Sensitivity Limits due to Photon Statistics:

Shot noise,
Other 'optical' noise sources, and
Optical configurations

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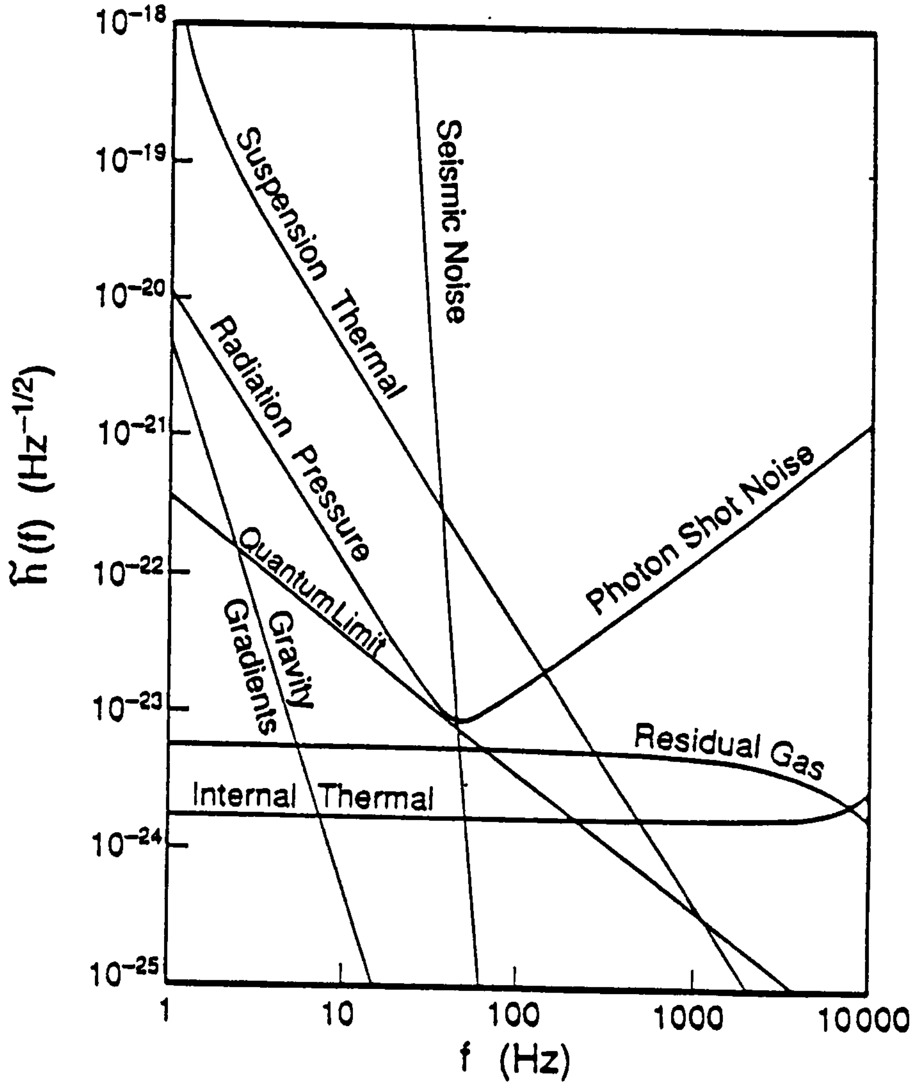
LIGO G940002-00-D

Noise Budget For First LIGO Detectors

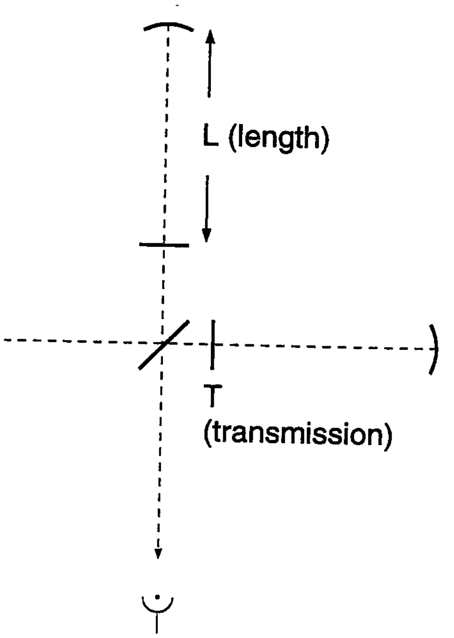
- 5 Watt Laser
- Mirror Losses 50 ppm
- Recycling Factor of 30
- 10 kg Test Masses
- Suspension Q=10^7



LIGO

Quantum limit for interferometer performance

Two important noise terms, inverse dependence on light power:



- Shot noise
  - fluctuations in number of photons/sec
  - equivalently, shot noise in photocurrent

$$\tilde{h} = \frac{T\lambda}{8\pi L}\sqrt{\frac{\mathrm{h}\nu}{P}}$$

- Radiation pressure
  - uncorrelated in arms
  - imparts random momentum to test masses

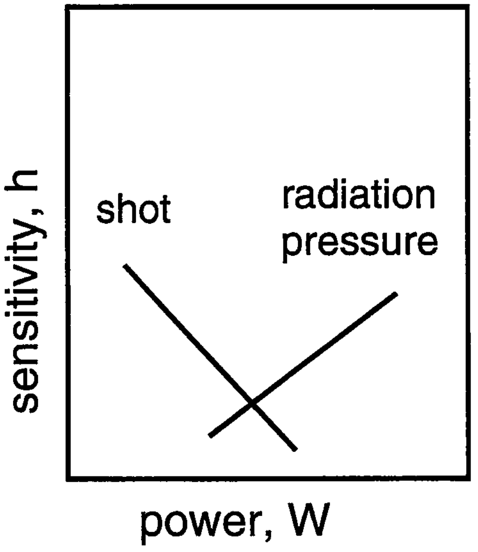
$$\tilde{h} = \frac{4}{cTLm\omega^2}\sqrt{P\mathrm{h}\nu}$$

  - minimum for

$$P_{\mathrm{opt}} = \frac{L^2\lambda m\omega^4}{2\pi c}$$

  - gives quantum limited sensitivity of

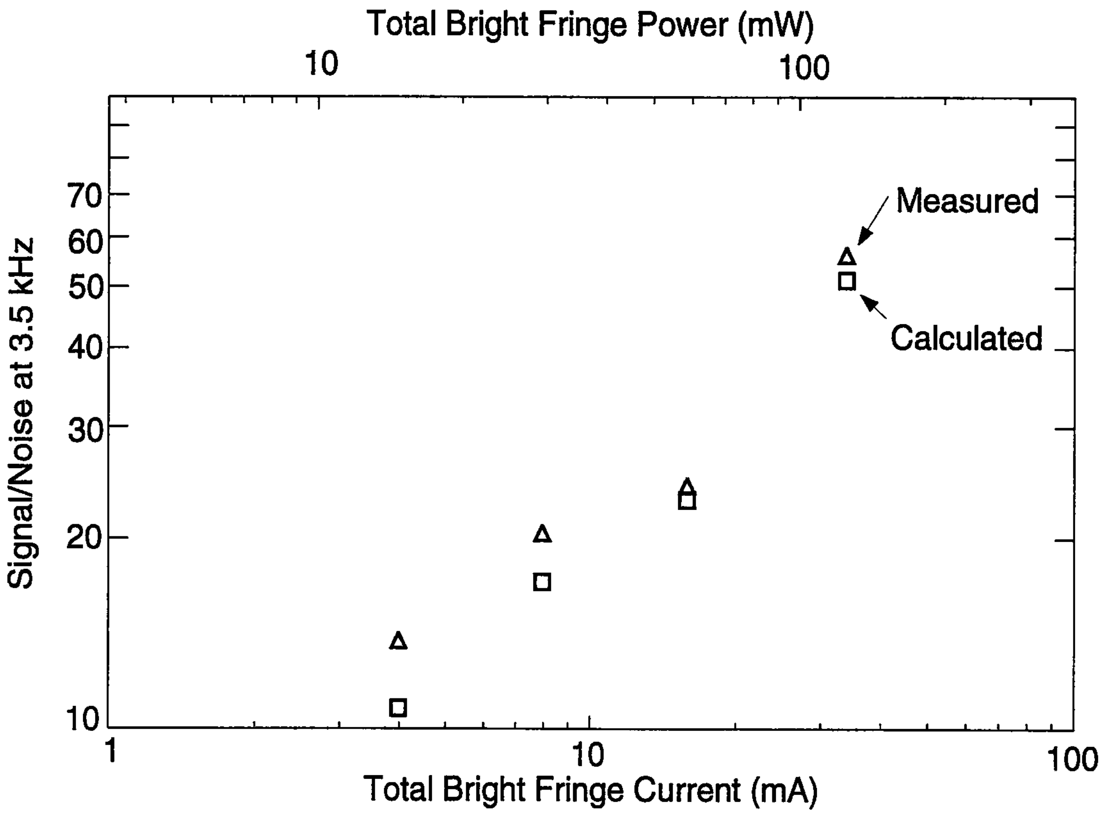
$$\tilde{h}_{\mathrm{QL}}(f) = \frac{1}{2\pi Lf}\sqrt{\frac{4\mathrm{h}}{\pi m}}$$

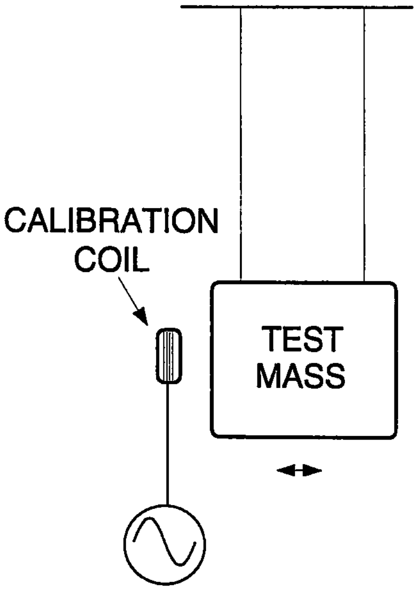


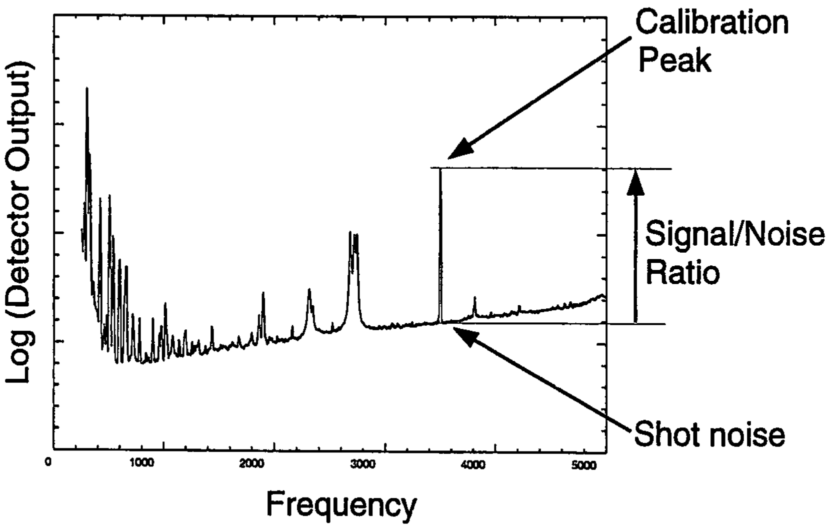
$\tilde{h}_{\mathrm{QL}} = 5\times10^{-24}\ \mathrm{Hz}^{-\frac{1}{2}}$ for $L = 4$ km, $f = 100$ Hz,
$m = 10$ kg, $\lambda = 514$ nm, $P = 7$kW;
a problem for second (or third?) generation antennas.

For now, wish to maximize circulating power.

Demonstration of shot noise in LIGO 40m prototype

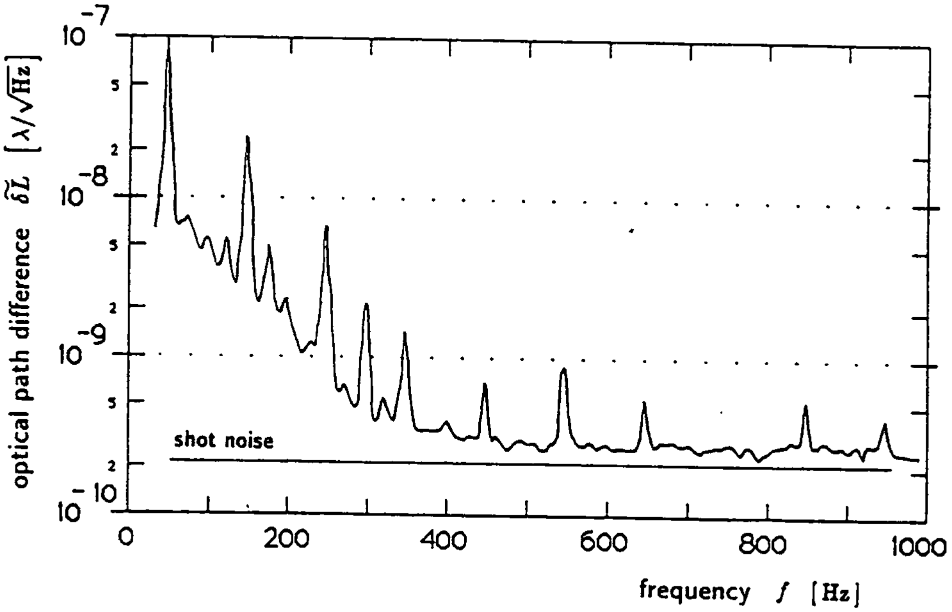


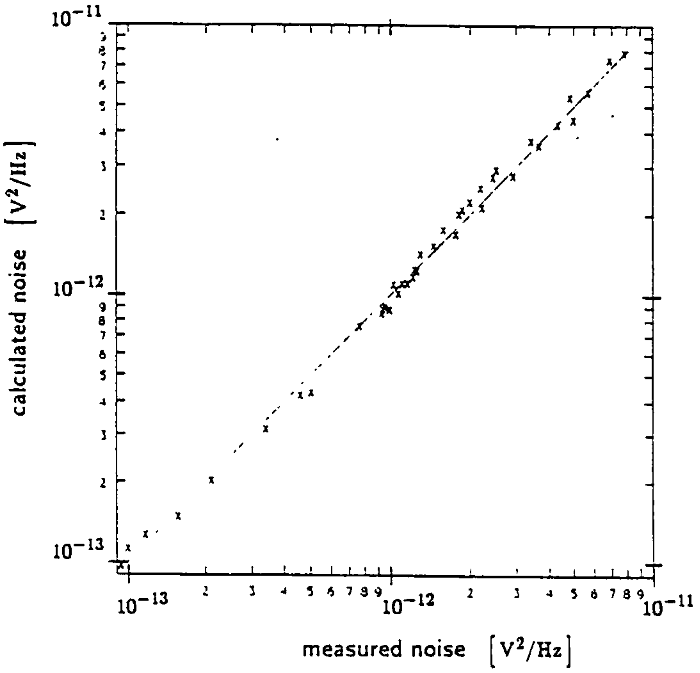




Demonstration of shot noise in Max Planck prototype

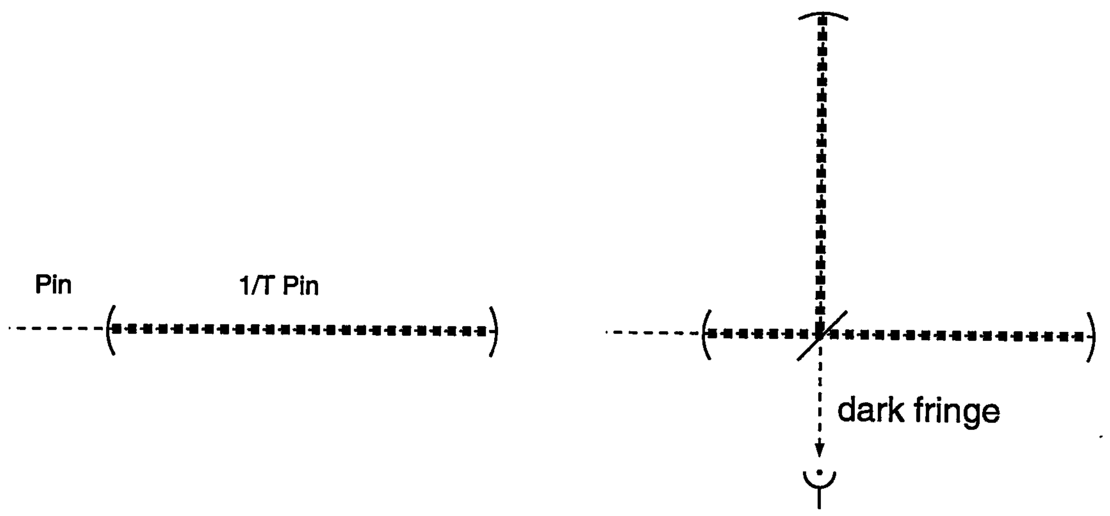
- Simple Michelson layout
  - reduces position sensitivity
  - eases test of splitting of fringe





- Full-power test planned in LIGO 5m prototype
  - demonstration of LIGO shot noise sensitivity
  - development of technology

Recycling: increasing the effective circulating power

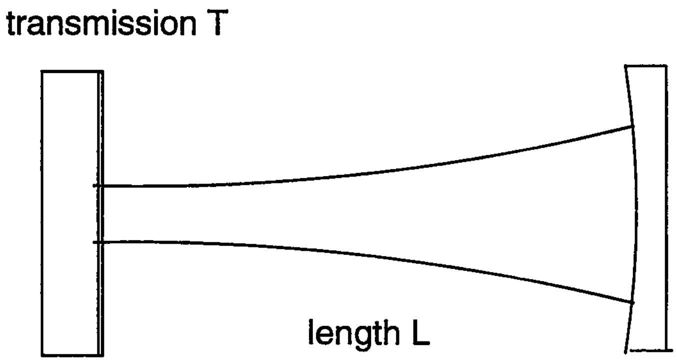


- form resonant cavity of interferometer, recycling mirror
  - interferometer antisymmetric output held on 'dark' fringe
- circulating power on beamsplitter determines shot noise sensitivity
  - 'P' to be used in shot noise formula

$$\text{Recycling gain} = \frac{\text{needed circulating power}}{\text{available laser power}}$$

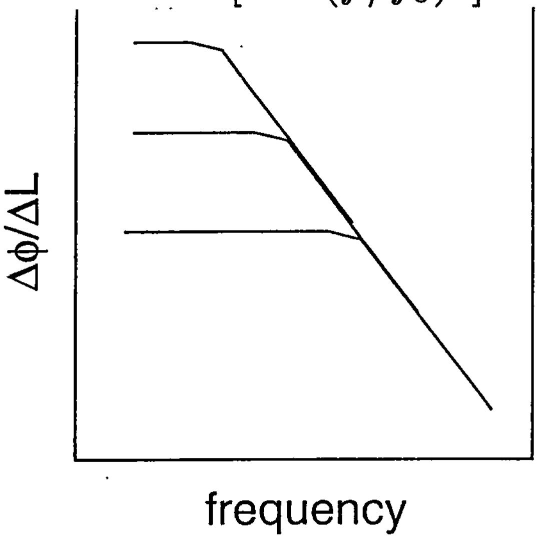
- limited by losses in recycling cavity; $\text{Gain}_{\text{max}} = 1/\text{Loss}$
  - constrains arm losses
- can reach initial LIGO sensitivity goal with
  - laser input power of $P_{\text{laser}}=2$ W
  - recycling gain of $G_{\text{rec}} = 30$
- does not change interferometer frequency response
- adds constraints to
  - interferometer operating point (dark fringe)
  - control system (additional degrees of freedom)
  - optical system (multiple constraints on gaussian beam parameters)

Folding of interferometer arms: Fabry-Perot cavities



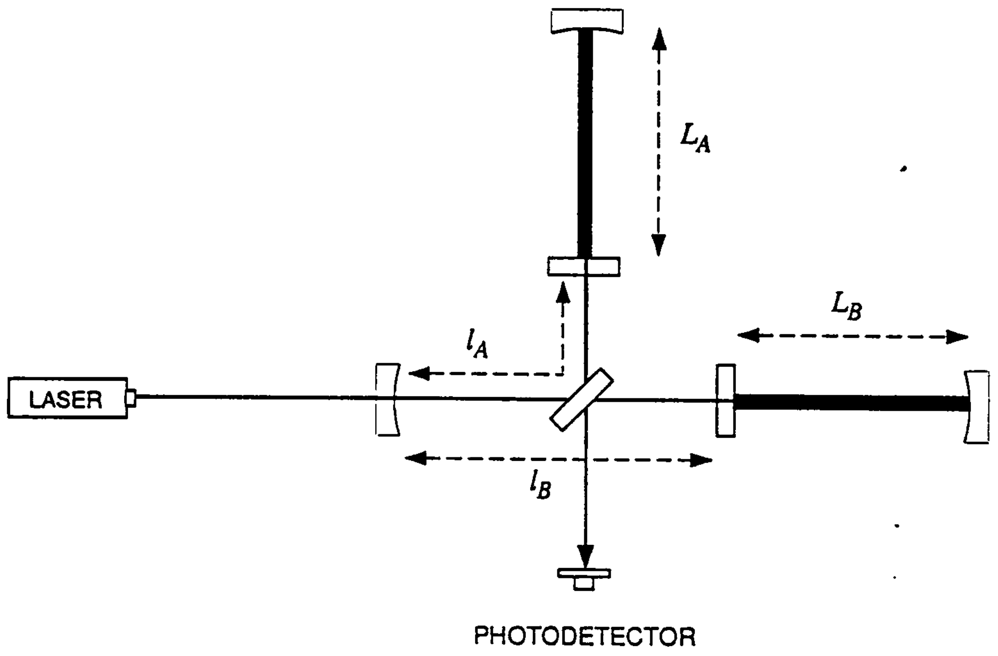
- increases the optical phase change from a given GW strain
  - for small motions ($\ll \lambda$) near optical resonance ($L = n\lambda/2$)

$$\frac{\Delta\phi}{\Delta L} \approx \frac{2L}{cT} \frac{1}{[1+(f/f_0)^2]^{1/2}}$$



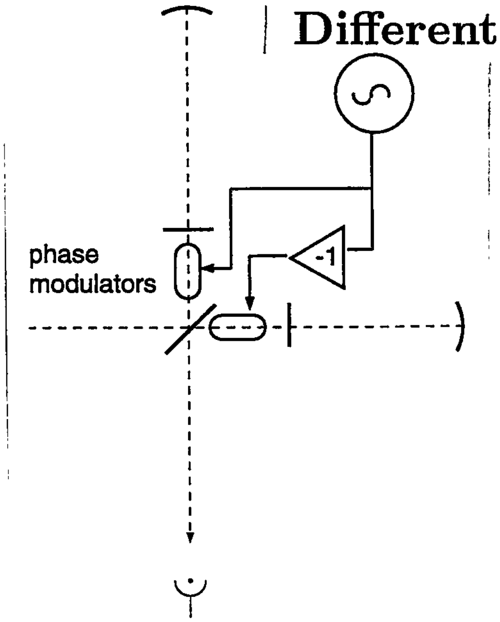
- corner frequency determined by mirror characteristics, length
- lower corner frequency, more effective bounces advantageous until
  - losses to recycling cavity become too large, or
  - other noise sources (e.g., seismic) completely dominate
- LIGO: $L = 4$ km, $T \approx 3\%$, $f_0 = 100$ Hz
- adds resonance constraint
- adds optical matching requirement

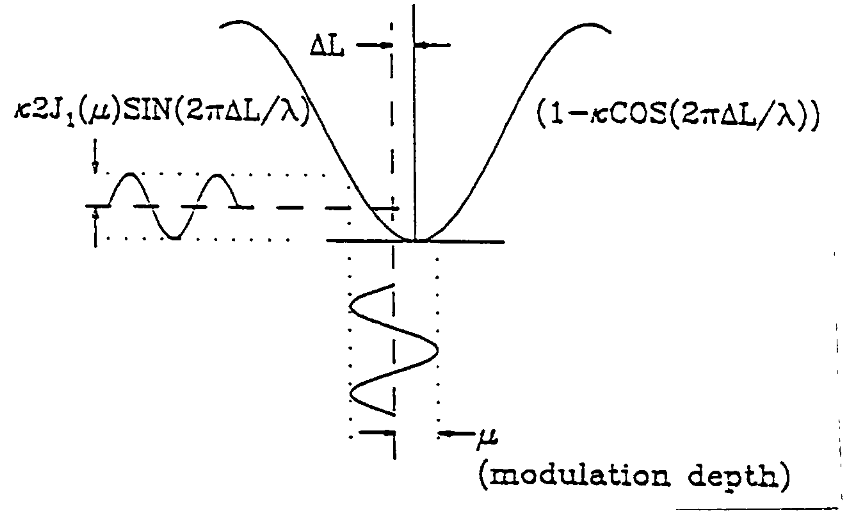
Interferometer degrees of freedom: readout and control



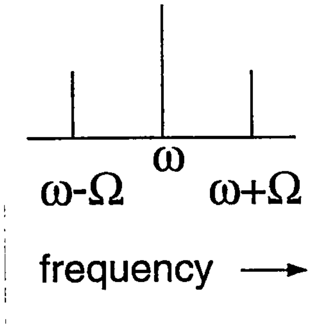
- Michelson with Fabry-Perot transducers and Power Recycling
- must readout GW with shot-noise limited sensitivity
- must hold Michelson on dark fringe
- must hold FP cavities and recycling cavity on resonance
- break system up into four DOF: differential and common modes
    - Gravitational wave signal: $L_a - L_b$
    - average light frequency correct: $L_a + L_b$
    - Michelson dark fringe: $l_a - l_b$
    - recycling cavity resonance: $l_a + l_b$

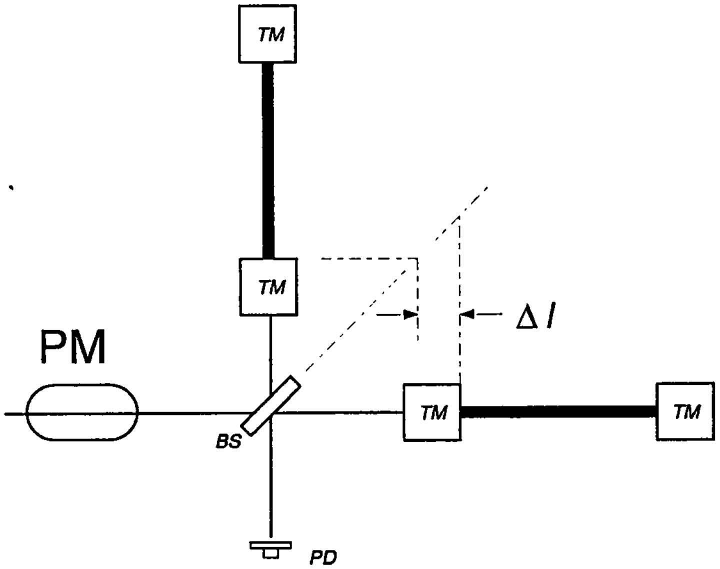
Differential mode readout means



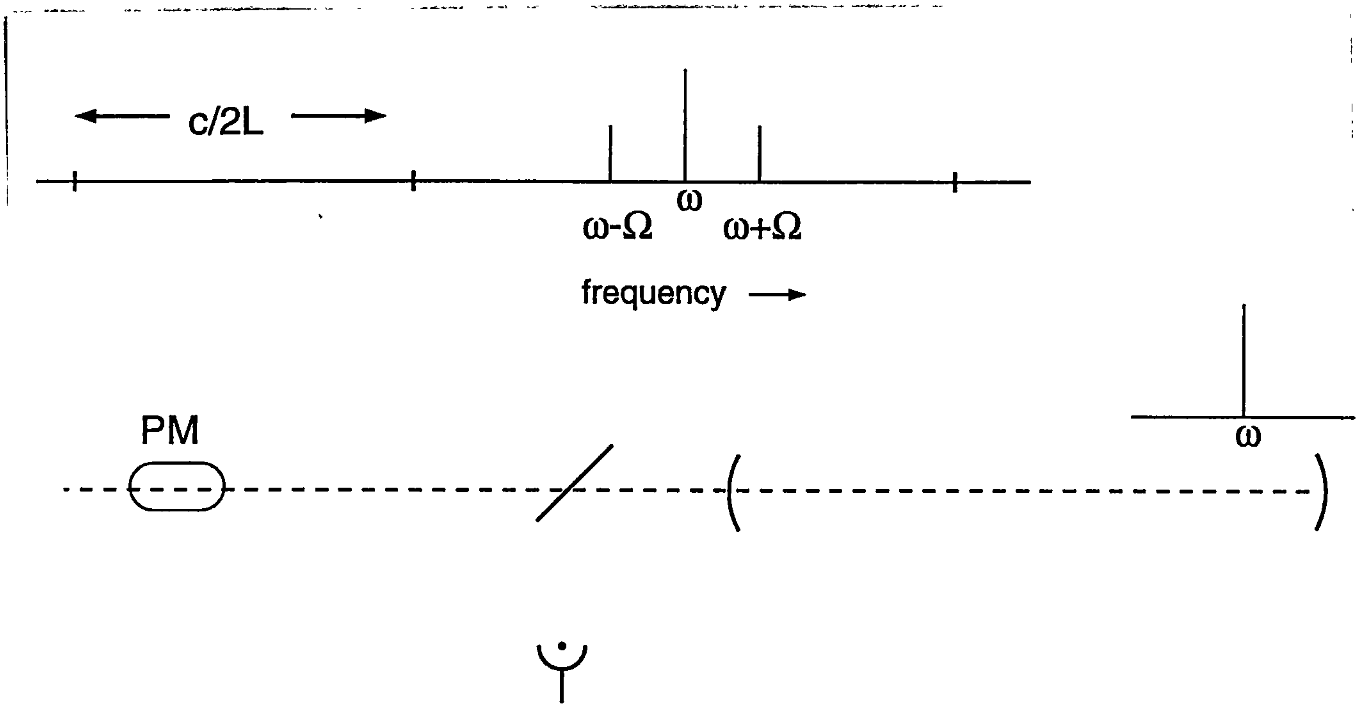


- synchronous modulation around the dark fringe
  - yields shot noise limited detection
  - uses phase modulators in arms of interferometer
  - not technically feasible for LIGO-like powers
- alternative: asymmetrize interferometer
  - (move $n \times \lambda/2$)
  - put phase modulator before interferometer
  - still on dark fringe for carrier
  - choose modulation frequency to be on bright fringe
  - $\lambda_{mod} = (l_a - l_b)/4$





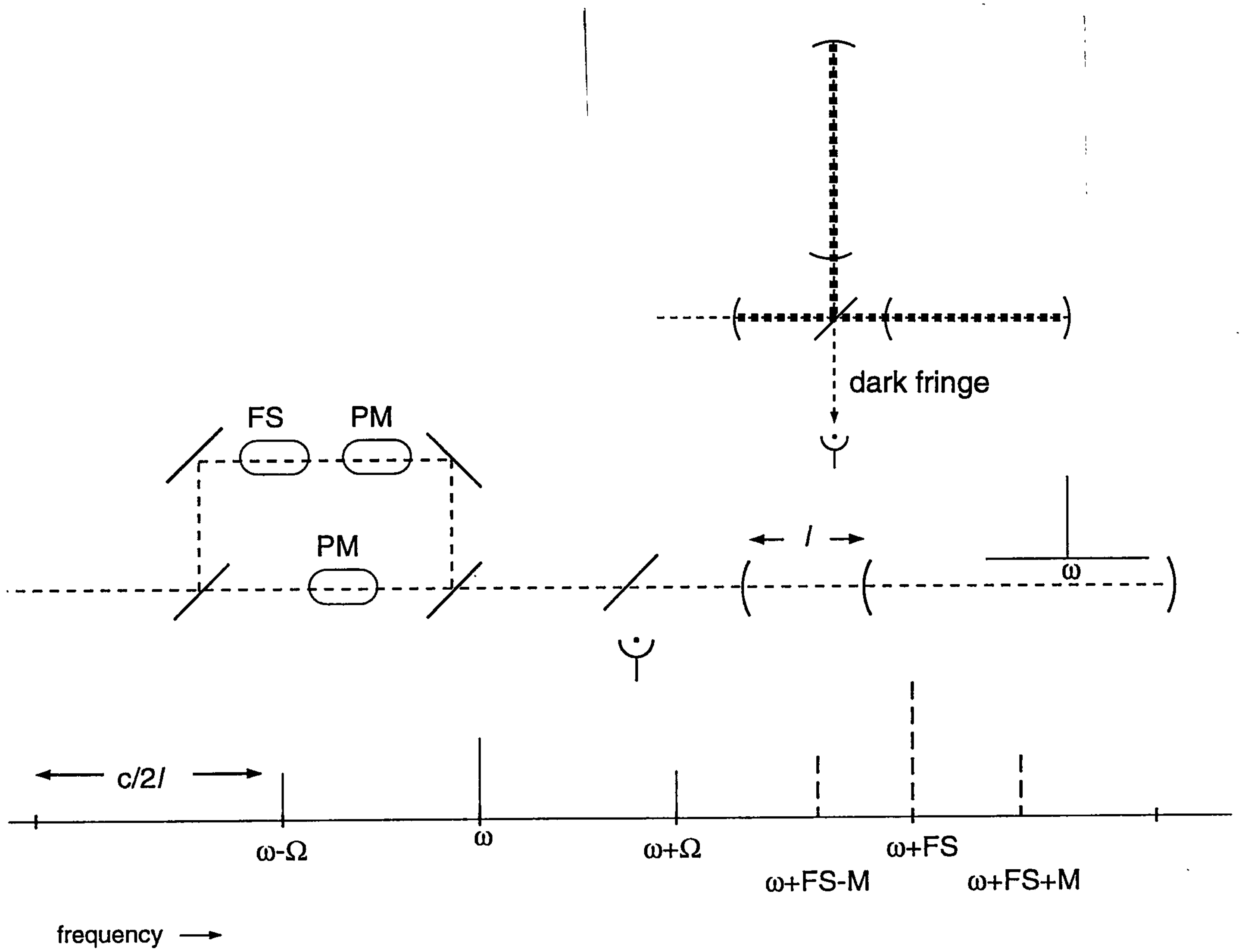
Common mode readout means



- use synchronous modulation frequency higher than cavity f_0
  - approximation of carrier and 2 symmetric sidebands
  - carrier resonant in FP cavity
  - sidebands reflected (off resonance)

- terms at f_{mod} proportional to distance from resonance
  - for $\Delta x \ll \lambda$

Separating near mirrors from far mirrors



- Problem: how to look 'inside' recycling cavity?
- establish 'subcarrier':
  - resonant in recycling cavity
  - off resonance of arm cavities
- senses only near mirror motion

Summary of initial LIGO interferometer configuration

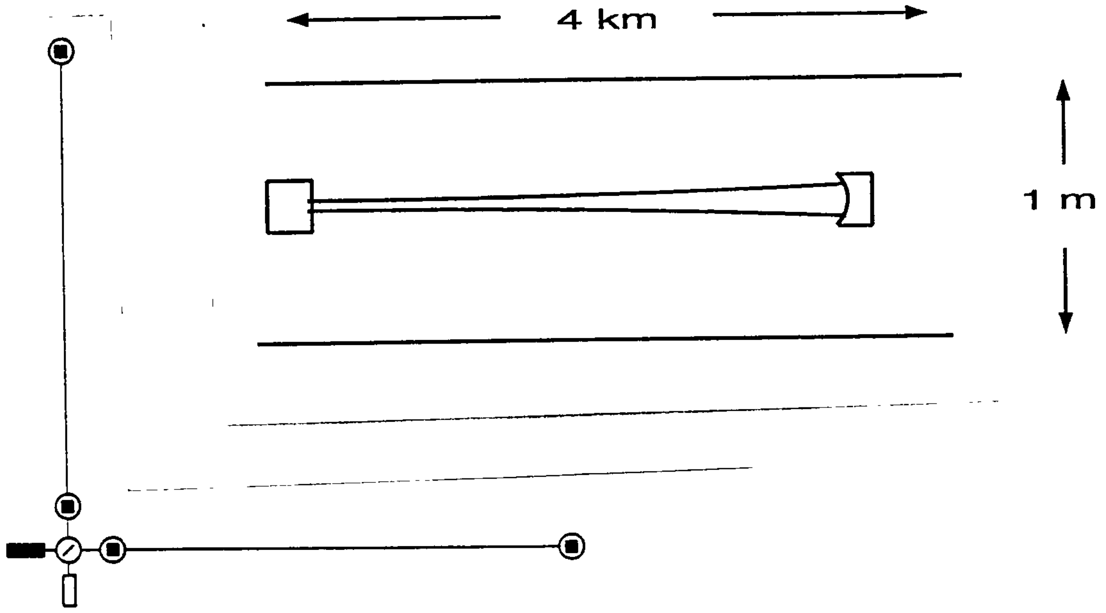
- Michelson
  - sensitive to differential excitation from GW
- Fabry Perot transducers to increase phase per strain
  - gives frequency response to interferometer
- recycling of input light to obtain needed shot-noise precision
- multiple light frequencies, phase modulations to read out lengths

- fundamental limits to sensing (shot, photon recoil)

Technical limitations to sensitivity

- mirror motions (seismic, thermal)
- imperfect optics
- length and alignment control systems
- laser light source
- residual gas

Imperfect optics, imperfect control



What does optical system look like?

- 25 cm diameter, 10 cm thick test masses
- at ends of a 1m diameter, 4 km long tunnel
- typical angle: 4cm/4km = 10μrad
- interferometer designed to work with TEM$_{00}$ mode
  - beam waist 2.5 cm, expands to 4 cm at far mirror

Mechanisms

- Light scattered out from arm cavities
  - dust, contamination on surfaces
  - 'short' (<1 cm) surface irregularities

- Absorption in mirror surface
  - conversion of laser light to heat

- Light scattered into higher spatial modes of cavities
  - scatter out of TEM_{00} mode, but onto far mirror
  - due to 'long' (>1 cm) surface irregularities
  - excitation of higher order optical spatial modes

- Limits to sensitivity due to
  - loss of light from system
  - degradation of interferometer contrast
  - rejection of light by system

- Scattering from tube wall, then recombination
  - adds spurious vector, random phase
  - gives interferometric sensitivity to wall motions

- Lead to requirements on mirror figure, absorption

- typical numbers:
  - unintentional transmission $\approx 10^{-5}$
  - absorptive losses $\approx 10^{-5}$
  - rms mirror figure $\approx \lambda/500$

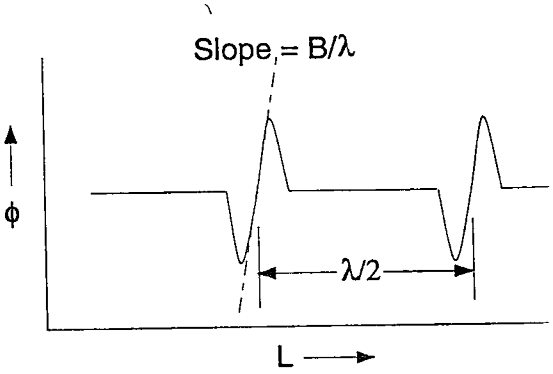
- also, tube wall treatment (baffles)

- Status
  - present state-of-the-art polishing, metrology required
  - large surface dielectric coating technology pushed

Length and alignment control

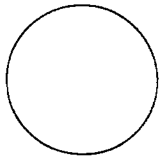
Length

- Deviations from desired lengths can lead to
  - reduced circulating power in recycling cavity
  - effective mismatching of two arm cavities
  - loss of light from dark port
- leads to requirements on
  - servo system gain
  - sensor signal-to-noise
- typical number:
  - arm lengths must be held to $\approx 10^{-12}$ m
  - (light $\lambda = 5\times10^{-7}$m; GW $x \approx 10^{-19}$ m/$\sqrt{\mathrm{Hz}}$)

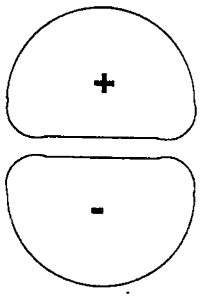


Alignment

- Optical system supports Gaussian spatial modes
  - designed to work with TEM_{00} exclusively
  - misalignments excite $\mathrm{TEM}_{\mathrm{nm}}$
  - critical angle determined by cavity geometry
- requires sensing system, resembling length control
- typical number:
  - test mass mirrors must be held to $\approx 10^{-8}$ rad
  - (about 1/2 mm over 4 km)
- Status
  - complete length prototype control systems demonstrated (see talks by Giaime, Regehr this afternoon)
  - alignment system principle tested, system tests starting

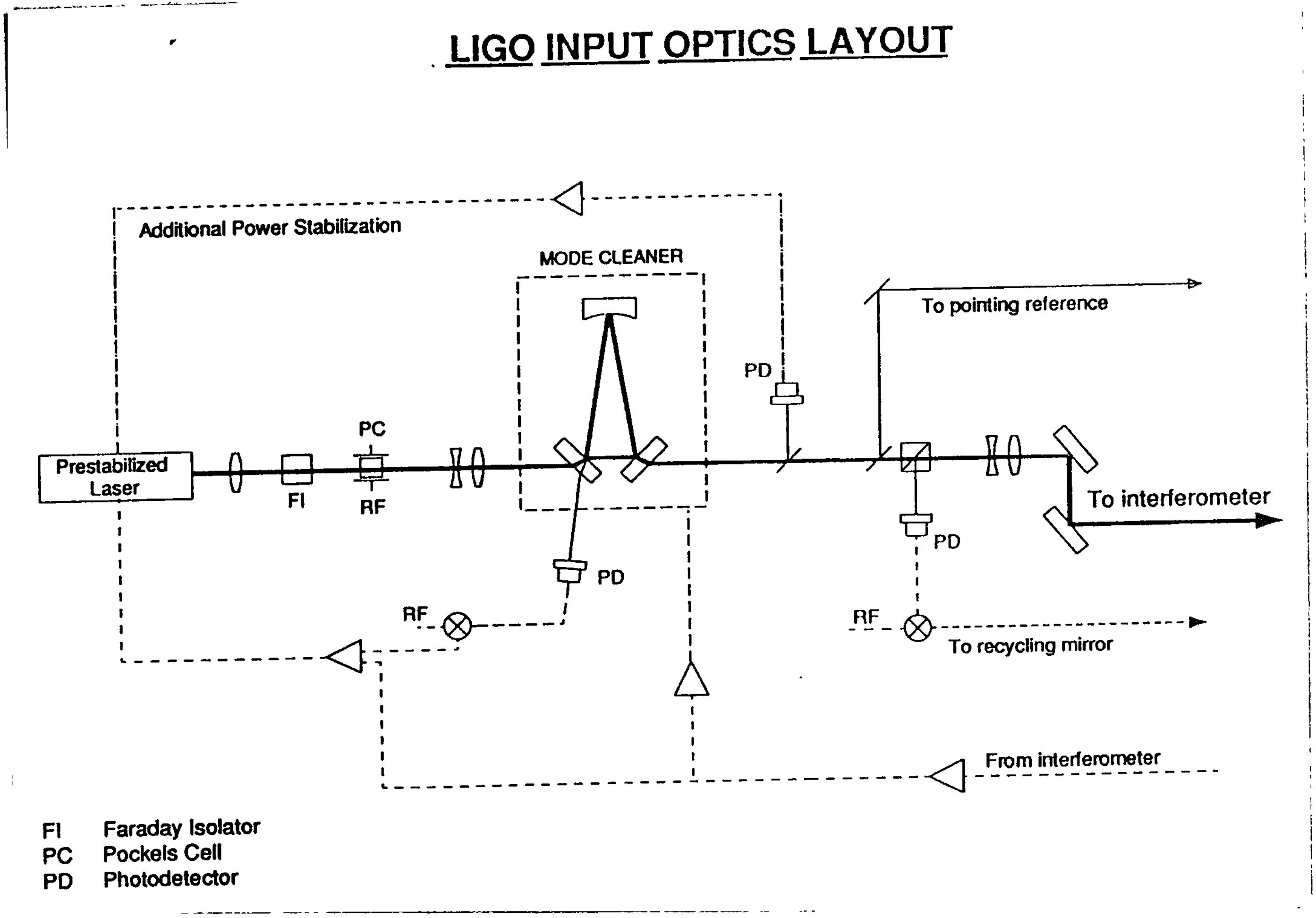


TEM_{00}



TEM_{01}

Laser source

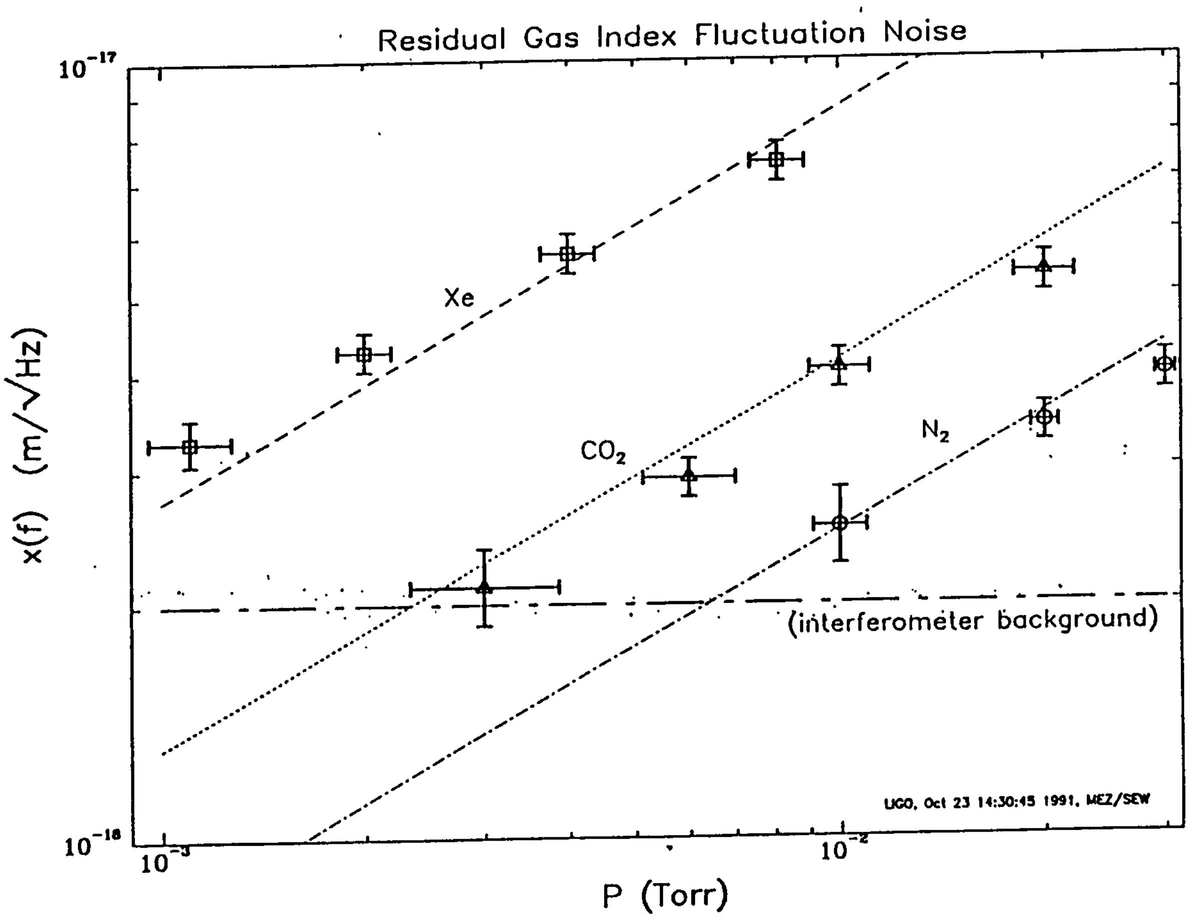


- Light source: Argon-ion gas laser
  - modified commercial system
  - 514 nm, green wavelength
- Passive spatial, frequency filtering
  - triangular Fabry-Perot used in transmission
- Power
  - to meet shot noise sensitivity requirement
  - 2 W at input to interferometer

Scattering from residual gas

- Gas remaining in vacuum system
  - ○ polarizability of molecules
  - ○ thermal velocities
  - ○ statistical variation in total number ($\sqrt{N}$)

  →fluctuation in apparent path length
- Gives requirements for vacuum system



Sensitivities due to interferometer asymmetries

- Perfectly symmetric system has no sensitivity to
  - frequency fluctuations
  - power fluctuations
  - position and beam geometry fluctuations
- Asymmetries exist:
  - intentional (readout system)
  - unintentional (mirror differences: loss, figure)
  - recombination of light with different histories
- Frequency stability
  - simple mechanism: different arm corner frequencies
  - short term stability needed (20 msec and shorter)
  - rough number: 10^{-5} Hz/$\sqrt{\text{Hz}}$ at input to interferometer
- Power stability
  - simple mechanism: asymmetry in beamsplitter
  - more subtle: imperfect interferometer dark fringe
  - rough number: $10^{-6} dI/I$ at input to interferometer
- position stability
  - simple mechanism: misalignment to interferometer
  - more subtle: coupling to different arm TEM_{nm}
  - rough number: 10^{-6} excitation at 100 Hz
- Status:
  - laser engineered
  - mode cleaner nearing installation

Where do we stand?

- Shot noise
  - demonstration at various power levels
  - full-power small-scale demonstration in preparation
- Configuration and control
  - extensive prototype tests and models performed
  - complete system prototype in preparation
- Optics
  - specifications developed
  - industry samples for substrates exist
  - coating challenge
- Laser and input optics
  - working systems on prototype
  - second generation to be installed
- Residual gas pressure fluctuations
  - models verified
  - vacuum system design consistent

So:

- Work to do
- Know how to get it done