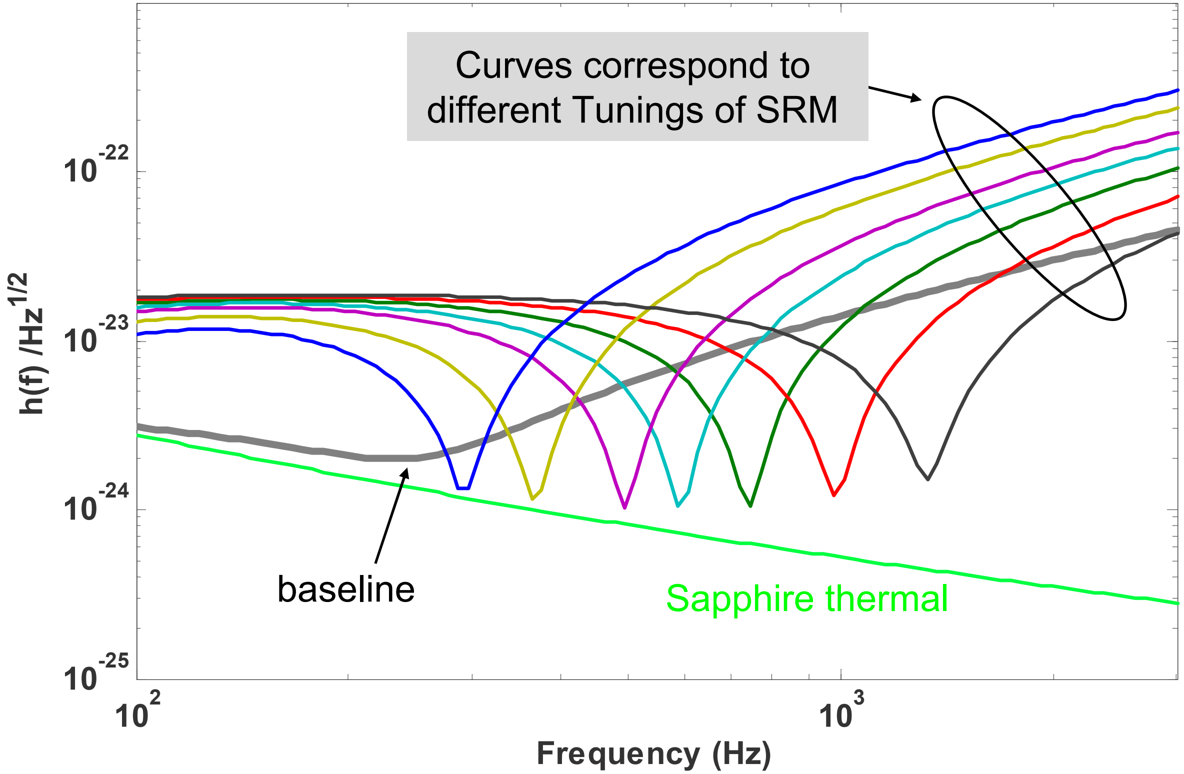


Vertical mode of suspension is allowed to be as high as 12 Hz: doesn't necessarily impose a low frequency detection limit

Gravity gradients

3rd interferometer: option for narrowband, tunable design

- Reasonable performance over 1-2 octaves with a fixed transmission SRM



NS inspiral range is typically ½ that of the baseline design

Bandwidth for a given tuning is approximately 100-200 Hz

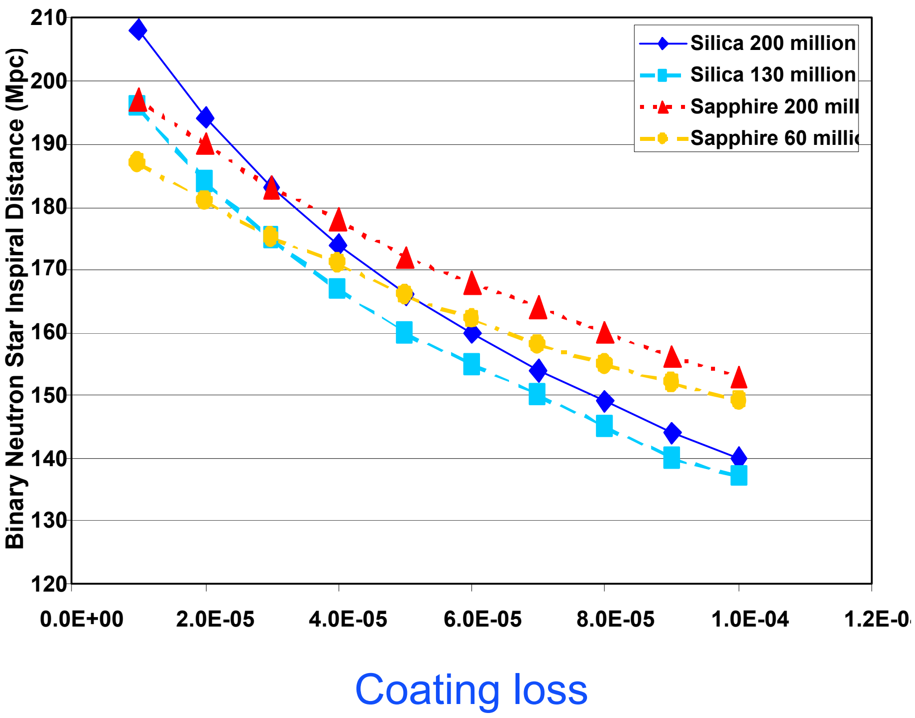
Test mass internal thermal noise

- Dominant noise source from ~60-200 Hz
- Beam size: make as big as possible
  - Bulk thermal noise scales as $w^{-3/2}$ for sapphire, $w^{-1/2}$ for silica
  - Coating thermal noise scales as w^{-1}
  - Beam gaussian radius is 6.0 cm (vs 4.0 in initial LIGO), limited by:
    - Aperture loss in arms
    - Ability to polish very long radii of curvature
    - Attaining polishing uniformity over a larger area
    - Stability of arm cavities against mirror distortions and misalignments
- Bulk loss
  - Sapphire is thermoelastic loss dominated (basic material params)
  - Silica: annealing, glass type → Q= 200 million seen in samples
- Optical coating loss …

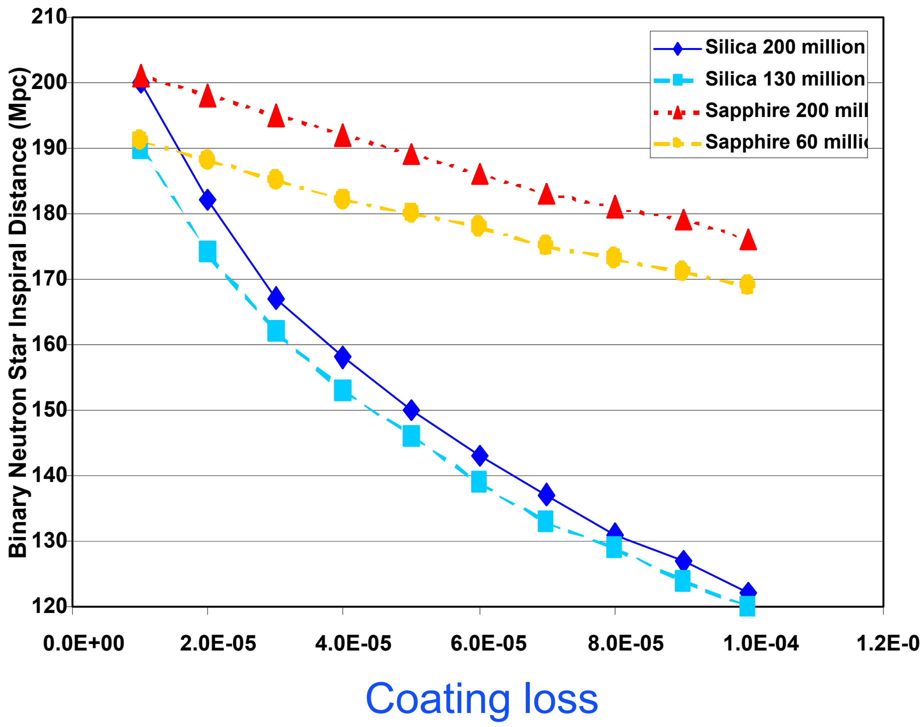
Impact of coating parameters on performance: sapphire & silica substrates

NS-NS binary inspiral range

Coating Young's modulus: 70 GPa



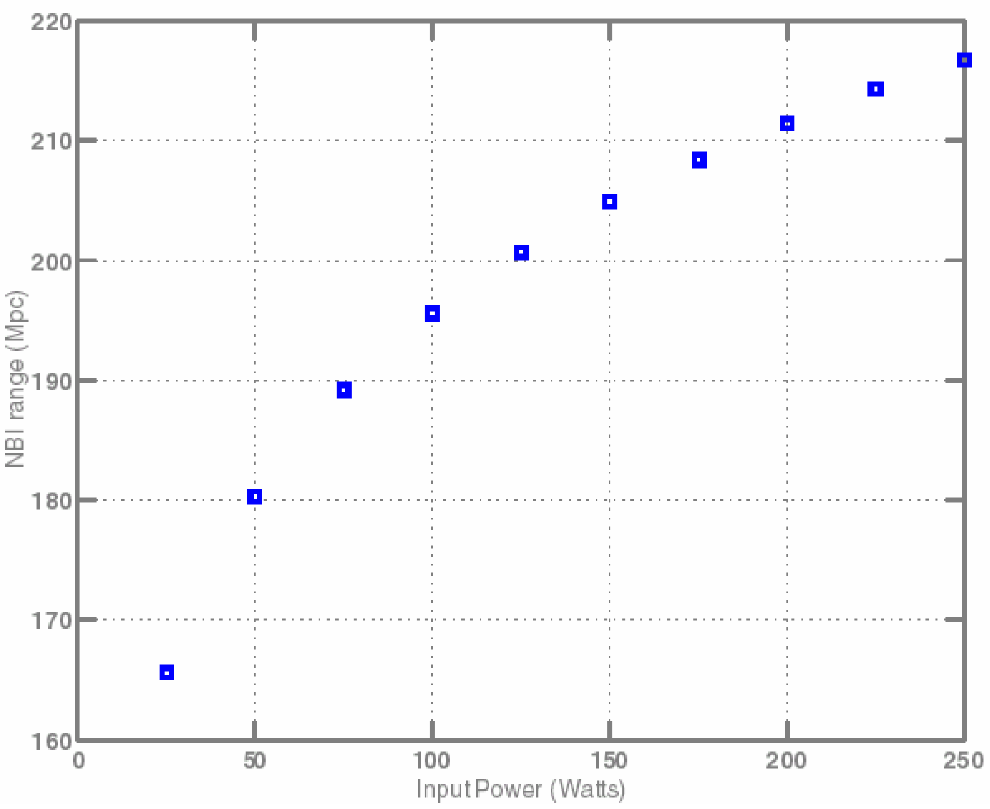
Coating Young's modulus: 200 GPa



Better coating materials needed to retain bulk loss performance!

Pre-stabilized laser reqs & design

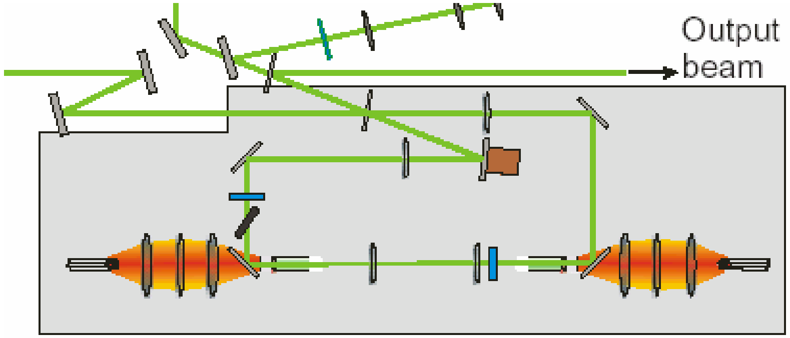
- Main requirement: **high power**
  - **200 W** laser a significant increase over present performance, but should be attainable



laser	PSL	MC
180 W →	165 W →	125 W

Design: *diode-pumped Nd:YAG rod-based oscillator, injection locked with a low-noise master oscillator*

*Developed by LZH: **80W** to date*

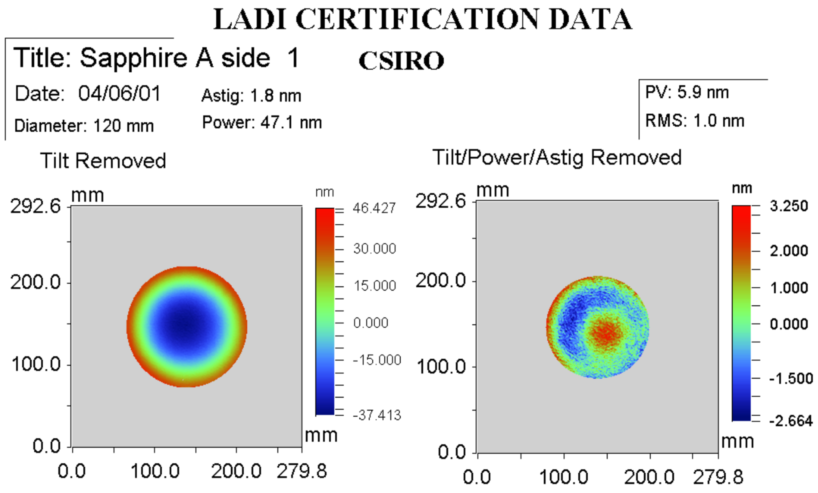


Input Optics: reqs. & design

- Requirements
  - Provide phase modulation for interferometer sensing
    - similar to initial LIGO, but with higher power
  - Beam stabilization: frequency, amplitude, and direction
    - Frequency & direction: similar to initial LIGO, but down to lower frequency
    - Amplitude stabilization: need significant improvement at low frequency due to technical radiation pressure imbalance: RIN = $2 \cdot 10^{-9}/\sqrt{\text{Hz}}$ @10Hz
  - Provide power control & IFO mode matching over a wide range of power
- Conceptual design
  - Electro-optic modulators: new material, RTA, with better power handling
  - Triangular mode cleaner: 7kg mirrors, triple pendulum suspensions
  - High-power, in-vacuum photodetector for amplitude stabilization
  - Compensation of thermal lensing for in-vacuum mode matching
    - Possibly passive or active

Core Optics: optical requirements

- ❑ Polishing uniformity
  - ➢ Allow 20 ppm effective loss per mirror
  - ➢ Requires 0.75-1.2 nm-rms uniformity over central 120 mm diameter
    - – Initial LIGO optics: 1-1.5 nm-rms over central 150 mm diam
  - ➢ CSIRO has polished a 15 cm diam sapphire piece: 1.0 nm-rms uniformity over central 120 mm



LADI CERTIFICATION DATA

Title: Sapphire A side 1

CSIRO

Date: 04/06/01

Diameter: 120 mm

Astig: 1.8 nm

Power: 47.1 nm

PV: 5.9 nm

RMS: 1.0 nm

- ❑ Bulk Homogeneity
  - ➢ Allow 10-20 nm-rms distortion
  - ➢ Sapphire as delivered typically has 50 nm-rms distortion
  - ➢ Compensation techniques
    - – Compensating polish: Goodrich has demonstrated 10 nm-rms
    - – Ion beam etching

- ❑ Coatings, optical properties
  - ➢ Absorption: 0.5 ppm OK, lower would be better: 0.1 ppm goal
  - ➢ Thickness uniformity, 0.1%
  - ➢ ITM transmission matching: 1%

Core optics development

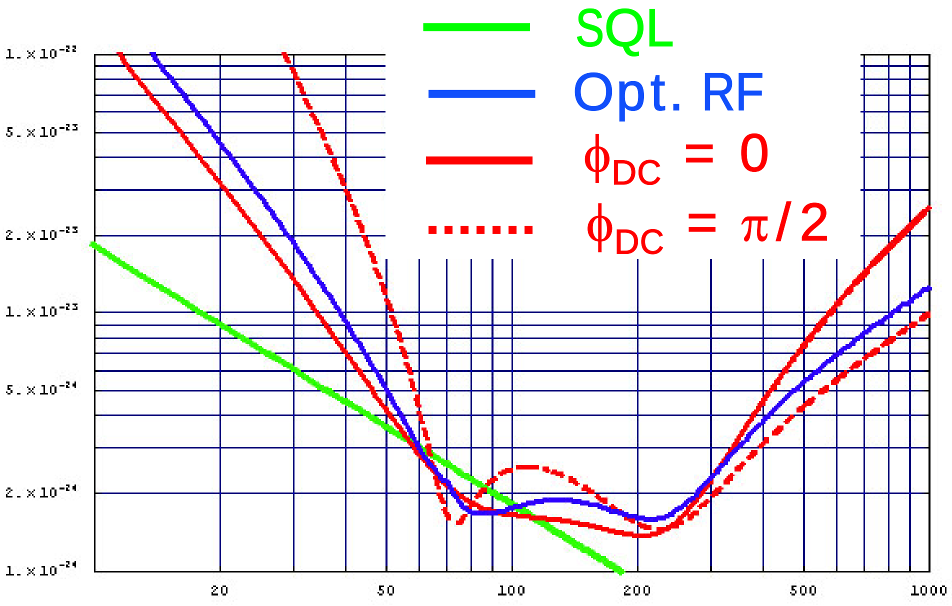
- Sapphire
  - Crystal growth
    - Crystal Systems, Inc., development of 40kg pieces required
    - Have grown ~half dozen 15“ diameter boules
    - Taken delivery of 2 for testing
  - Absorption
    - CSI material typically displays 40-60 ppm/cm absorption
    - Annealing studies at Stanford: 20-30 ppm/cm, small pieces so far
- Fused silica
  - Less material development required
    - Up to 75 kg available, with low-absorption (0.5 ppm/cm) and good homogeneity
  - Mechanical loss of fused silica under intense study

Interferometer Sensing & Control

- Acquire lock of the interferometer
  - Similar problem as initial LIGO, with additional DOF to control (SRM)
  - Locally controlled motion of mirrors should be *much less* (1000x in 1-10Hz band) than in initial LIGO due to active seismic isolation, but …
  - Available force much smaller too
- Control longitudinal and angular DOF to requisite residual levels
  - Lengths: not significantly more stringent than initial LIGO – will be easier due to reduced seismic noise
  - Angles: targeting 10x smaller residual, 10^{-9} radian, to reduce beam jitter noise
  - Must deal with significantly larger radiation pressure
- Provide a low-noise readout of the differential arm strain

GW channel readout

- RF readout, as in initial LIGO, using RF phase modulation of input light, demodulation of detected light
  - Except, with signal recycling, modulation sidebands not balanced at output
  - Leads to extremely stringent req. on phase noise of modulation source
- **DC readout** – baseline design
  - Small offset from carrier dark fringe, by pulling the arm cavities slightly off resonance (~1 pm)
  - Carrier light is the local oscillator
  - Phase is determined by fringe offset + contrast defect field
  - 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 ar RF not critical
    - Quantum-limited sensitivity nearly equal-to-somewhat better than RF



Quantum noise: RF vs DC readout

Output mode cleaner

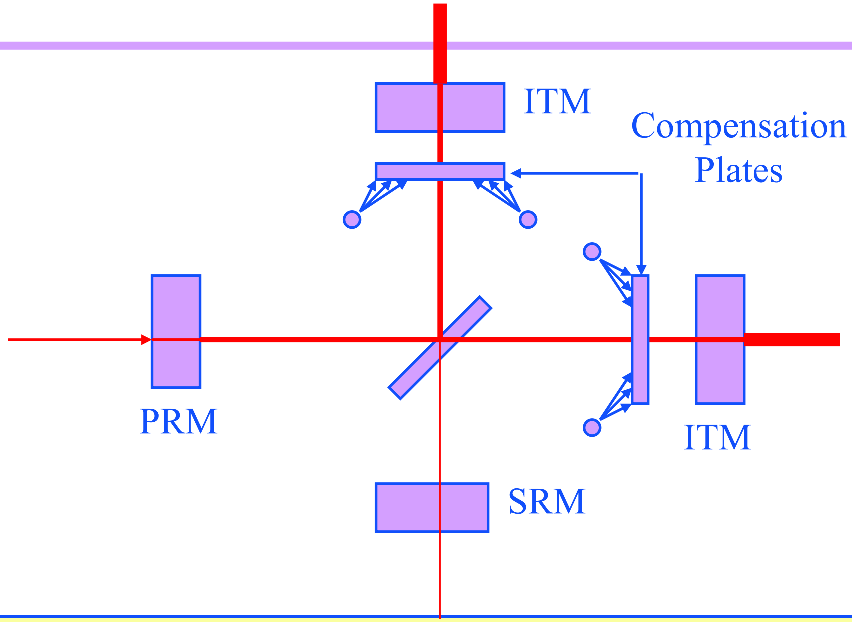
- Reduce the output power to a manageable level
  - 20x higher input power (compared to initial LIGO) leads to 2-3x higher output power
    - 1-3 watts total power w/out a mode cleaner
  - Output mode cleaner leaves only the TEM00 component of the contrast defect, plus local oscillator
    - tens of mW total power w/ mode cleaner
  - Necessary for dc readout scheme
    - Technical laser intensity noise must be controlled
- Conceptual design:
  - Short (~1 m) rigid cavity, mounted in vacuum
  - Modest isolation needs
  - Coupled with in-vacuum photodetector

Core Optic Thermal Compensation

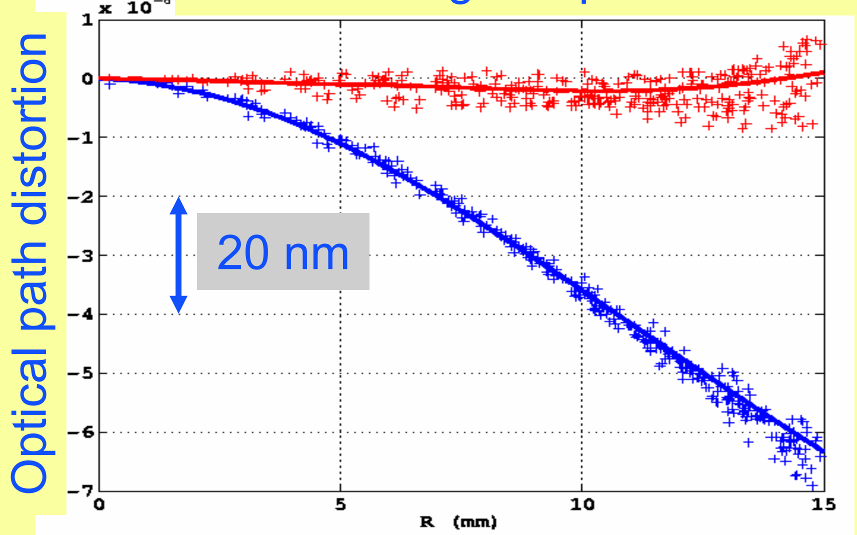
- Thermal loading comparison

Parameter	***Initial LIGO***	***AdL sapphire***	***AdL silica***
Power in bulk material	100 W	2.1 kW	1.3 kW
Power in arms	13 kW	850 kW	530 kW
Total ITM absorbed power	25 mW	350-1600 mW	60-340 mW
ITM optical path distortion	20 nm	20-80 nm	50-300 nm
Required compensation	***Point design***	***10x***	***20-50x***

Thermal compensation design



Shielded ring compensator test



- Design utilizes a fused silica suspended compensation plate
  - No direct actuation on ITMs for greater noise tolerance, simplicity and lower power
- Two actuators:
  - Heater ring close to optic for large scale symmetric corrections
  - Scanned CO_2 laser directed from outside vacuum for small scale asymmetric corrections

Addt’l system level requirements

- ❑ Technical noise sources
  - ➢ Each noise source must be held below 10% of the target strain sensitivity over the full GW band – down to 10 Hz
- ❑ Non-gaussian noise
  - ➢ Difficult to quantify a requirement, but components are designed to avoid potential generation of non-gaussian noise
- ❑ Detector availability – as for initial LIGO
  - ➢ 90% single, 85% double, 75% triple coincidence
- ❑ Environmental sensing
  - ➢ Initial LIGO PEM system basically adequate, some sensor upgrades possible
- ❑ Data acquisition
  - ➢ Same sample rate and timing requirements as initial LIGO
    - – 16 bit ADCs still adequate for dynamic range
  - ➢ Large number of additional channels due to increase in controlled DOF