LIGO Interferometers

LIGO PAC Meeting

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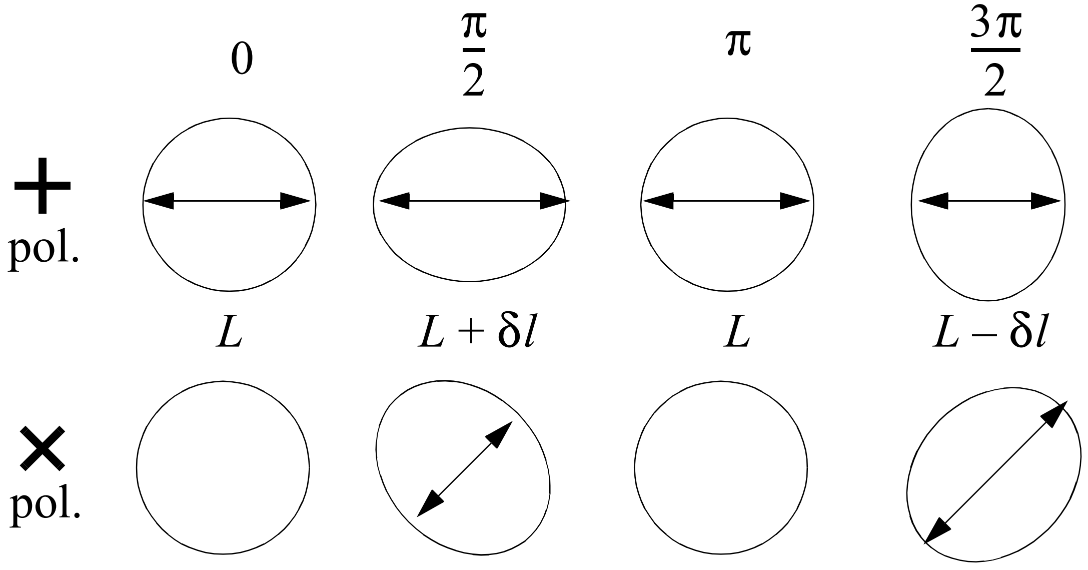
Organization of presentation

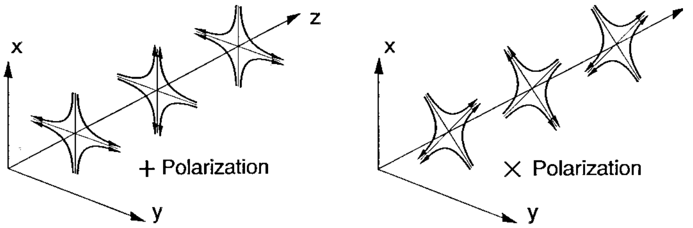
- fundamentals of the detection mechanism
- limitations to sensitivity
- overview of previous and ongoing R&D for the *initial* ifo
- the initial LIGO interferometer configuration and performance
- status and schedule for initial detector implementation

Basis of the detection

Assume General Relativity

- wave is transverse, like radio waves
- propagates at speed of light
- two polarizations are at 45^{O}
- passing GW leads to change in proper distance $\delta l \approx \left(\frac{1}{2}h(t)\right)L$ between points of initial separation L





This is the key for the detection of GWs.

Characteristics of radiative process

Lowest order radiation term: quadrupole

- wavefield proportional to $\ddot{Q}$, second derivative of quadrupole
- or, non-spherical part of kinetic energy
- dimensional analysis leads to $h \approx \frac{G}{c^4}\frac{\ddot{Q}}{r}$
- $G/c^4 = 10^{-33}$ (MKS), numerically very small

One way to get BIG quadrupoles: disrupt stars

- one solar mass at the Virgo Cluster (15 Mpc, ~50 million light years) could become a supernova with some asymmetry ε
- $h \approx 10^{-20}\left(\frac{E_{\text{non-sphere, kinetic}}}{M_o c^2}\right)\left(\frac{15\text{Mpc}}{r}\right)$
- or, circle of pearls 1m in diameter would change by $\varepsilon \cdot 10^{-20}$ m.

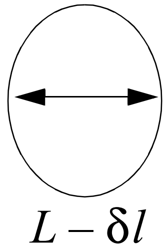
Coalescing Compact Binaries

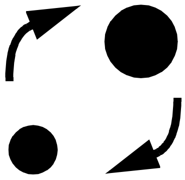
Standard candle: Binary stars

- Taylor-Hulse Binary 1913+16 shows clear spin-up
- almost certainly due to GW radiation at present 8h period
- later in life (10^8 yr.), period shortens to audio frequencies
- spends ~1 minute in frequency range from ~30 Hz-1 kHz
- our detector will target this frequency range.

for most of life, waveform well known if masses known

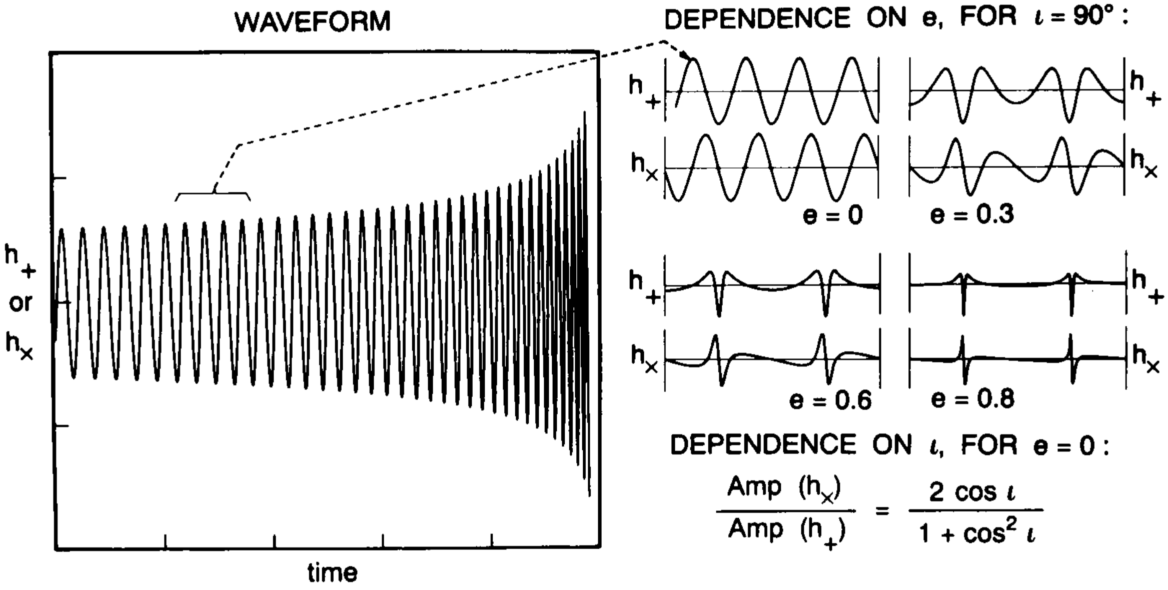
- allows calculation of signal amplitudes, optimal filters
- end of life (coalescence) yet to be calculated (measure first?)
- typical number: $h \approx 10^{-21}$ for 1.4 M_o, 200 Mpc, ~3 events/yr.
- since $h = \delta l / L$, expect $\delta l = 10^{-21}$ m for $L = 1$ m

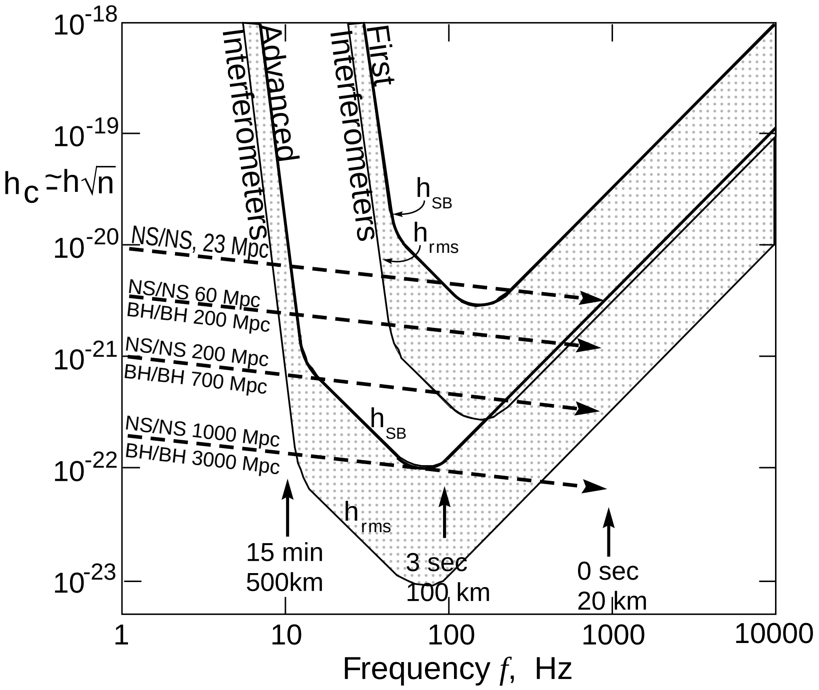




Coalescing Compact Binaries

Waveforms of final minutes, for various ellipticities



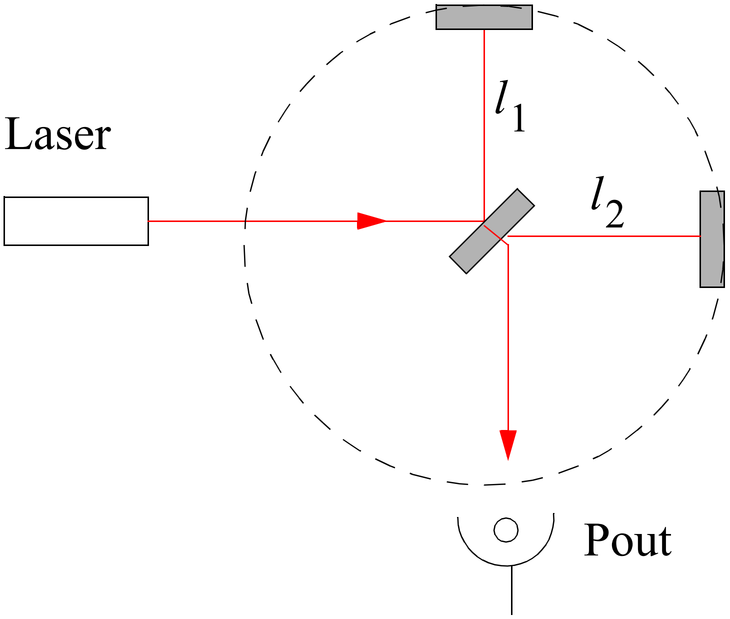


Spectral representation, with LIGO sensitivity curves

Basic principle of detection

Laser Interferometry

- basic sensing mechanism: a Michelson Interferometer



- GW strain induces differential length changes in arms
  - › proportional to arm length, up to fraction of GW wavelength
- lengths are measured using light beams and ‘free masses’

Realistic interferometer not so simple

- will explore limitations to understand initial LIGO design

Principal limitations to sensitivity

Limitations in sensing the position of the test masses

- shot noise
  - › (photon momentum transfer to the test masses)
- scattered light losses and parasitic interferometric effects
- fluctuations in the optical path due to residual gas

→ beam tube vacuum system

Motions of the test masses

- seismic noise - a good ‘engineering’ problem
- thermal noise - a hard materials problem coupled with art
- gravity gradients - probably inescapable

→ km-long arms to make δl large compared with motions

→ seismically quiet, isolated sites

...and, no less important,

Configuration and Control Issues

- acquisition of operating lengths
- closed-loop control of lengths
- closed loop control of angles

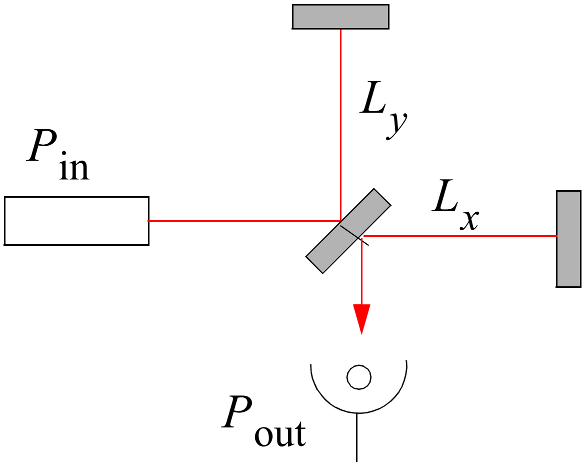
Shot noise

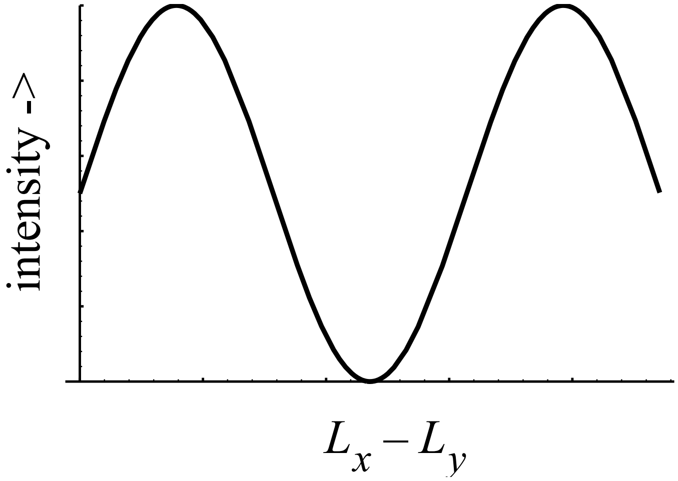
Required: Ability to sense the phase to 1 part in 10^{10}

- intensity at ifo output is a function of arm length difference:

$$(P_{\text{in}}/2)(1+\cos 2k(L_x - L_y));(L_x - L_y) = h(t)L$$

- maximum slope: $\frac{dP}{d\delta l} = \frac{2\pi}{\lambda}P_{\text{in}}$
- uncertainty in intensity due to counting statistics: $\tilde{p}_{\text{out}} = \sqrt{\frac{h_{\text{Pl}}\omega}{P_{\text{in}}}}$
- can solve for equivalent strain: $h_{\text{shot}} = \frac{\delta l}{L} = \frac{1}{L}\sqrt{\frac{h_{\text{Pl}}c\lambda}{2\pi P_{\text{in}}}}$
- Note: scaling with $1/\sqrt{P_{\text{in}}}$





Quantum Noise

Radiation Pressure

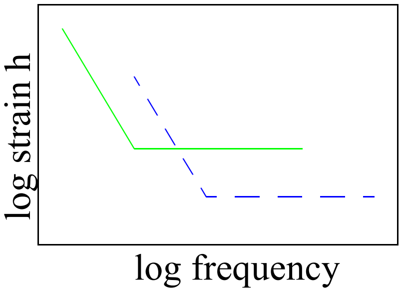
- quantum-limited intensity fluctuations anti-correlated in two arms
  - › can be seen as the action a statistical beamsplitter
  - › better, as result of vacuum fluctuations entering ‘dark port’
- photons exert a time varying force, with spectral

density $\tilde{f} = \sqrt{\dfrac{2\pi h P_{\mathrm{in}}}{c\lambda}}$

- results in opposite displacements of EACH of the masses:

$$\tilde{x}(f) = \frac{1}{mf^2}\sqrt{\frac{hP_{\mathrm{in}}}{8\pi^3 c\lambda}}, \text{ or strain } h = \frac{\delta l}{l} = \frac{2\tilde{x}}{L}$$

- NOTE: scaling with $\sqrt{P_{\mathrm{in}}}$
- scaling with the arm length L



Total readout, or quantum noise

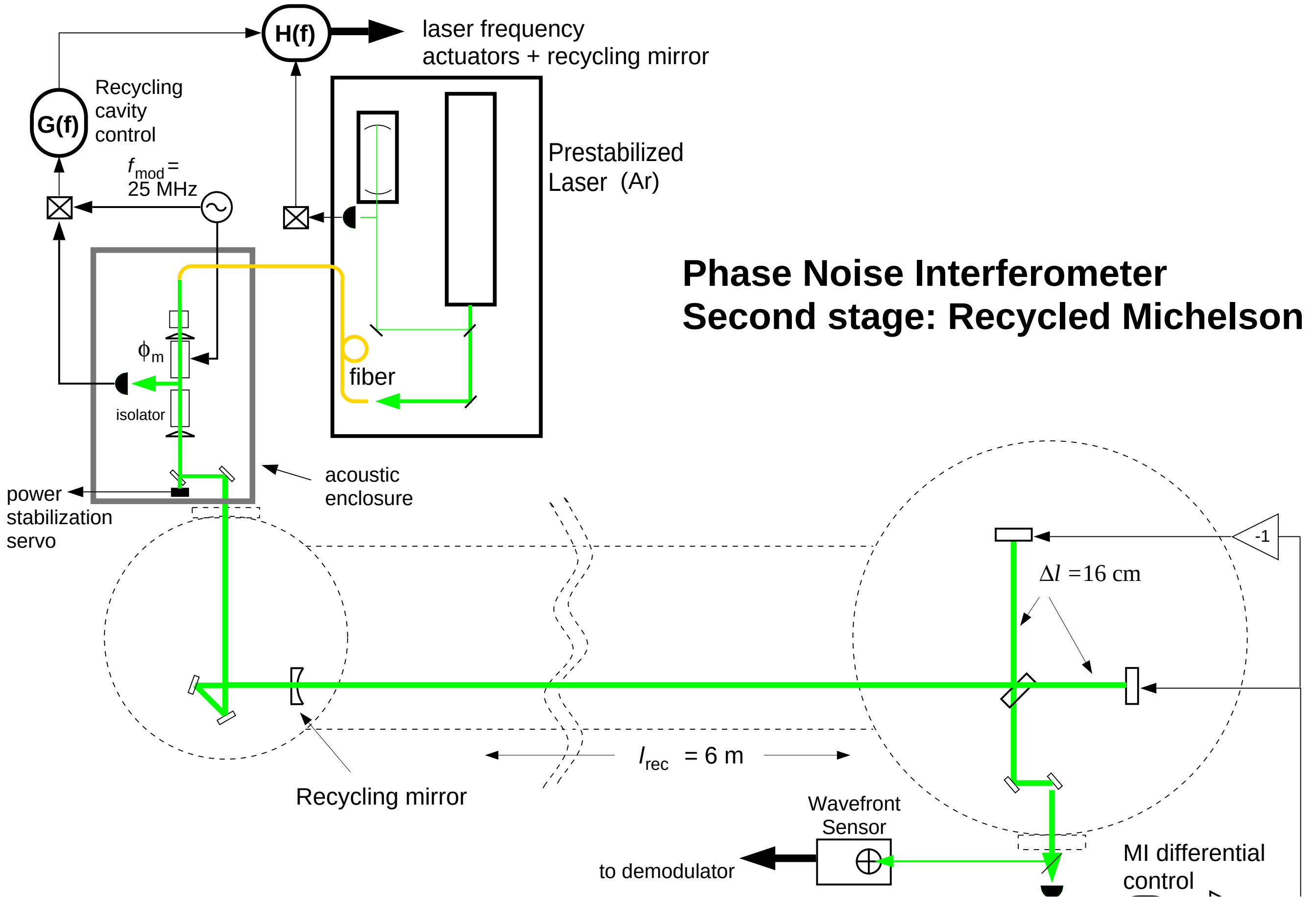
- quadrature sum $h_q = (h^2_{\mathrm{shot}} + h^2_{\mathrm{rad\ press}})^{1/2}$
- *NOT true for signal-recycled interferometers!*
- frequency dependence according to ifo configuration, but
- always a minimum for a given frequency as a function of Power
- for simple Michelson, $P_{\mathrm{opt}} = \pi c\lambda m f^2$; later limitation, not now

R&D: Phase Noise Research

Goal: to demonstrate required initial LIGO phase sensitivity

- test models for shot-noise, sensing system
- develop photodetector technology
- uncover laser, servo, scattered light problems/solutions

Simplified optical system to minimize position sensitivity

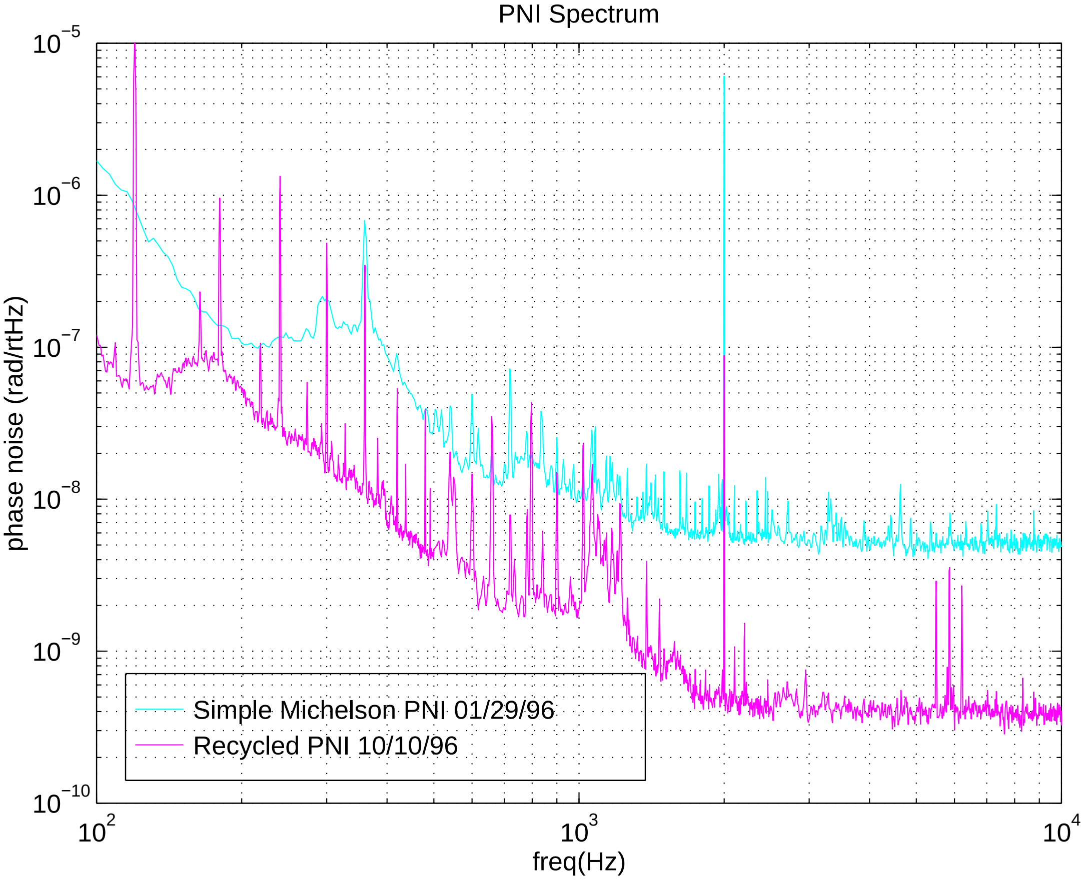


Phase Noise Interferometer
Second stage: Recycled Michelson

R&D: Phase noise research

Comparison of recycled, unrecycled cases

- high-frequency noise, 4×10^{-10} rad/$\sqrt{\text{Hz}}$, shot noise limited
- low-frequency noise from parasitics, frequency noise....



Next phase: conversion to Nd:YAG/1064 nm

- experiment will run to ~Jan 98
- tests low-power IR laser in characterized testbed

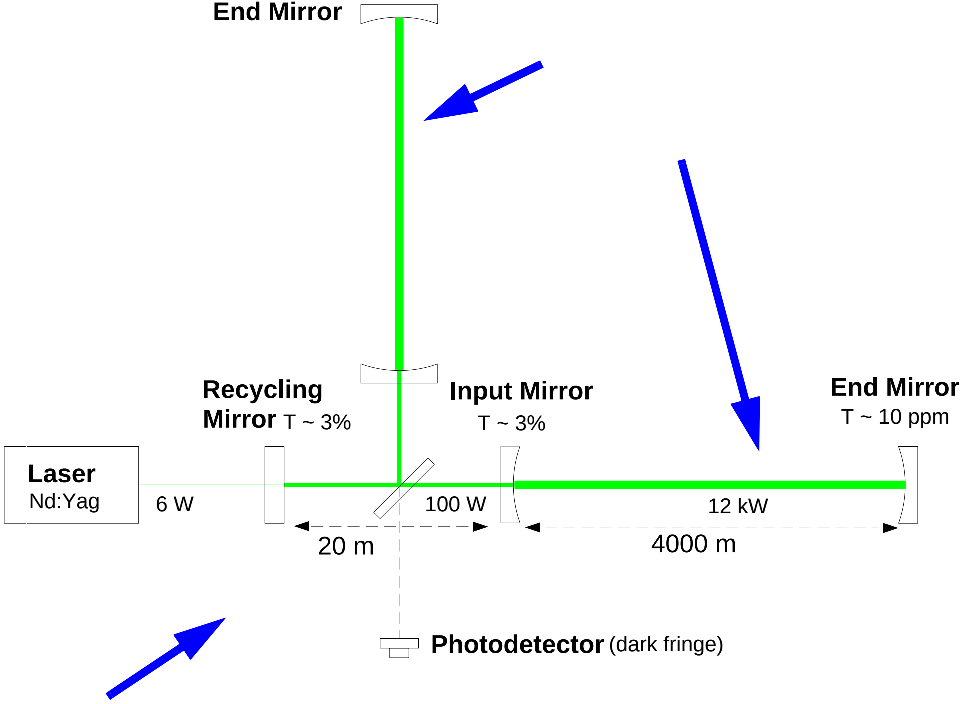
Interferometer Configuration

Additions to simple Michelson to increase sensitivity

- addition of recycling to increase power incident on beamsplitter
- folding of arms to increase phase change per length change

both are needed, with 4km arms, to reach initial LIGO goals

Arm cavities: accumulate phase shift over ~ half a GW period



Recycling cavity: reuse “bright fringe” power

R&D: Configuration Research

Table-top realizations of optical configurations, sensing

- recombined Fabry-Perot Michelson
- recycled FP MI with multiple frequency sensing
- recycled FP MI with multiple detector sensing

Modeling of linear and non-linear control regimes

- triggered by 'surprising' results above
- general methods for recycled interferometers developed
- refined to include finite light storage times, cavity coupling

Partial tests on 40m, refined tabletop experiments

- guided acquisition of 40m cavities
- recombination of 40m system

Alignment research

- modal model for small misalignments developed
- tested in a complete LIGO-configuration tabletop experiment

Reconfiguration of 40m as recycled Fabry-Perot Michelson

- significant activity in '97
- gives data directly to interferometer length control design
- allows tests of models in dynamic regime

R&D: Alignment Sensing/Control

Alignment of cavities to laser beam

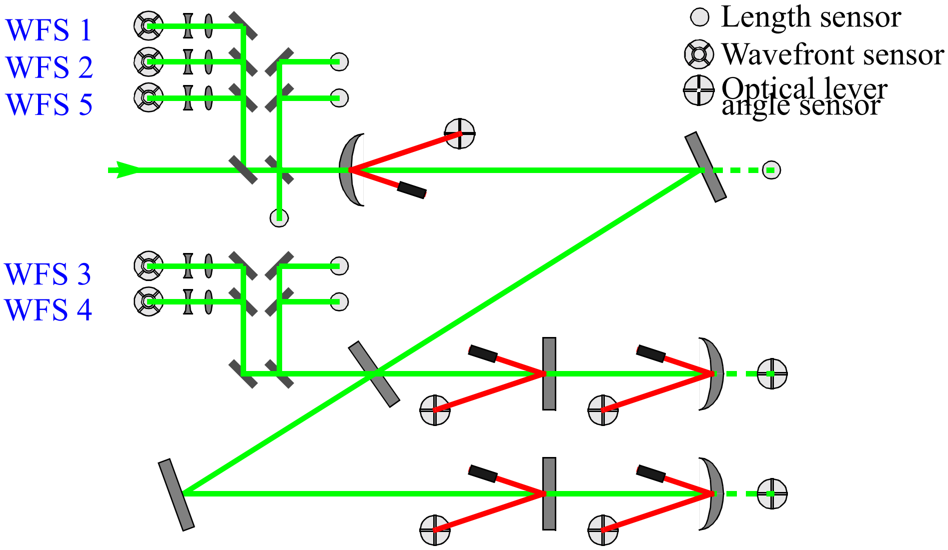
- effective use of laser power
- avoid spurious effects from undesired modes
- performance requirement of ~10^{-8} rad
- elegant model using expansion in modes of cavities

Sensing analogous to length sensing

- add spatial resolution to photodetectors
- look in near field/far field to separate translations, angles

Experimental test on table-top

- model verified



- digital signal acquisition/processing/control demonstrated

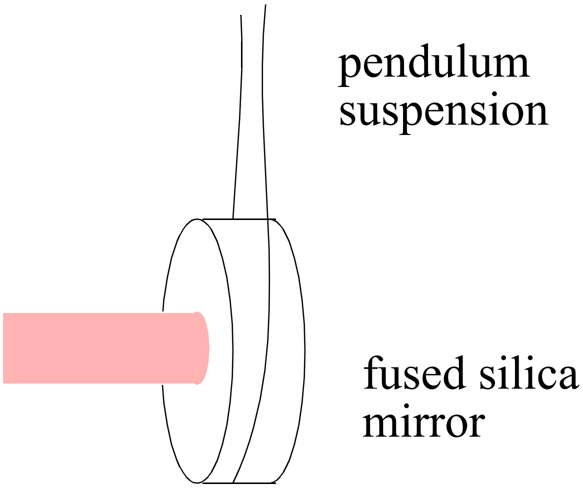
Thermal Noise

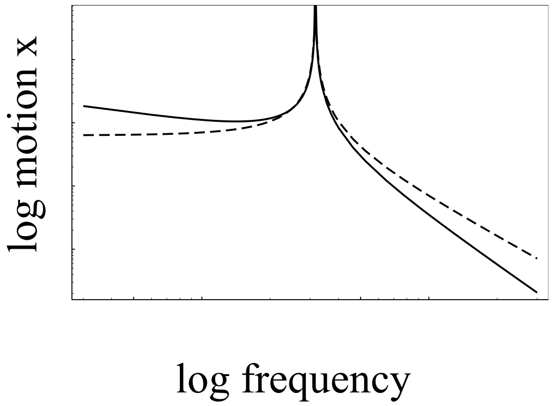
Mechanical systems excited by the thermal environment

- results in physical motions of the tests masses
- total energy of $k_B T$, leads to $\tilde{x} = \sqrt{\frac{k_B T}{k_{\mathrm{sping}}}}$ for integrated motion
- spectrum according to Fluctuation-Dissipation theorem:

$$\tilde{x}(f) = \frac{1}{\pi f}\sqrt{\frac{k_B T}{\Re(Z(f))}}\ ,\ \Re(Z(f))\ \text{ the real (lossy) impedance}$$

- e.g., damping term in an oscillator: $F_{\mathrm{ext}} = m\ddot{x} + \Re(Z(f))\dot{x} + kx$
- usually think of viscous damping: $\Re(Z(f)) = b$, a constant
- most real materials show internal friction,
- $F = -kx$ replaced by $F = -k(1 + i\phi(f))x$, $\phi(f)$ often constant

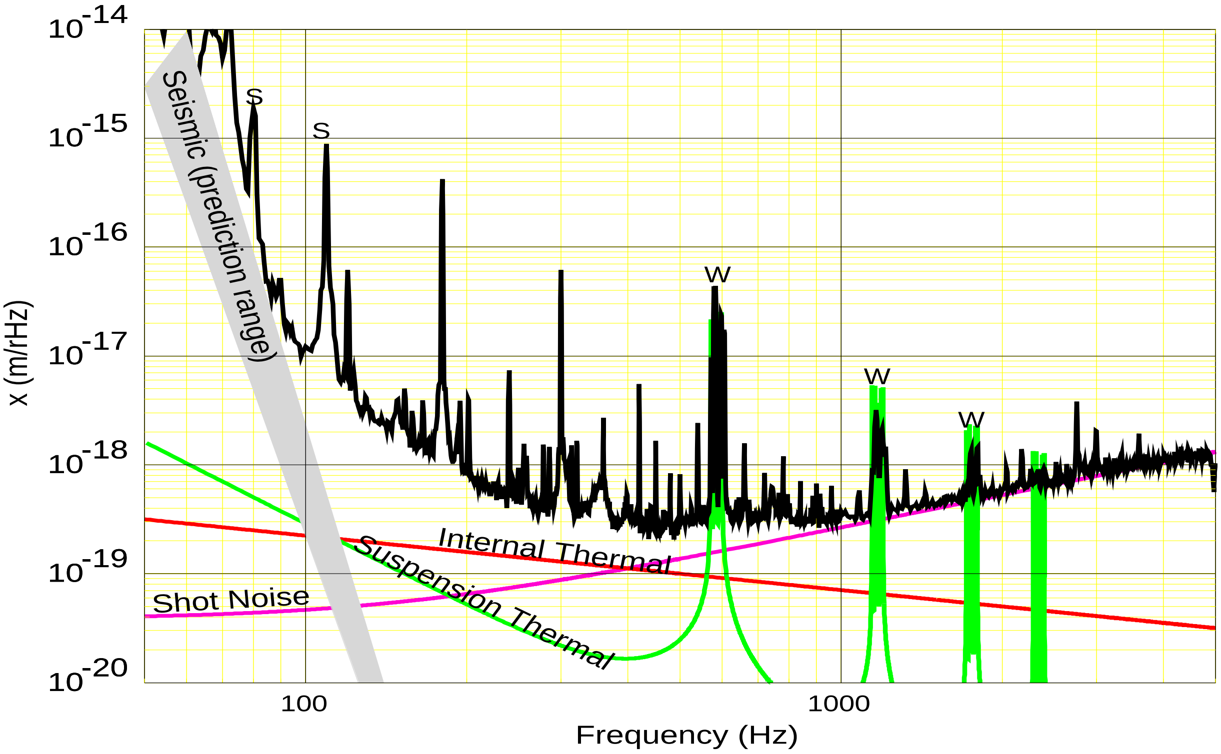




R&D: Thermal Noise research

Models, independent measurements, 40m tests

- thermal noise of substrate, pendulum significant for LIGO
  - previously no direct experimental observations to verify models
  - opportunity to observe in 40m by changing test masses
- thermal noise in compound test masses carefully calculated
  - measurements on 40m in good agreement
- new monolithic masses studied separately
  - coupling of control/sensing magnets/fins, suspension wires...
- installed in 40m; spectrum consistent with thermal noise model
- scaled thermal noise for LIGO meets initial curve

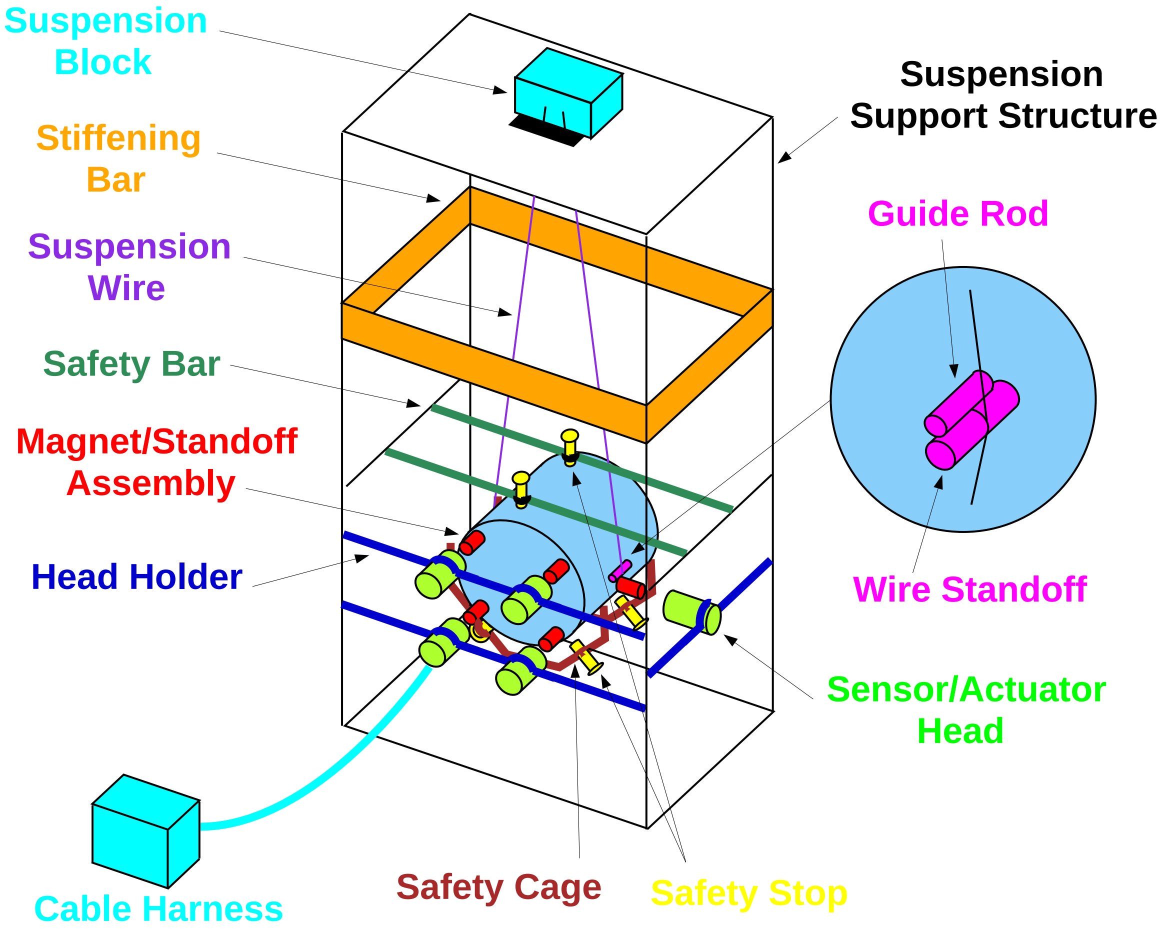


R&D: Suspension Research

Pendulum suspension serves several purposes

- minimizes thermal noise generated by test mass suspension
  - high-Q pendulum
- provides seismic isolation, ~f^{-2} above resonance
- allows translation and orientation forces to be applied

Prototypes tested separately, and in, interferometers



Seismic Noise

Motion of the earth

- driven by ocean tides, wind, volcanic/seismic activity, humans
- for LIGO sites, characterized by $10^{-7}/f^2 \ \mathrm{m}/\sqrt{\mathrm{Hz}}$
- requires e.g., roughly 10^9 attenuation at 100 Hz

Approaches to limiting seismic noise

- careful site selection
  - › far from ocean, significant human activity, seismic activity
- careful building design
  - › low air velocities in HVAC, put refrigeration at a distance
- simple damped harmonic oscillators in series
  - › LIGO: ‘stacks’, using lossy Viton springs and SS masses
  - › alternatively, constrained layer damped spring
- one or more low-loss pendulums for final suspension
  - › gives $1/f^2$ for each pendulum

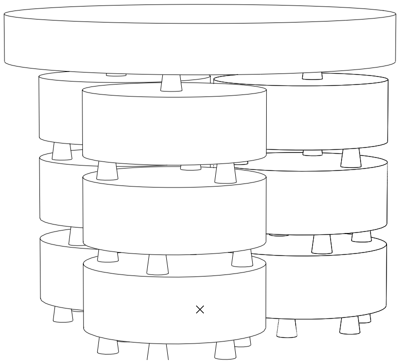
Gravitational gradients

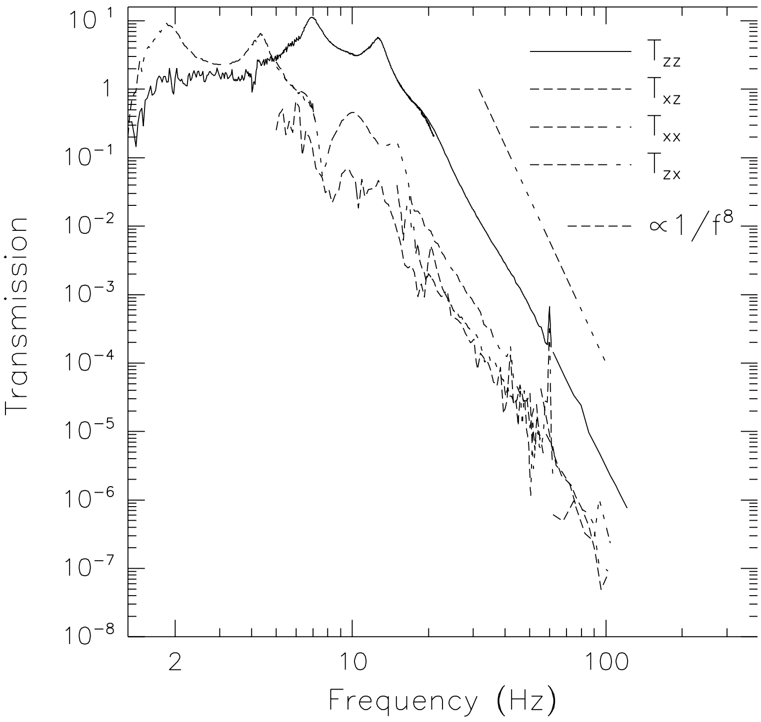
- direction of local gravitational pull a function of mass distribution
- time varying mass distribution indistinguishable from GW
  - › seismic compression/rarefaction of earth
  - › clouds
  - › important at frequencies below 10 Hz

R&D: Seismic Isolation systems

Passive elastomer-steel ‘stacks’

- damped SHOs in series
- in-vacuum: extra design constraints
- separate tests, followed by
  - › interferometer tests





Initial interferometer design

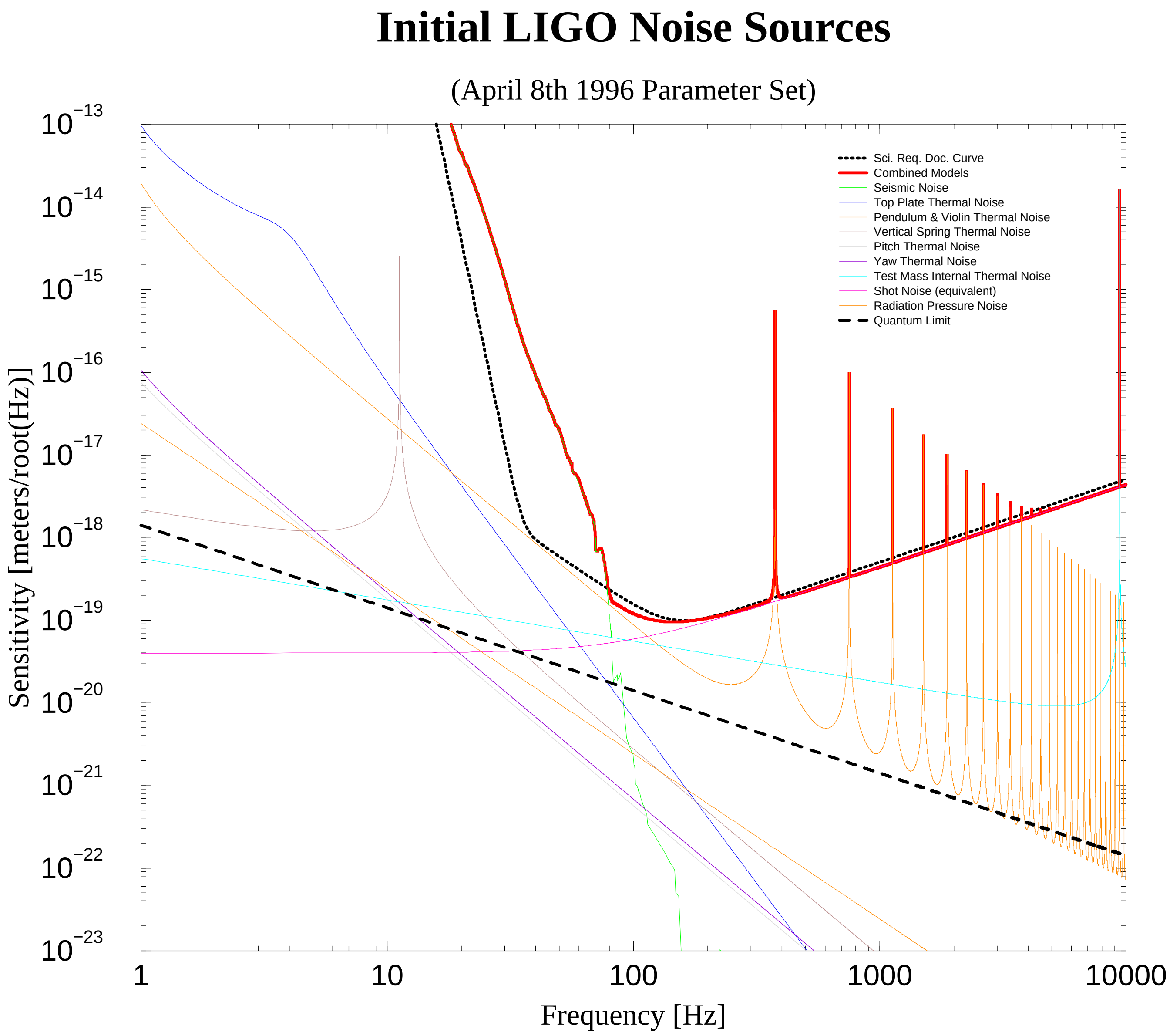
Philosophy of initial design

- conservative: designs tested, many in sensitive interferometers
- minimum of extrapolation required
    - › displacement, phase sensitivity demonstrated
- some systems revised from first design
    - › Argon laser, Viton springs
- leaves clear paths for advanced subsystems

Role of R&D in process

- modeling helps target important/difficult design questions
- small-scale experiments test models in some regimes
- iterative process, leading to scaled design
- in general, test in sensitive interferometer follows
- actual LIGO design then possible

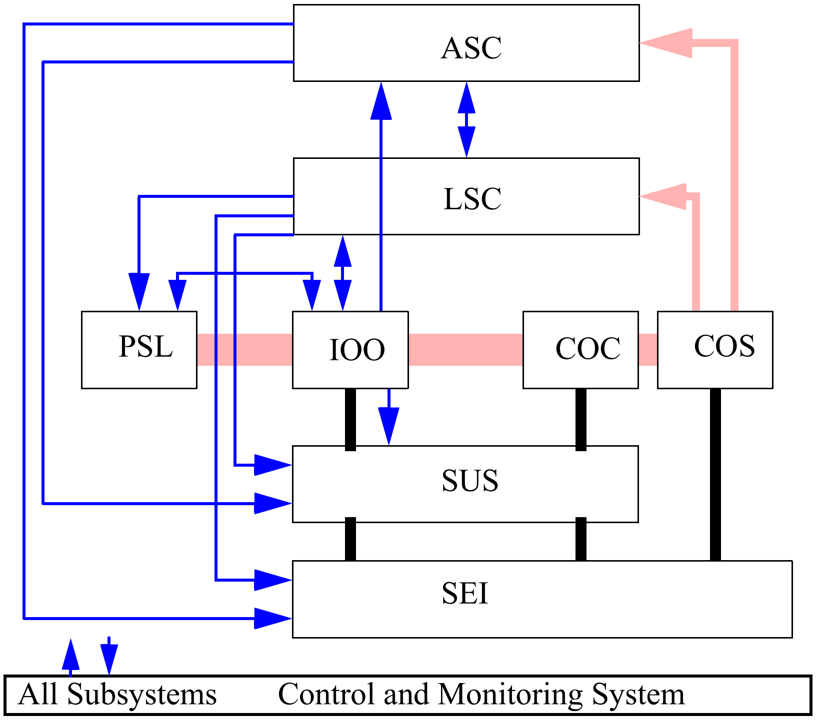
Initial LIGO sensitivity



LIGO Interferometer Design Status

Subsystems breakdown

- Pre-Stabilized Laser
- Input Optics
- Core Optics Components, Support
- Suspension
- Seismic Isolation
- Length Control
- Alignment Control
- Physics Environment Monitor
- Control and Data System



Pre-stabilized laser

Laser Source

- being developed and produced by Lightwave, Inc.
- monolithic Nd:YAG oscillator, followed by amplifier; 10 W output
- first units to be delivered in Oct 97

Stabilization

- based on rich experience with Argon Ion lasers
- modifications for Nd:YAG; e.g., filter cavity (Stanford)
- development underway using available 700 mW laser
- initial prototype for test in Phase Noise Ifo., in coming months

Input Optics

Under development in collaboration with Univ. Florida

- helped by clean interfaces, frequent visits, good communication

Principal components

- phase modulation system (multiple sidebands required)
- 3-mirror Fabry-Perot suspended mode cleaner
- matching telescope to main optics; reflective

Core Optics

‘Pathfinder’ process

- exploring/developing polishing, metrology, coating technologies
- significant progress on all fronts

Substrates: fused quartz, 25cm x 10 cm

- Heraeus low-OH material where absorption critical
- Corning for other applications

Polishing

- Three firms qualified for LIGO polishing
- 1 nm surface figure over 10cm required, and possible!

Coating

- REO and LIGO cooperating in measurement, characterization
- converging on processes to maintain required phase flatness

Metrology

- NIST is the independent contractor for Pathfinder
- comparisons with vendor metrology; probably the limiting technology

Core Optics Support

- baffling, in-vacuum relay mirrors, etc.

Suspensions

Two basic flavors:

- Small Optic Suspensions: Input Optics components
- Large Optic Suspensions: Core Optics

Prototypes in construction/test

- challenges in fiber attachment (Q), initial balancing
- also in control electronics: severe dynamic range requirements
- tests in 40m interferometer for control, noise performance

Seismic Isolation

Design contracted to Hytec, Inc.

- requirements developed by LIGO
- design makes incremental changes in initial design
- principal change in springs: Constrained Layer Damping

Requirements in control, GW band

- resonances create servo-control challenges, but...
- attenuation in signal band crucial

Preliminary design well advanced

- actuators for drift, tidal, microseismic peak also in development

Length Sensing/Control

Phase modulation key to obtaining signals

- Pound-Drever-Hall reflection locking techniques
- Asymmetry in Michelson to give differential signals

Designs tightly coupled to work on 40m, Phase Noise Ifo.

- acquisition and operation are both challenges
- modeling crucial, due to scaling required from lab to LIGO
- recycling experiment on 40m will give system test

Largely digital servoloop to be used

- transmission of signals over 4km eased (dynamic range!)

Alignment Sensing/Control

Model and prototypes tested on table-top system

- beautiful confirmation of Modal Model
- digital acquisition/control demonstrated
- wavefront sensor head, demodulation system shaken down

Many aspects to complete design

- initial alignment; pre-operational; operational

Physics Environment Monitor

All probable paths from environment to interferometer

- seismic (low ‘drift’ frequencies to GW band)
- acoustic
- electromagnetic: lightening, RFI, magnetic fields
- temperature, etc.

Characterization of transfer functions

- stimulus-response

System separate from interferometer

- to be used for veto, correlation, regressions
- principally commercial instruments

Early to the sites

- portable carts to enable measurements as buildings go up
- measure changes in the environment
- early data on correlations between sites

Control and Data System

Backbone of the interferometer

- electronics standards and design
- communications between subsystems
- all centralized control, monitor, operator consoles
- timing
- software up to the data analysis

Data Acquisition

- order of 5 MB/sec per interferometer total data rate
- data assembled into frames, short and long term storage

On-line Diagnostics

- interferometer console to allow quick-look, scripts

Prototyping and design well advanced

- much R&D now using CDS electronics
- several subsystems tests (laser)
- data acquisition/frame builder in test

Plans for ‘97 and beyond

R&D for initial interferometer: ends in ‘97

- all designs finished, fabrication underway
- 40m recycling
  - › length control acquisition
  - › length control operational mode
  - › tests of CDS electronics, data acquisition, etc.
- Phase noise measurements
  - › characterization of Nd:YAG laser
  - › guidance to Pre-Stabilized Laser design
  - › experience with infra-red optics, components
- Suspension tests in 40m
  - › control and mechanical stability
  - › internally-generated noise mechanisms
  - › installation practice
- Thermal noise research
  - › measurements of Q for suspended test mass optics
- Temporal, spatial modeling
  - › to support design activities; integration of models

Initial interferometer schedule

- overlapping design/fabrication/installation schedule
- **both interferometers installed by mid-1999**