Research and Development for Advanced LIGO

Aspen winter conference

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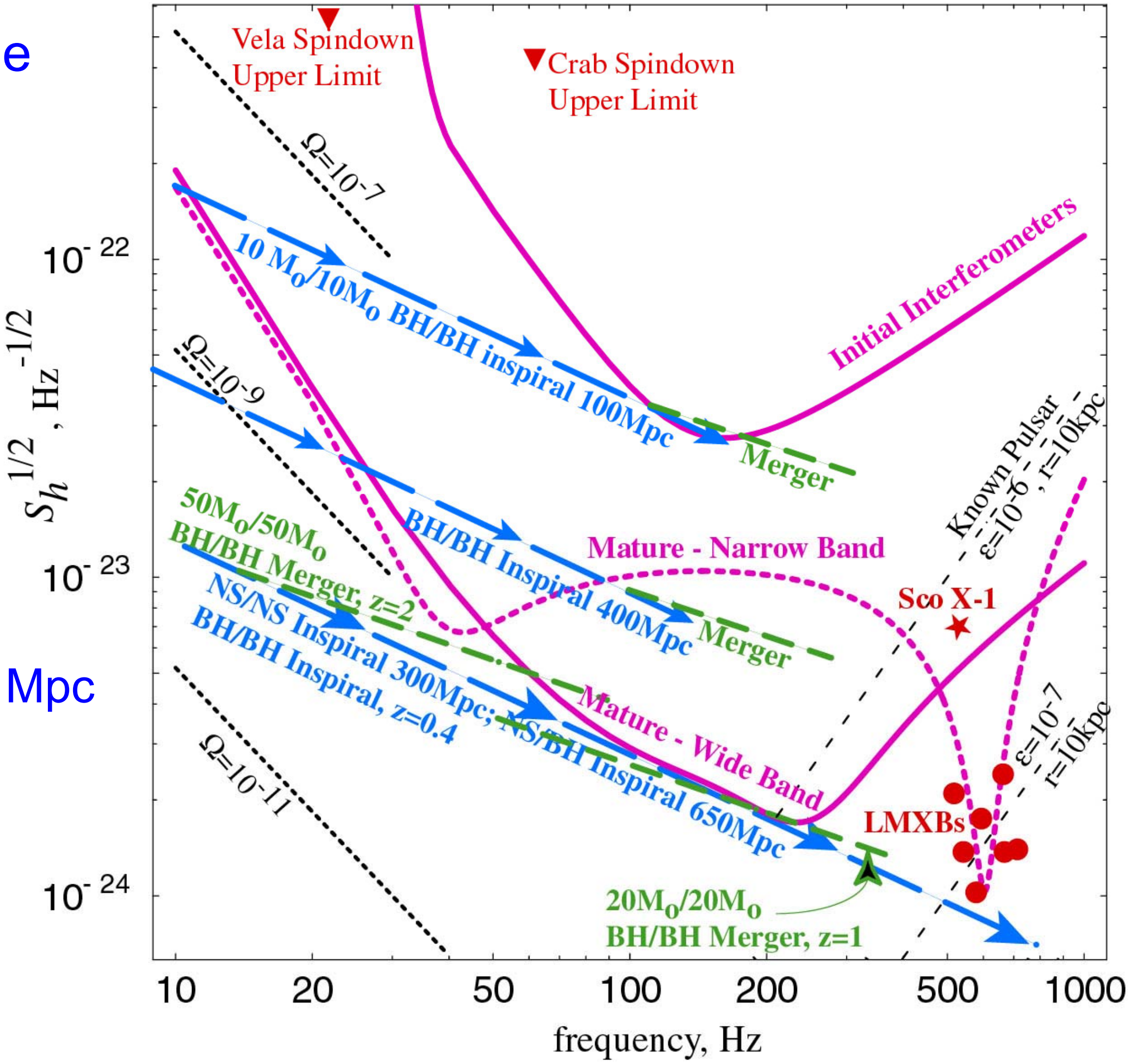
and the LSC collaboration

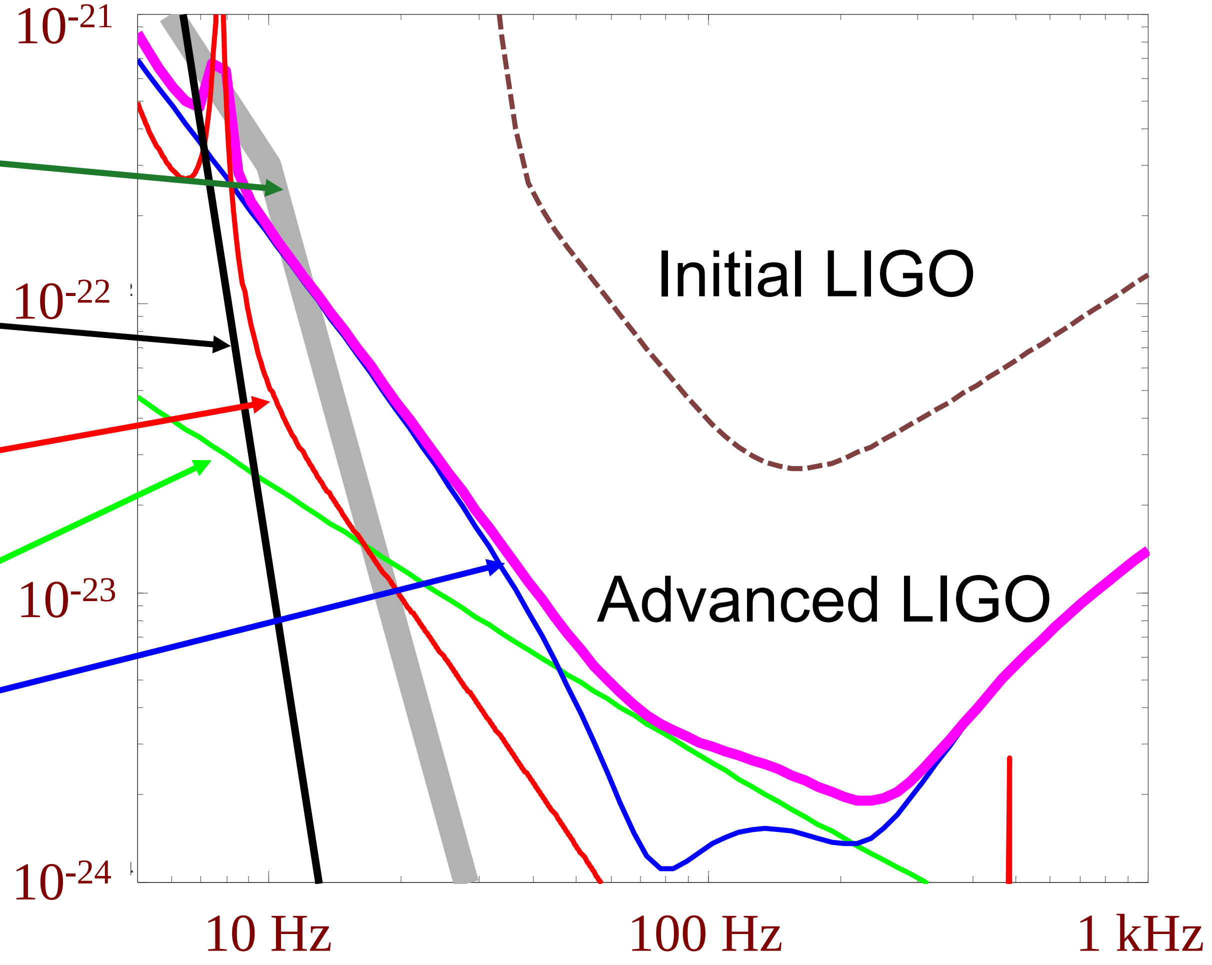
Initial and Advanced LIGO

- Factor 10 better amplitude sensitivity
  - (Reach)^3 = rate
- Factor 4 lower frequency bound
- NS Binaries: for three interferometers,
  - Initial LIGO: ~20 Mpc
  - Adv LIGO: ~300 Mpc
- BH Binaries:
  - Initial LIGO: 10 M_o, 100 Mpc
  - Adv LIGO : 50 M_o, z=2
- Stochastic background:
  - Initial LIGO: ~3e-6
  - Adv LIGO ~3e-9

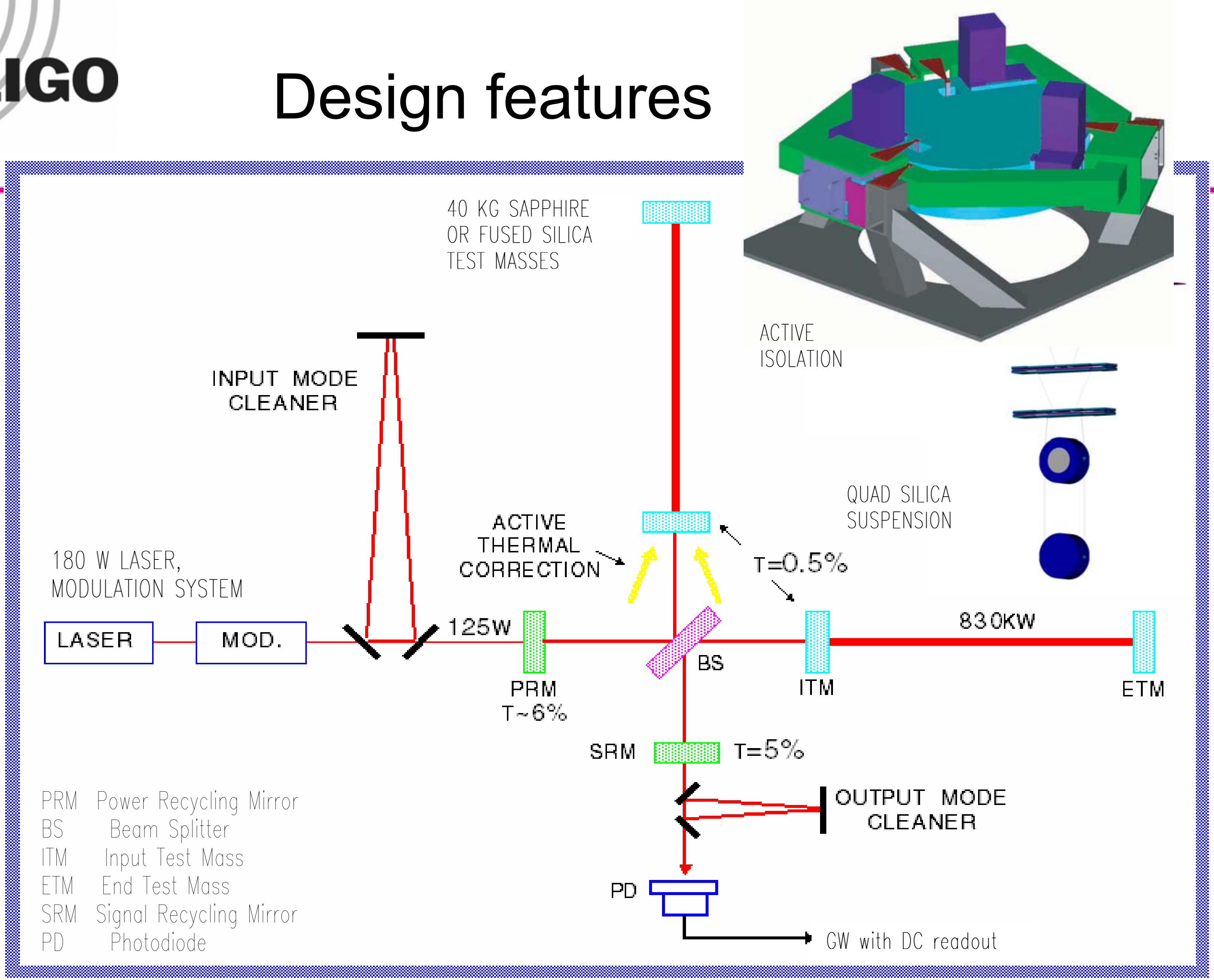


Anatomy of the projected Adv LIGO detector performance

- Newtonian background, estimate for LIGO sites
- Seismic ‘cutoff’ at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Unified quantum noise dominates at most frequencies for full power, broadband tuning

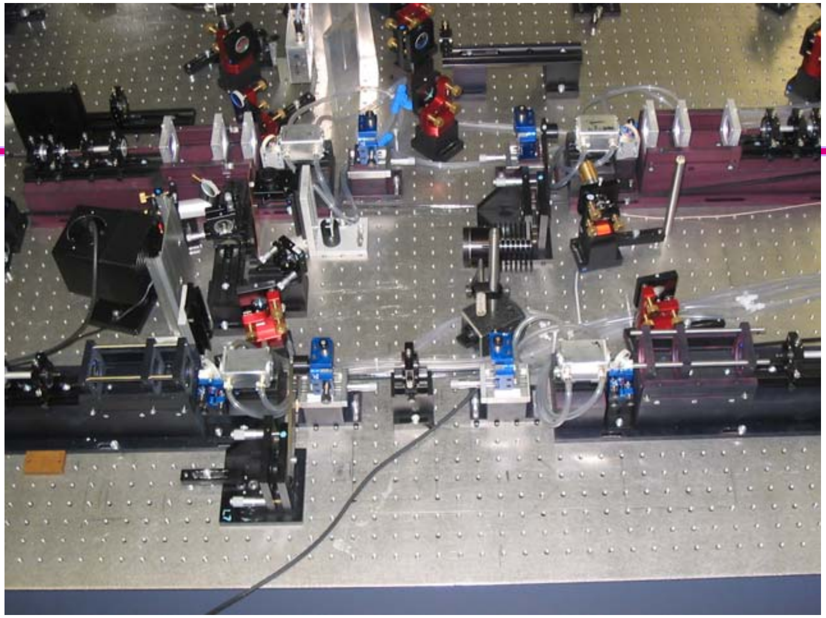


Design features

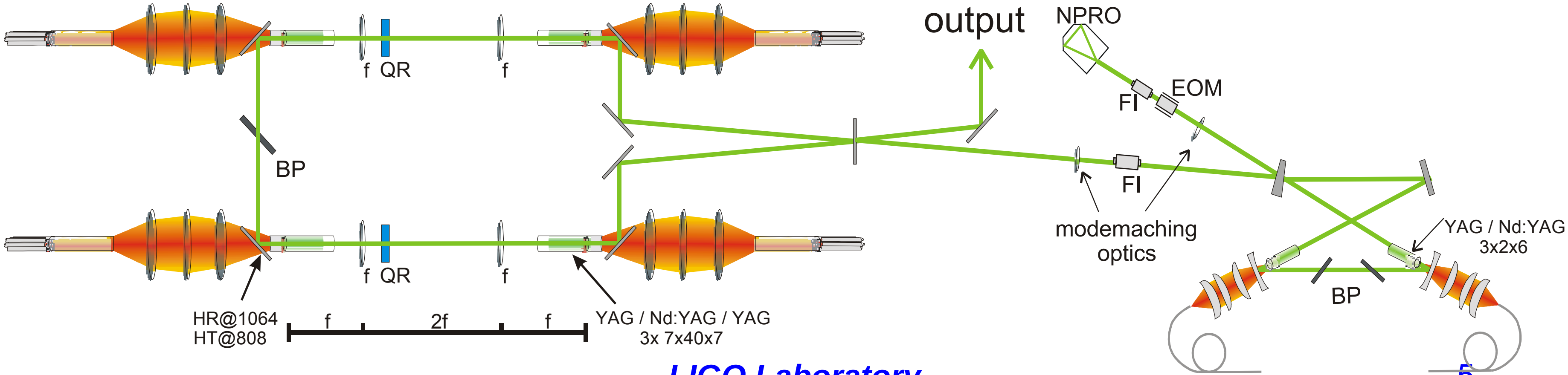


PRM	Power Recycling Mirror
BS	Beam Splitter
ITM	Input Test Mass
ETM	End Test Mass
SRM	Signal Recycling Mirror
PD	Photodiode

Pre-stabilized laser



- Requirements: 180 W at output of laser
- Frequency stabilization
  - 10 Hz/Hz$^{1/2}$ at 10 Hz required
  - 10 Hz/Hz$^{1/2}$ at 12 Hz seen in initial LIGO
- Intensity stabilization
  - 2x10^{-9} ΔP/P at 10 Hz required
  - 2003: 1x10^{-8} at 10 Hz demonstrated
- 2004: Full injection locked master-slave system running, 200 W, linear polarization, single frequency, many hours of continuous operation (LZH, AEI)



High Power Slave

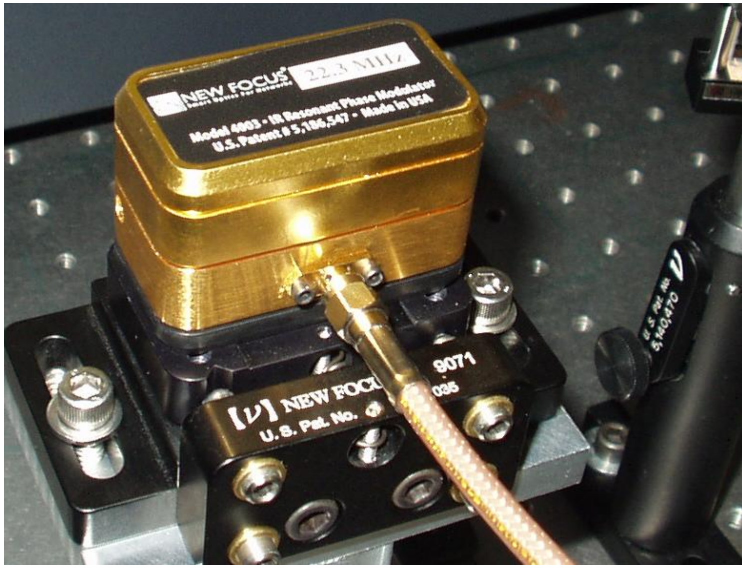
20 W Master

Input Optics

- Provides phase modulation for length, angle control
- Stabilizes beam position, frequency with suspended mode-cleaner cavity
- Matches into main optics (6 cm beam) with suspended telescope

- Design similar to initial LIGO but 20x higher power
- Challenges:
  - » Modulators
  - » Faraday Isolators

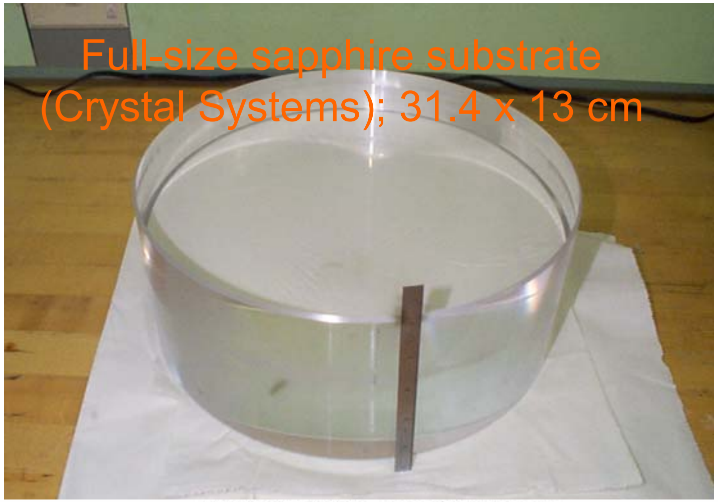
- 2004: Prototype RTP modulator – UF/New Focus
  - » 4 mm clear aperture
  - » 90W, 700 micron beam
  - » RFAM < 10-5
  - » Some anticipated lensing, but no evident damage



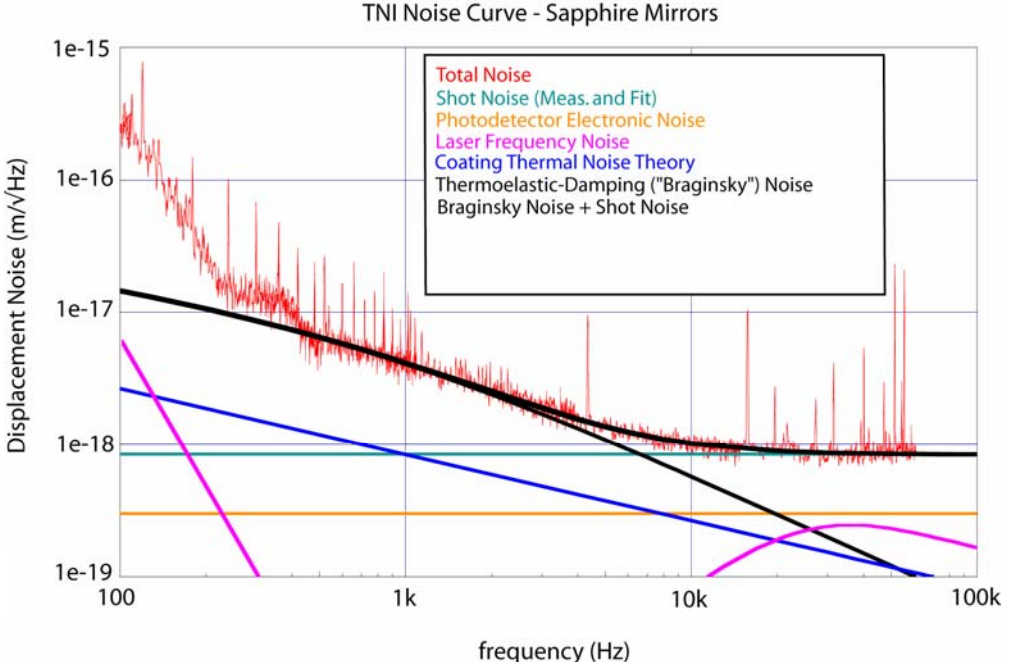
- Faraday Isolator
  - » 10 mm FI being tested at LZH – ok at 120 W!

Core optics / Sapphire

- Low mechanical loss, high Young's modulus, high density, high thermal conductivity
  - » Highest Q measured at >250 million
- Higher thermoelastic noise, inhomogeneous absorption
  - » Average level ~60 ppm, 40 ppm desired
  - » Variations large, relatively abrupt, 10-130 ppm
- Thermoelastic noise
  - » Significant in Sapphire, negligible in Fused Silica
- Elegant direct measurements at Caltech confirm model; follow up by Japanese group also agrees

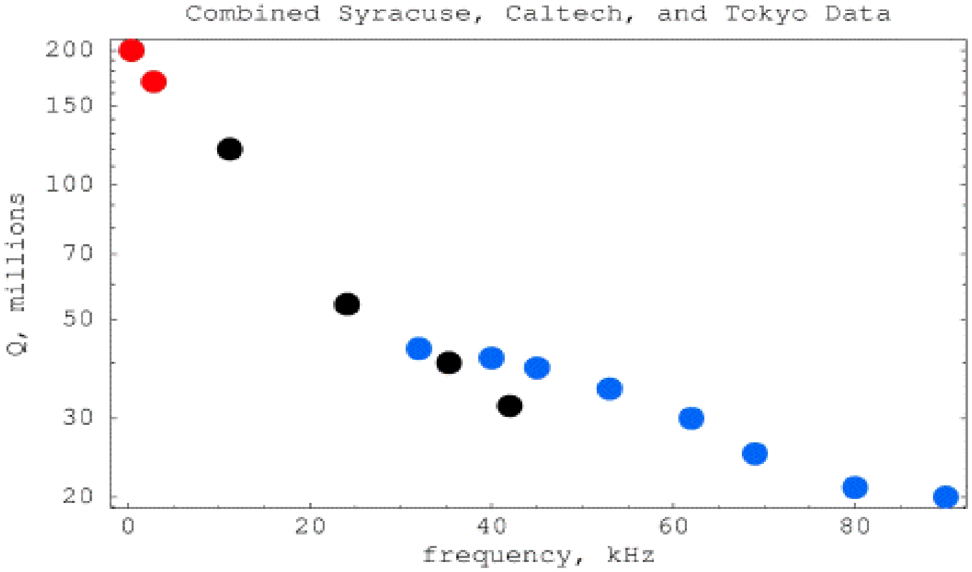


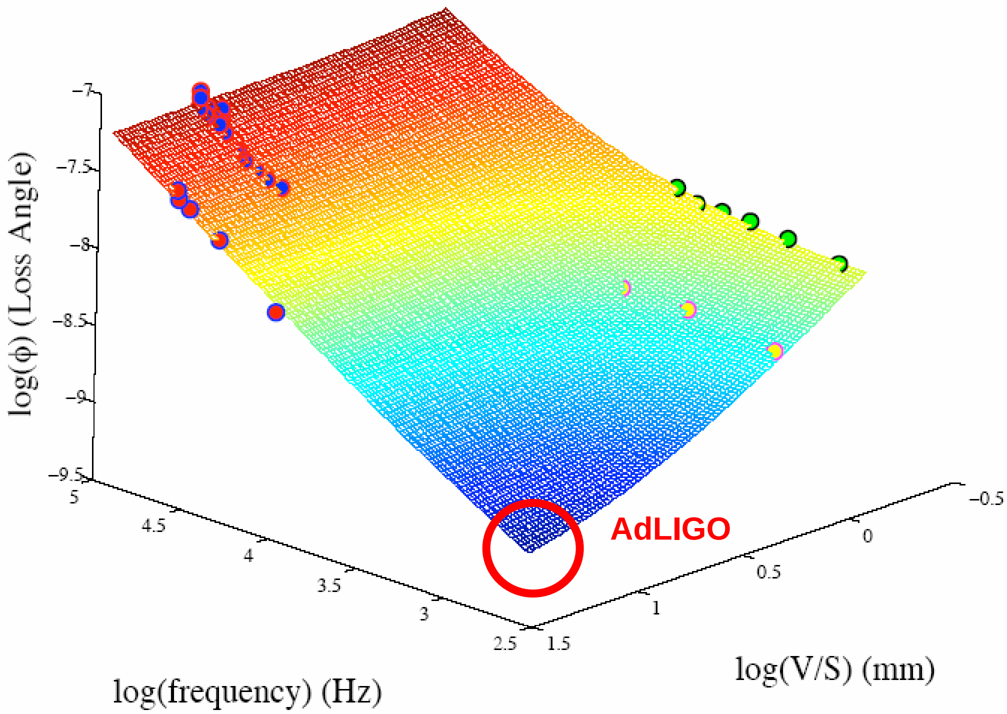
Full-size sapphire substrate (Crystal Systems); 31.4 x 13 cm



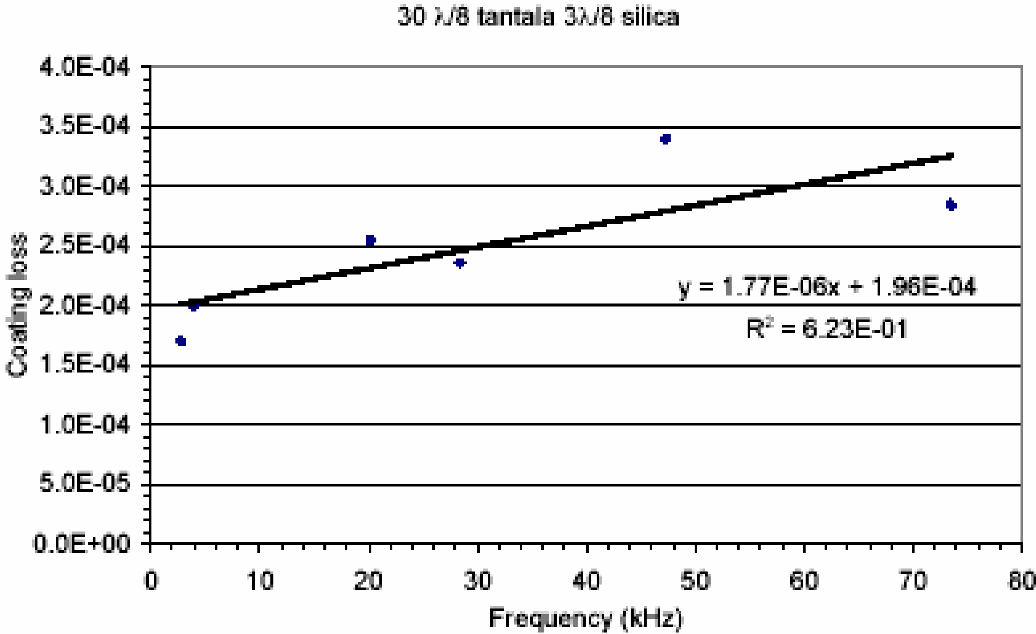
Core optics / Fused Silica

- Fused Silica is the 'traditional' material
- Production of 40 kg pieces with absorption, homogeneity
- Familiar; fabrication, polishing, coating processes well refined
- Development program to reduce mechanical losses, understand frequency dependence
  - » Annealing proven on small samples, needs larger sample tests
- Assembly of available data of Q vs. Freq, volume/surface
  - » Consistent with theory for relaxation process in silica





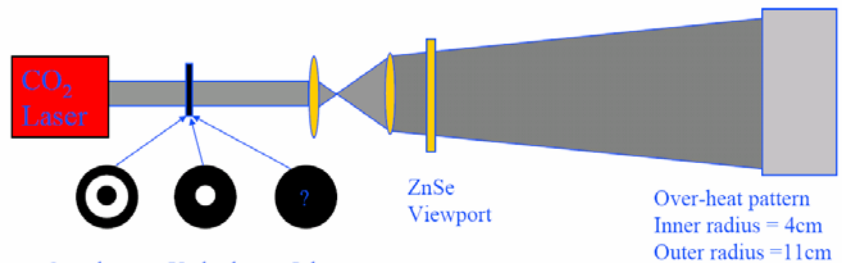
Test mass coatings: Thermal noise

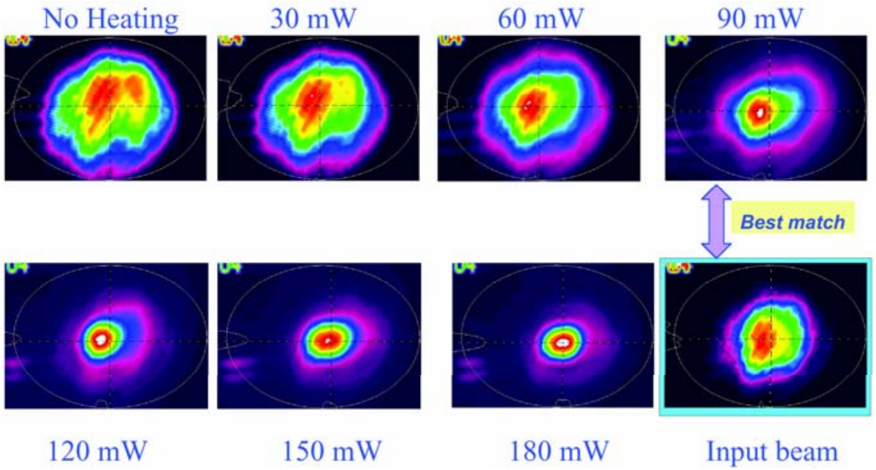


- Evidence of frequency dependence of coating mechanical loss
- Increasing Titania dopant reduces mechanical loss (LMA)
  - » So far, loss 2.7 10^{-4} → 1.6 10^{-4} ;
- Secondary ion-beam bombardment reduces loss (CSIRO)
  - » So far, loss 4.4 10^{-4} → 3.2 10^{-4}
- Both approaches still require tests for optical properties, optimization, checks if compatible and if both work at lower losses
- Seems likely that we can approach goal of 5 10^{-5} with such incremental improvements

Active Thermal Compensation

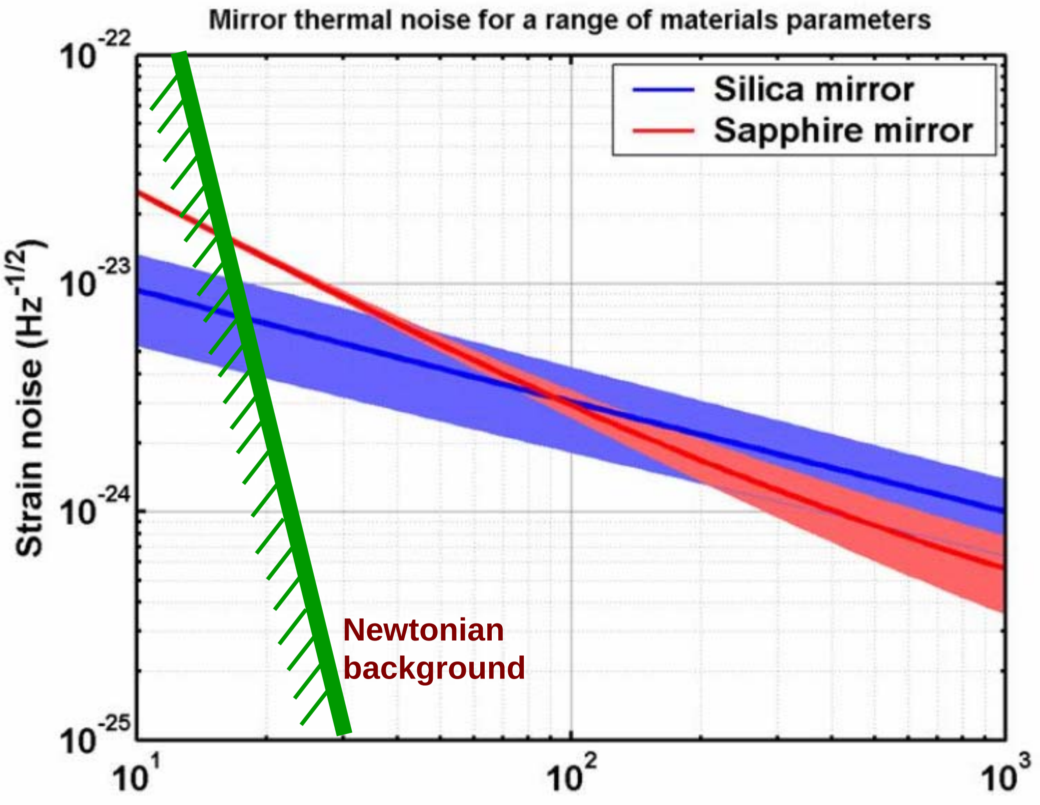
- Removes excess ‘focus’ due to absorption in coating, substrate
- Allows optics to be used at all input powers
- 2004: Successful application to initial LIGO using new ‘staring’ approach
- Modeling, investigating effect on sidebands and point absorbers
  - » Silica and Sapphire behave differently due to thermal expansion, thermal conductivity differences;
  - » Some (dis)advantages for each, with Silica better on balance for ‘clean’ coatings





Test Mass downselect

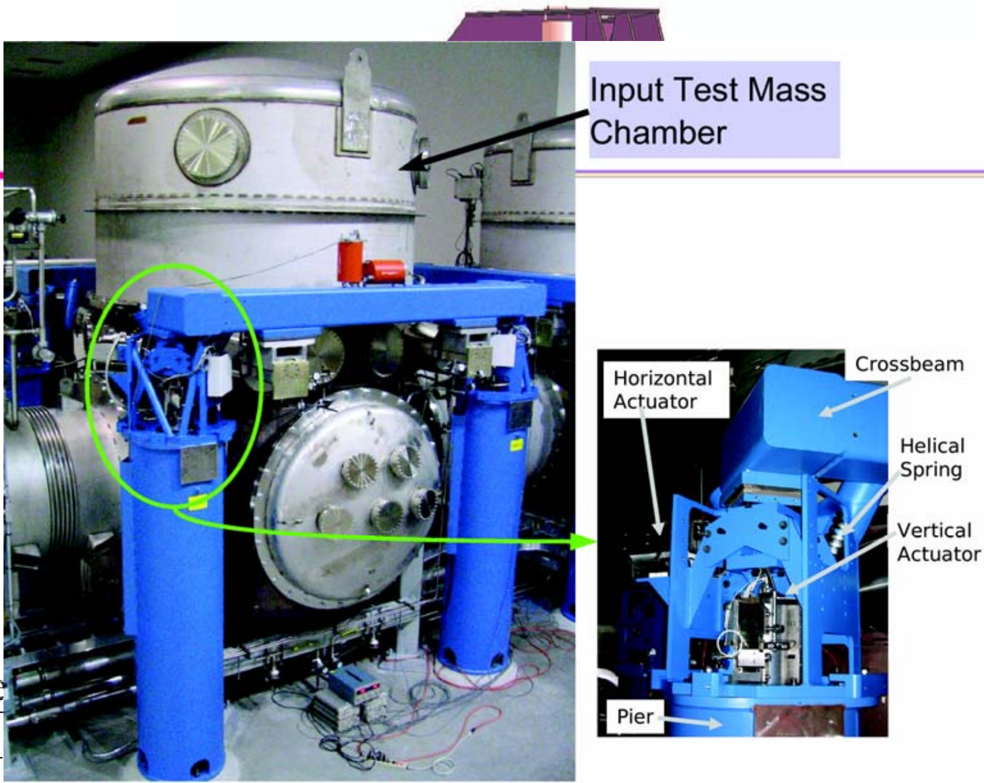
- Astrophysics advantages for both substrates
- Risks in production greater for sapphire
- Recent new ingredient: thermal compensation
- Basic suspension design could accommodate either substrate
- Recommendation this month

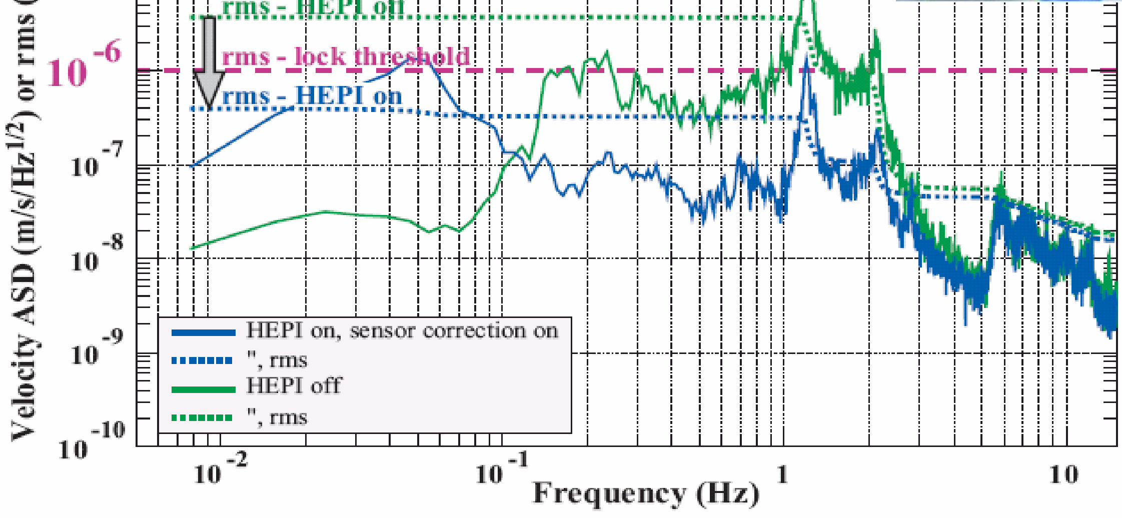

Mirror thermal noise for a range of materials parameters

		pessimist - baseline - optimist
NS-NS	sapphire	165 - 191 - 208
Mpc	silica	153 - 191 - 254
10Ms BHBH	sapphire	762 - 923 - 1016
Mpc	silica	775 - 1052 - 1510
XRB, 730 Hz	sapphire	9.6 - 6.8 - 4.5
x10^-25	silica	16 - 12 - 7.2
Stochastic	sapphire	1.7 - 1.7 - 1.6
x10^-9	silica	1.9 - 1.2 - 1.1

Isolation: HEPI

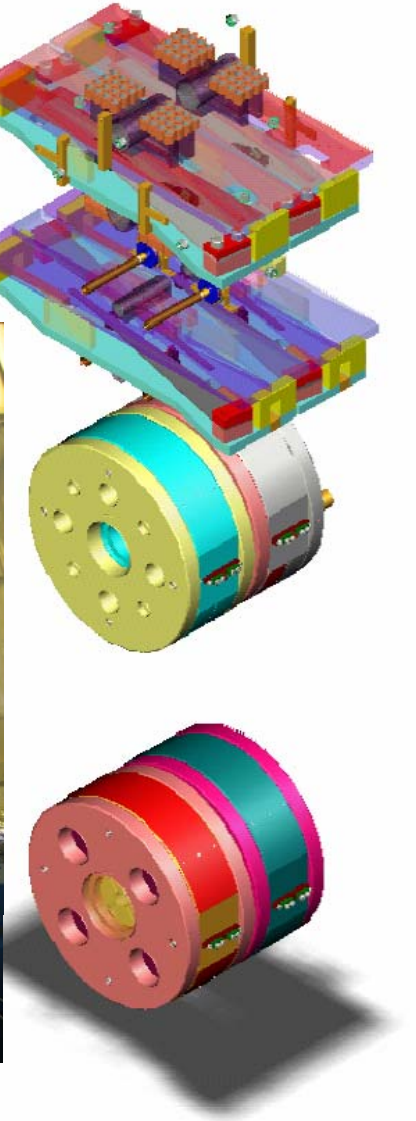
- 2004: External pre-isolator installed, in commissioning at Livingston
  - » System performance meets initial needs
  - » Exceeds Advanced LIGO requirements
  - » Livingston interferometer locks during day and through train transits





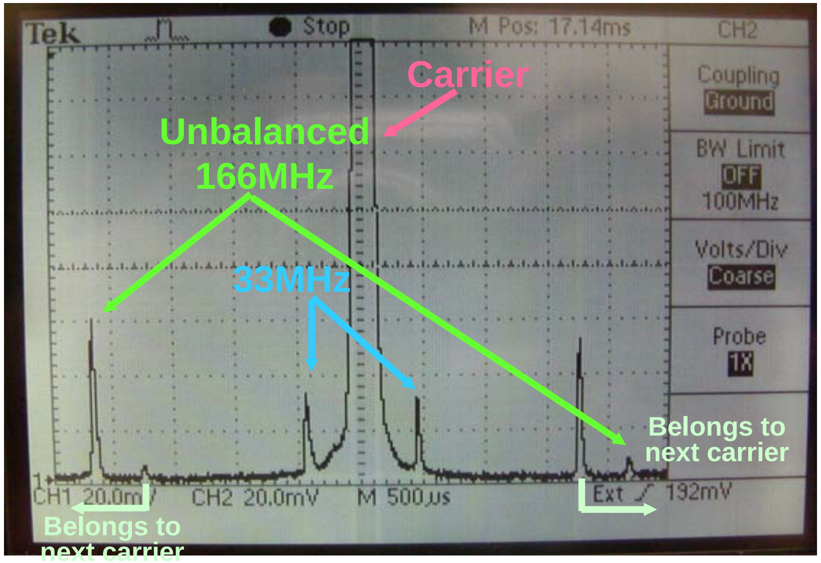
Suspensions

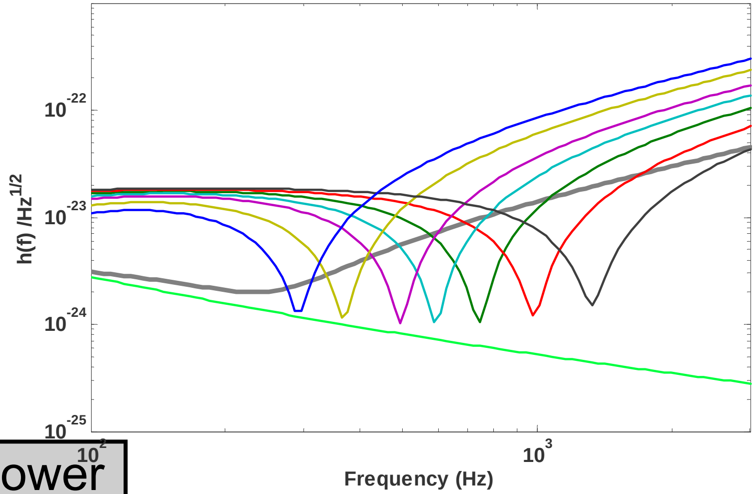
- Quadruple pendulum design chosen
  - Fused silica fibers, bonded to test mass
  - Leaf springs (VIRGO origin) for vertical compliance
  - Quad lead in UK; U Glasgow, Birmingham, Rutherford
- Detailed design underway
  - ‘Mass catcher’ frame
  - Interface with Seismic Isolation
  - Finite element modeling
- Triple suspensions for auxiliary optics
  - Relaxed performance requirements
- 2004: Mode Cleaner suspension installed in LASTI full-scale testbed
- Uses HEPI as ‘shake table’ for excitation
- Characterization of modes, isolation match model nicely



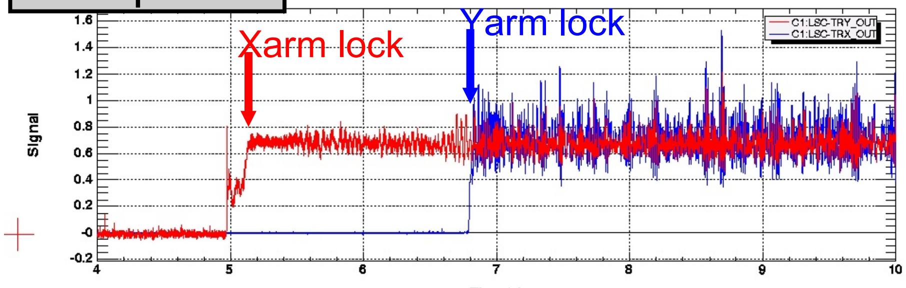
GW readout, Systems

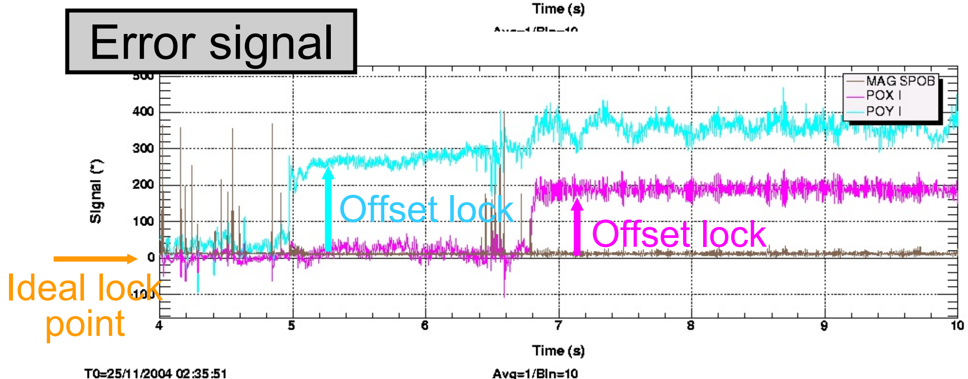
- 2004: Caltech 40m prototype giving guidance to design
  - » Exploring modulation techniques; adoption of Mach-Zehnder design to avoid ‘sidebands on sidebands’
  - » Off-resonant arm lock with Dual-recycled Michelson





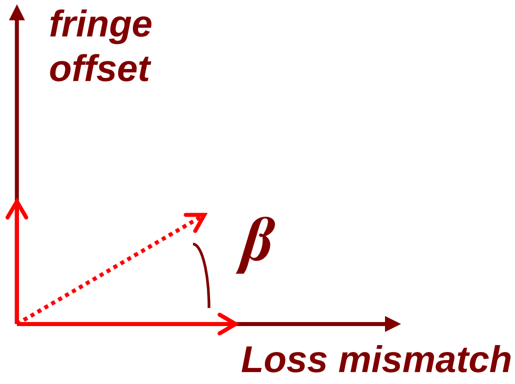
Arm power



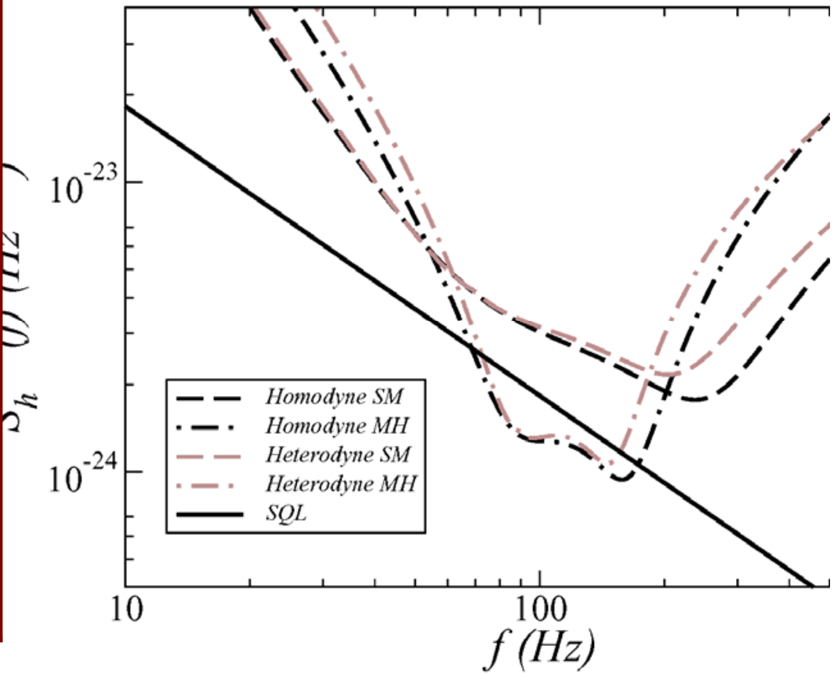


GW readout, Systems

- DC rather than RF for GW sensing
  - » Requires Output Mode-Cleaner to reject RF
  - » Offset ~ 1 picometer from dark fringe can tune from 0 to 80 deg with 0-100 mW of fringe offset power



Noise Source	*RF readout*	*DC readout*
Laser frequency noise	~10x more sensitive	Less sensitive since carrier is filtered
Laser amplitude noise	Sensitivity identical for frequencies below ~100 Hz; both driven by technical radiation pressure	
	10-100x more sensitive above 100Hz	Carrier is filtered
Laser pointing noise	Sensitivity essentially the same	
Oscillator phase noise	-140 dBc/rtHz at 100 Hz	NA



Baseline plan

- Initial LIGO Observation at design sensitivity 2005 – 2010
  - Significant observation within LIGO Observatory
  - Significant networked observation with GEO, VIRGO, TAMA
- Structured R&D program to develop technologies
  - Conceptual design developed by LSC in 1998
  - R&D progressing toward Final Design phase
- 2004: NSB recommends Advanced LIGO for funding consideration
- 2007: First (possible) funds arrive
  - Test Mass material, seismic isolation fabrication long leads
  - Prepare a ‘stock’ of equipment for minimum downtime, rapid installation
- 2010: Start initial decommissioning/installation
  - Baseline is a staggered installation, Livingston and then Hanford
- 2013: Coincident observations
  - At an advanced level of commissioning