L190-G920010 00-R

INTERFEROMETER DESCRIPTION AND R&D

S. Whitcomb, R. Spero, L. Sievers,
F. Raab, M. Zucker, D. Jungwirth

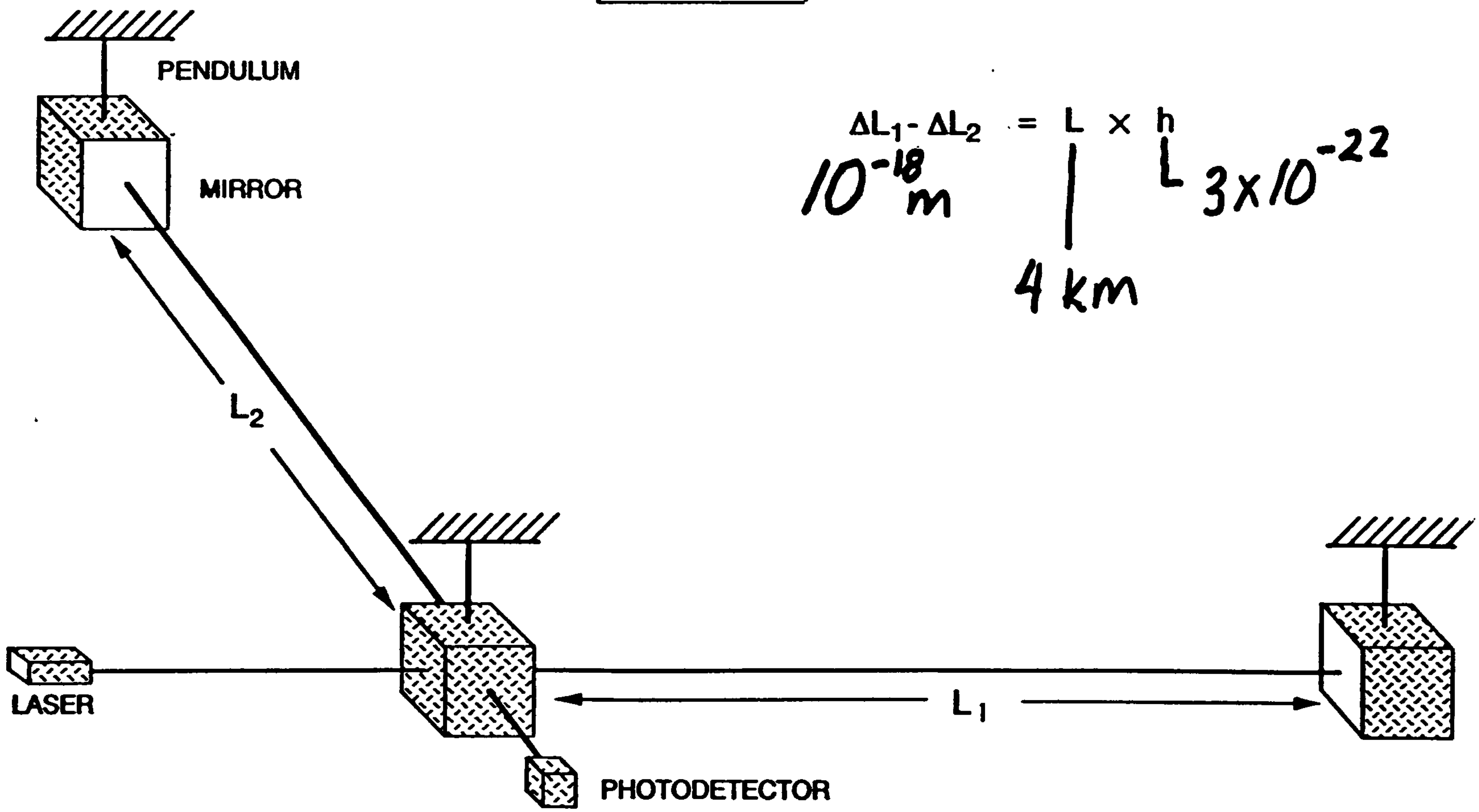
December 11, 1992

Interferometers

- Interferometer Description
- 40 m Interferometer
- R&D Progress
  - Shot Noise
  - Seismic Noise
  - Thermal Noise
  - Optics Development and Testing
- Mark II 40 m Interferometer

SIMPLIFIED DETECTOR

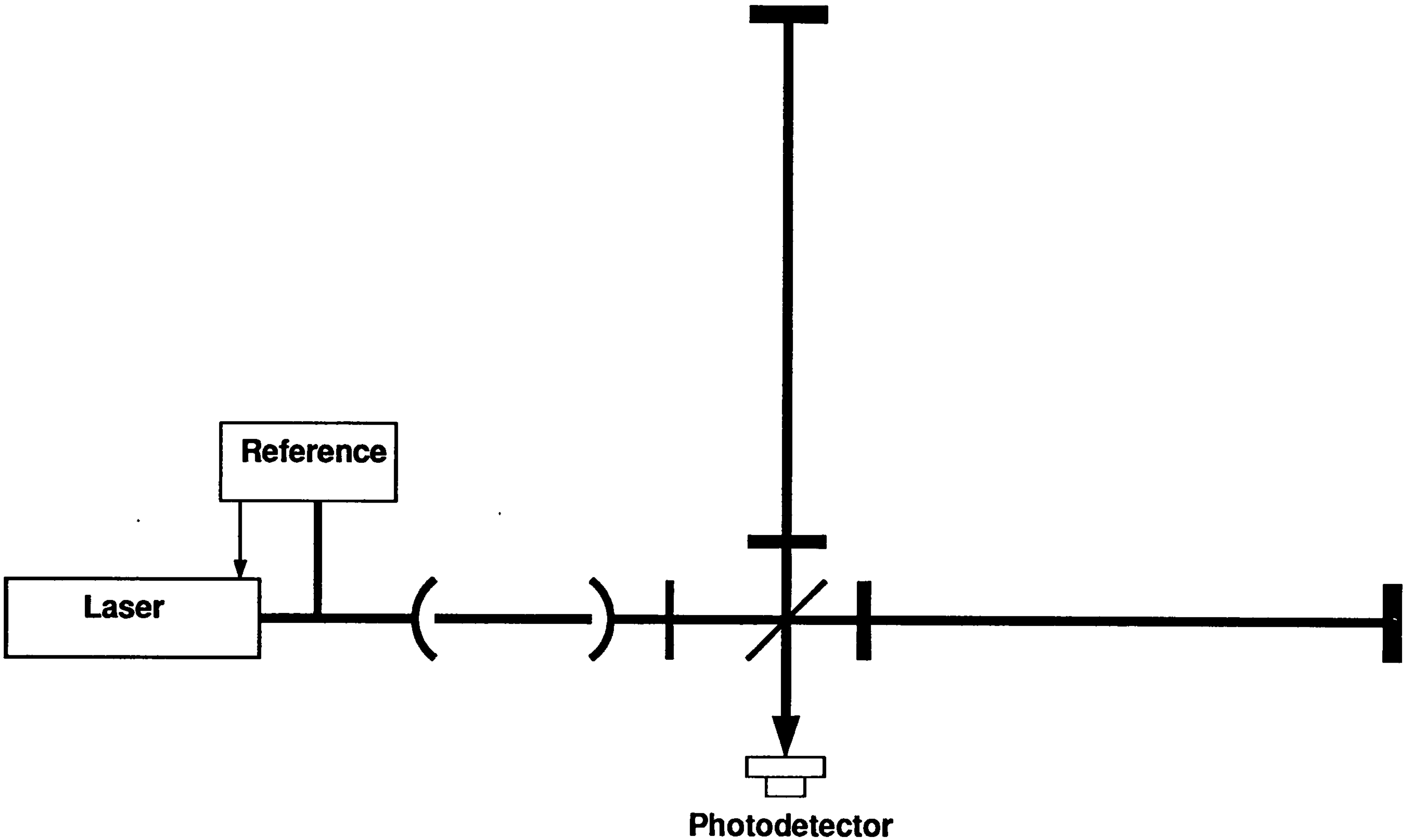
$\Delta L / L = h$



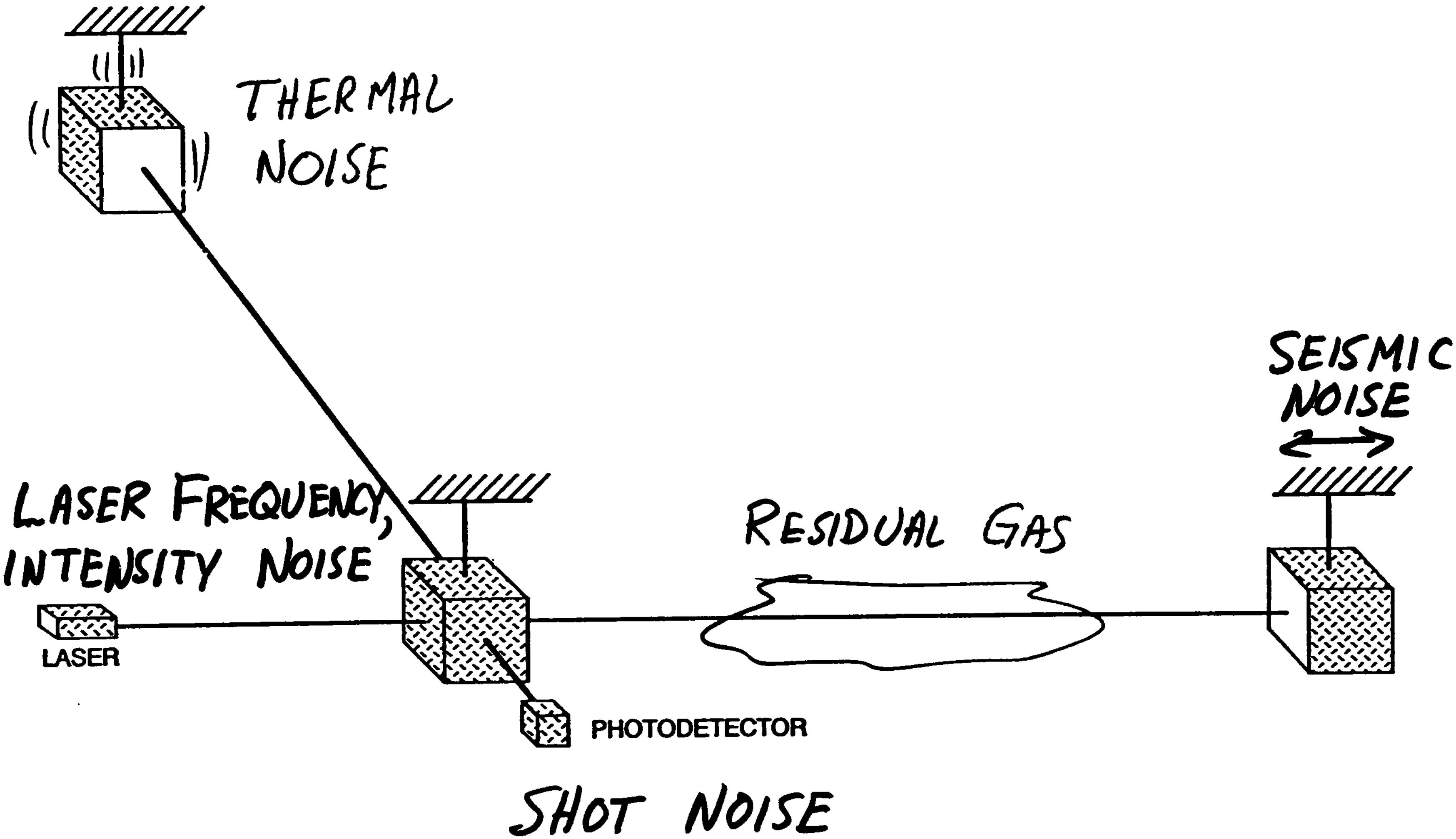
$\Delta L_1 - \Delta L_2 = L \times h$

10^{-18} m | 4 km | 3×10^{-22}

Optical Layout and Operation

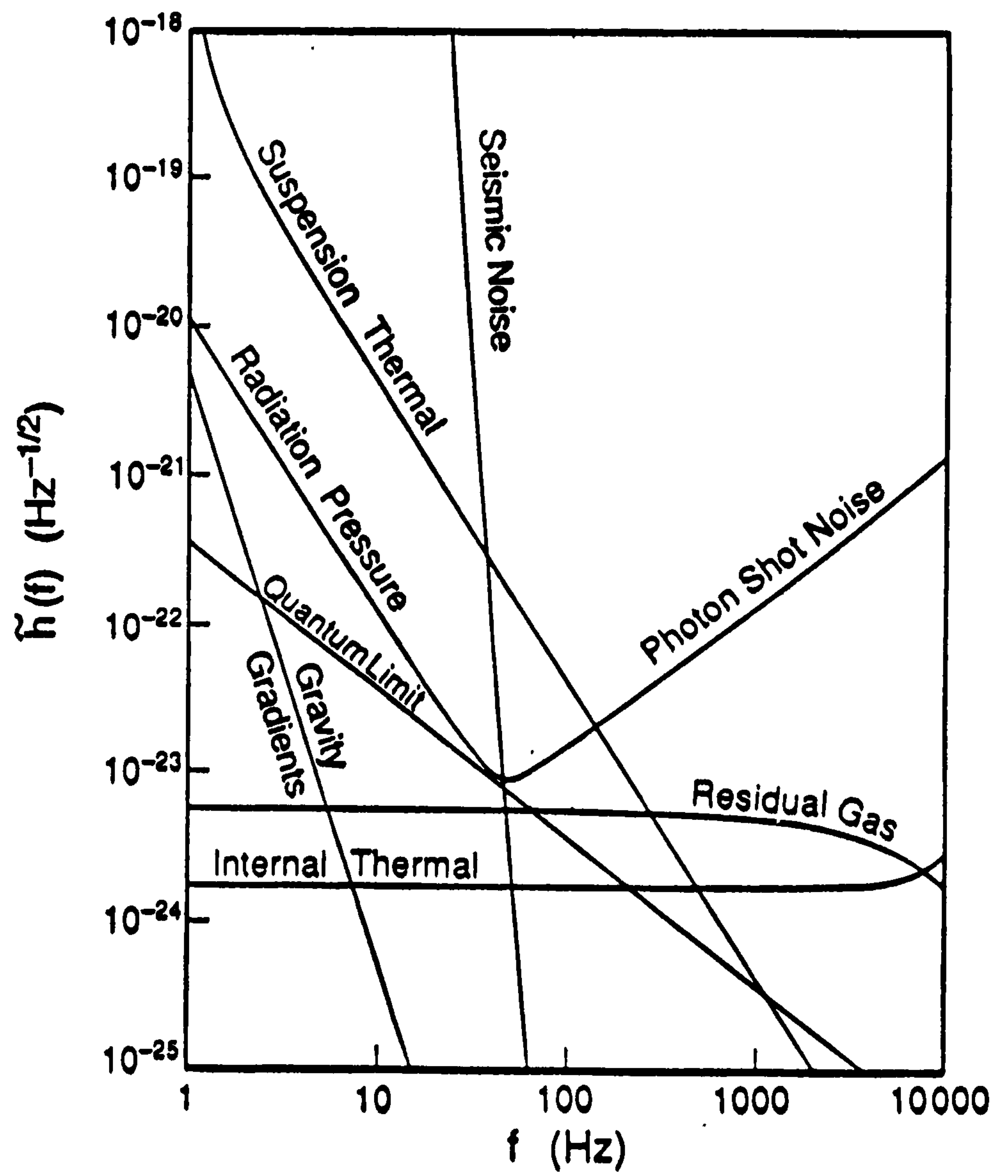


NOISE SOURCES



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



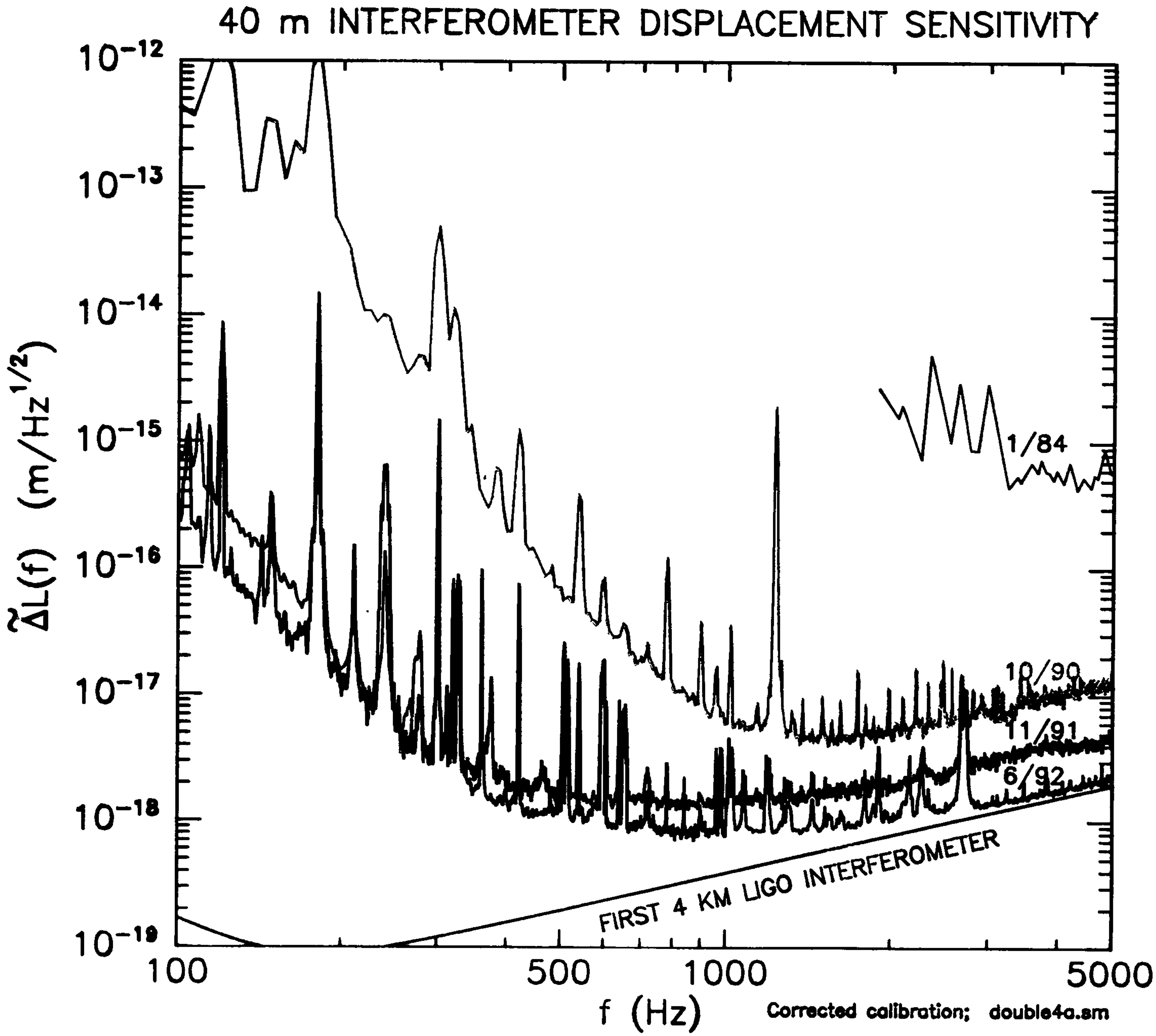
LIGO

Role of Laboratory Interferometers

- NOT Simply a Scaled Version of LIGO Interferometer
  - Configuration and Scaling of Interferometer Depends on Aspect of Full-Scale Interferometer That Is Being Investigated
- Demonstrate Understanding of Fundamental Noise Sources, Scaling Laws, and Parameters Appropri-ate to Full-Scale Interferometer
- Test LIGO-Scale Subsystem Prototypes

40 m Interferometer

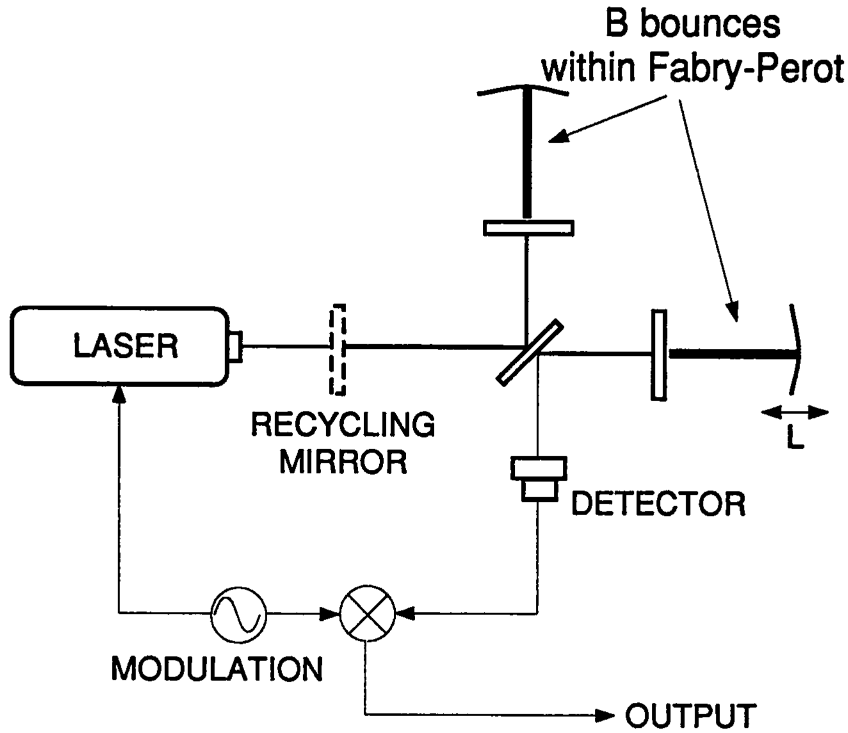
LIGO


40 m INTERFEROMETER DISPLACEMENT SENSITIVITY
$\tilde{\Delta}L(f)$ (m/Hz$^{1/2}$)
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
100
500
1000
5000
f (Hz)
1/84
10/90
11/91
6/92
FIRST 4 KM LIGO INTERFEROMETER
Corrected calibration; double4a.sm

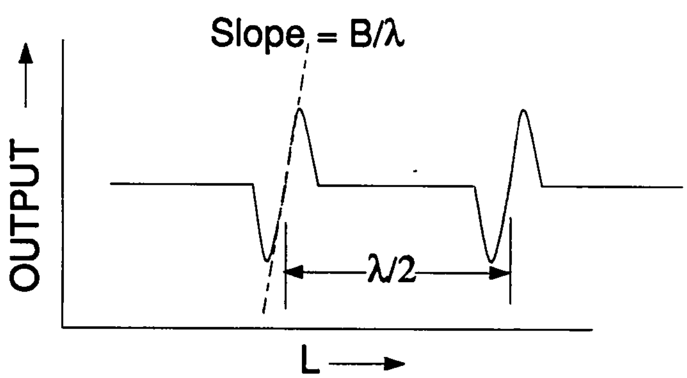
Shot Noise

LIGO

SHOT NOISE LIMIT TO SENSITIVITY



PHASE DETECTION



Output $\propto$ Phase ϕ

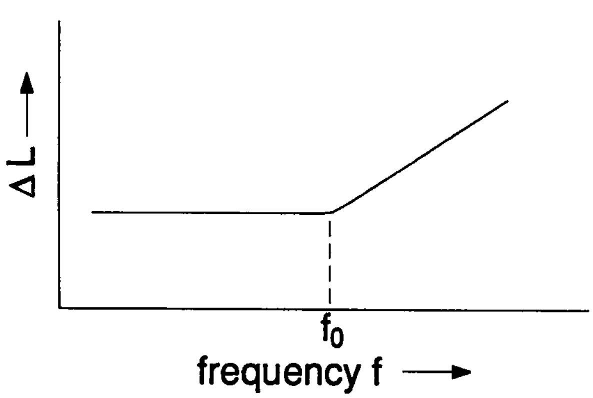
Precision $\Delta\phi \cong \frac{1}{\sqrt{N}}$

$N \propto$ Power at beam splitter

$\propto$ (Laser power) x (# of recycles)

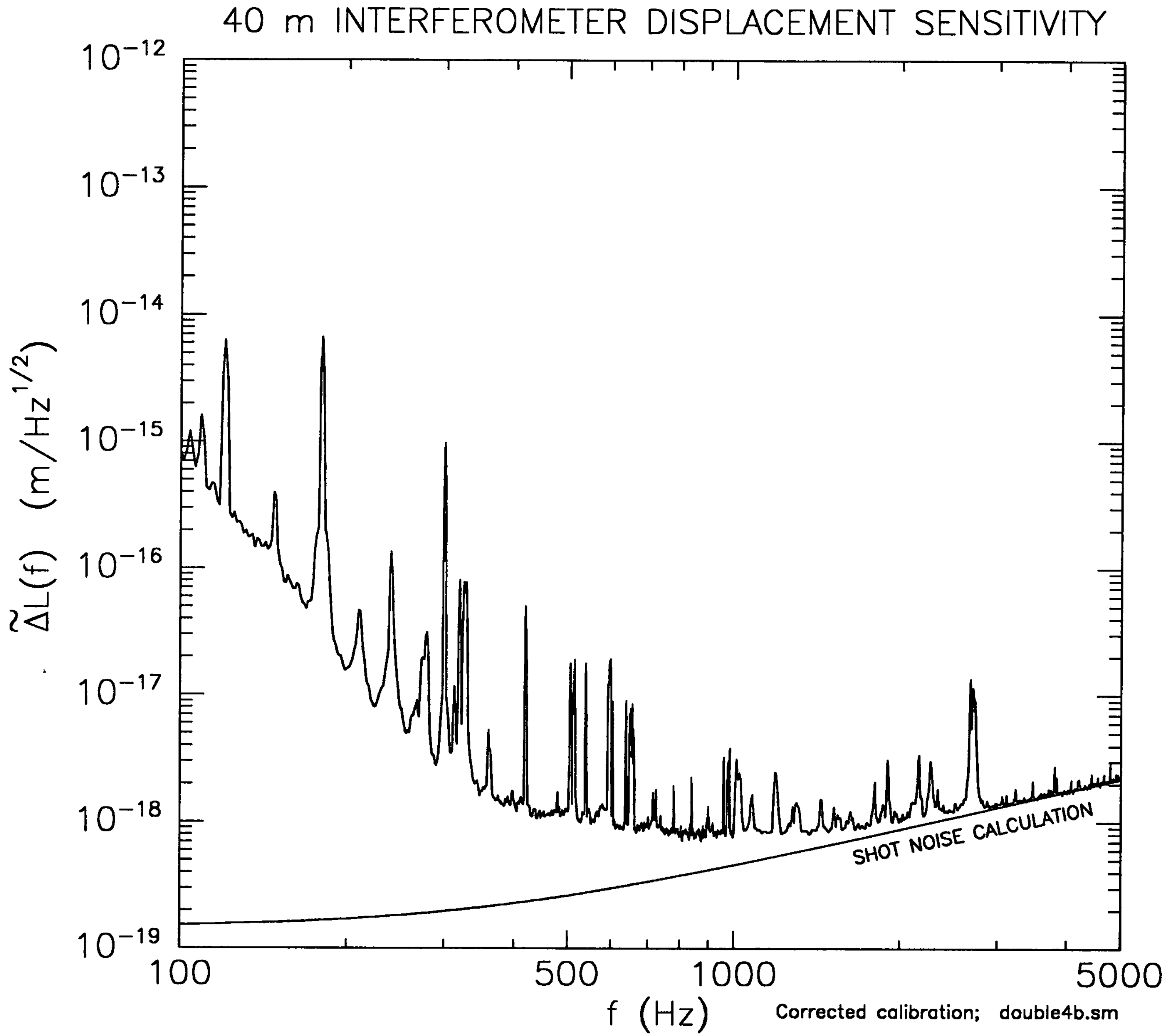
Noise Equivalent $\Delta L \cong \frac{\lambda}{B}\frac{1}{\sqrt{N}}$

FREQUENCY DEPENDENCE

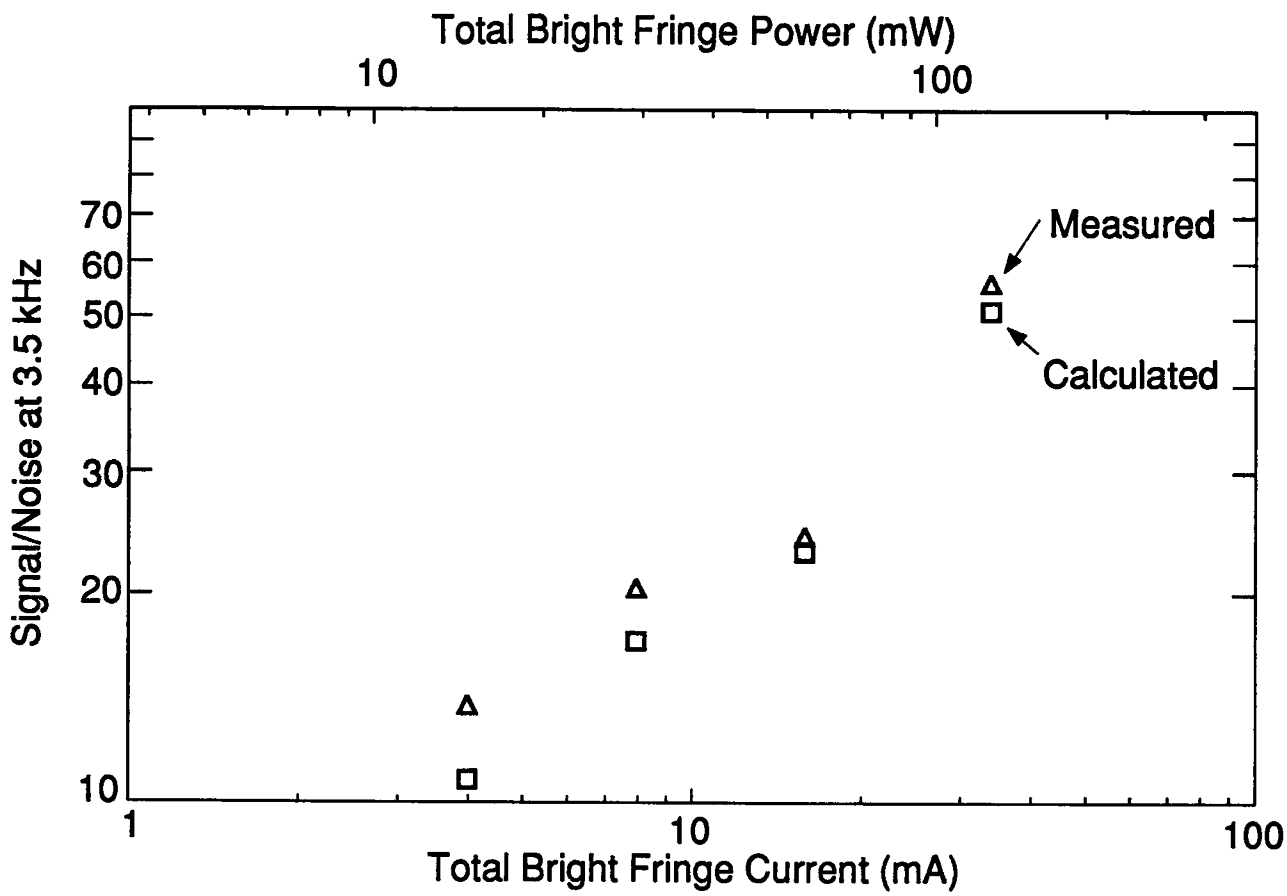


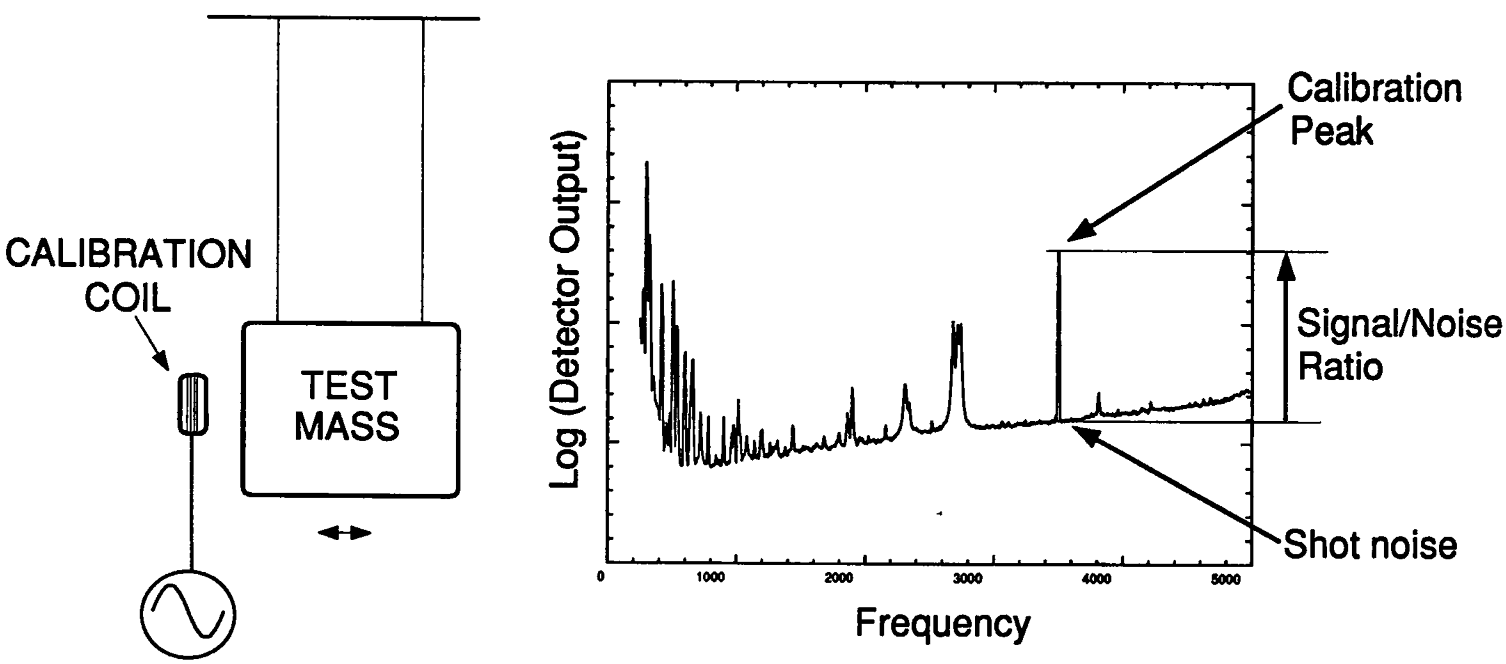
Noise Equivalent $\Delta L \propto \sqrt{1 + (f/f_0)^2}$

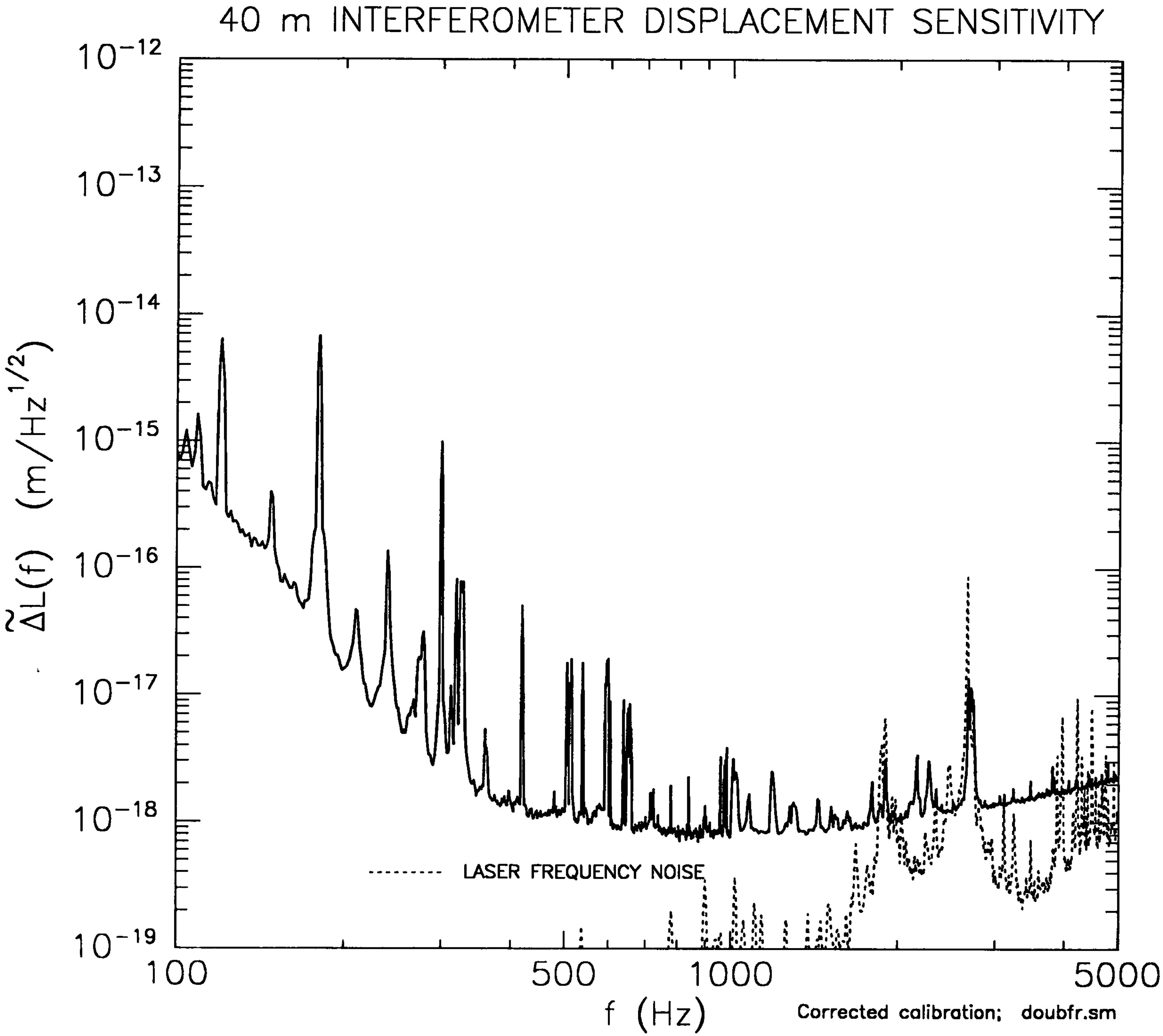
set $f_0 \cong$ lowest expected signal frequency


40 m INTERFEROMETER DISPLACEMENT SENSITIVITY
$\tilde{\Delta L}(f)$ $(m/Hz^{1/2})$
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
SHOT NOISE CALCULATION
100
500
1000
5000
f (Hz)
Corrected calibration; double4b.sm

POWER DEPENDENCE OF SHOT NOISE






40 m INTERFEROMETER DISPLACEMENT SENSITIVITY
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$\tilde{\Delta L}(f)$ (m/Hz$^{1/2}$)
LASER FREQUENCY NOISE
100
500
1000
5000
f (Hz)
Corrected calibration; doubfr.sm

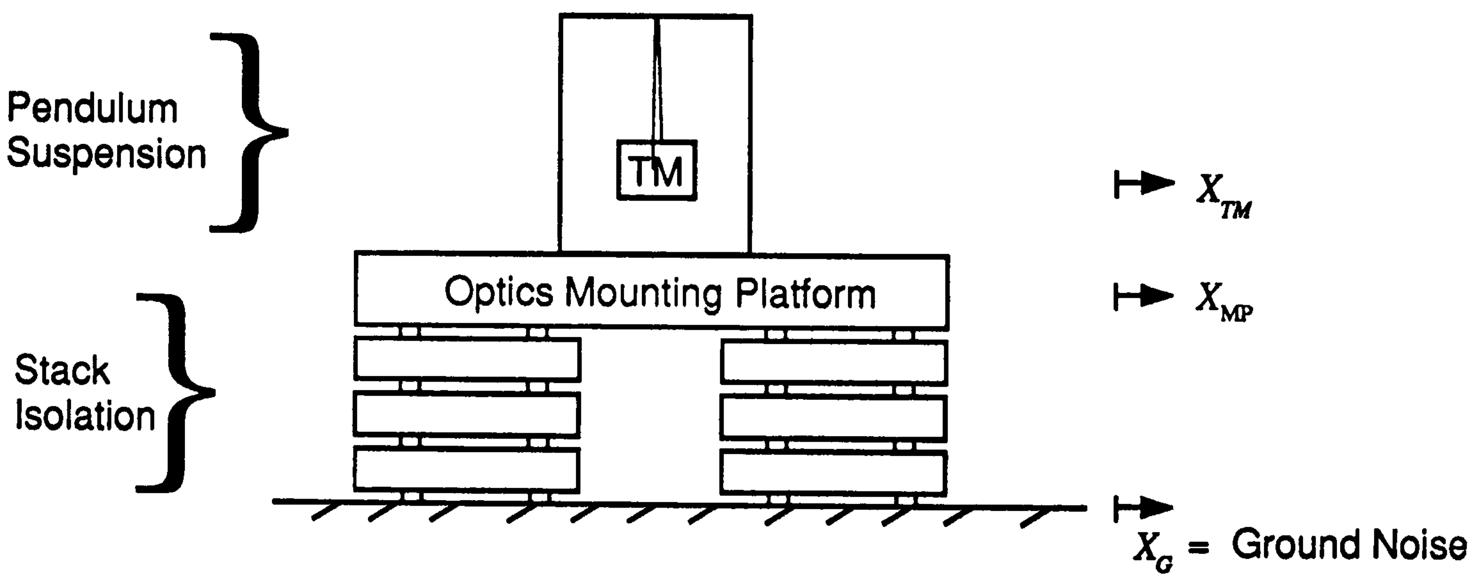
Seismic Noise

SEISMIC ISOLATION OF TEST MASS

Seismic Isolation of test mass is composed of 2 components:

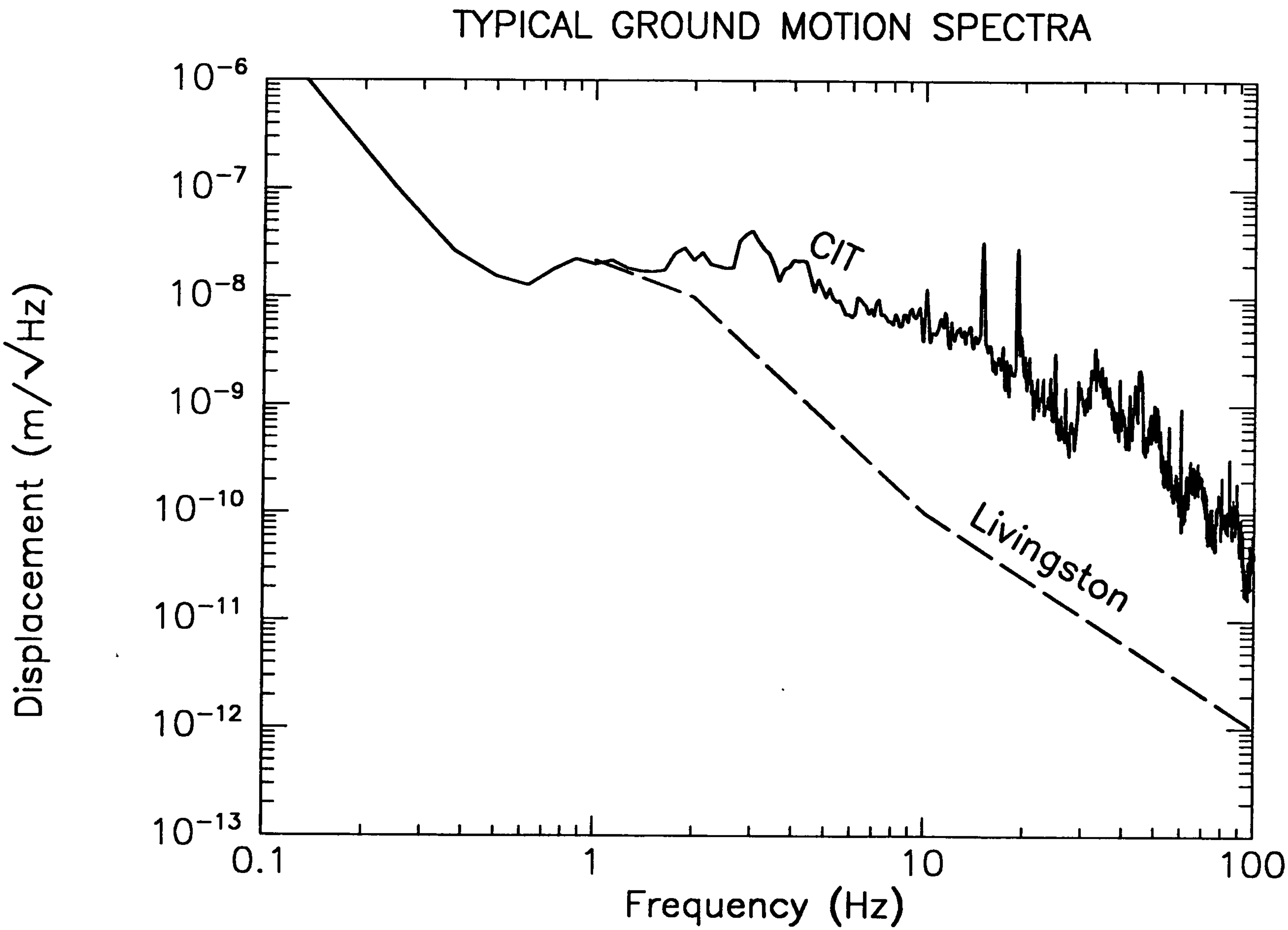
- **Stack Isolation**
- **Pendulum Suspension**

The ground noise at the sites drives the requirement on the amount of isolation necessary



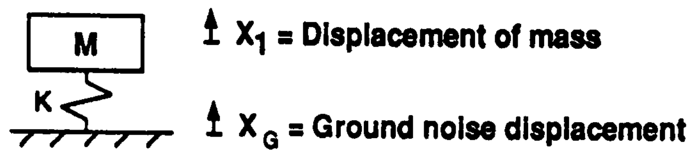
$$X_{TM} \sim \left[\frac{X_{TM}}{X_{MP}}\right]\left[\frac{X_{MP}}{X_G}\right] X_G$$

LIGO

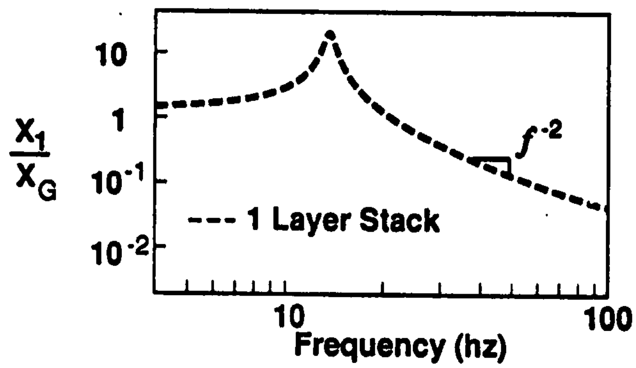

TYPICAL GROUND MOTION SPECTRA
Displacement (m/√Hz)
Frequency (Hz)
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
0.1
1
10
100
CIT
Livingston

PASSIVE ISOLATION CONCEPT

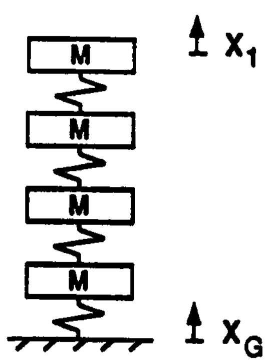
MODEL OF 1 LAYER STACK



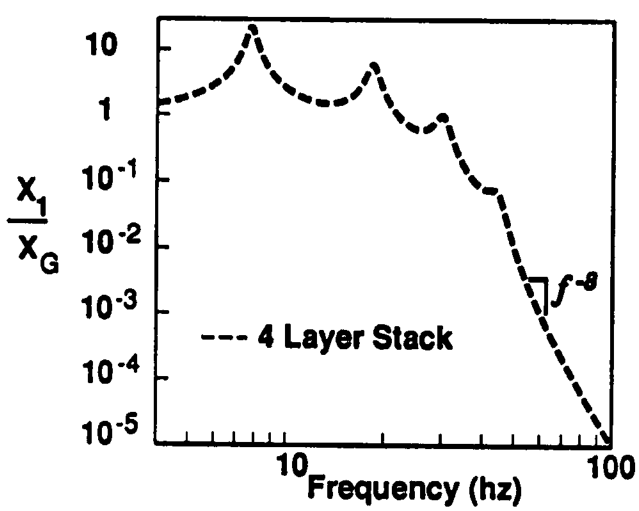
- MEASURE OF ISOLATION: X_1/X_G



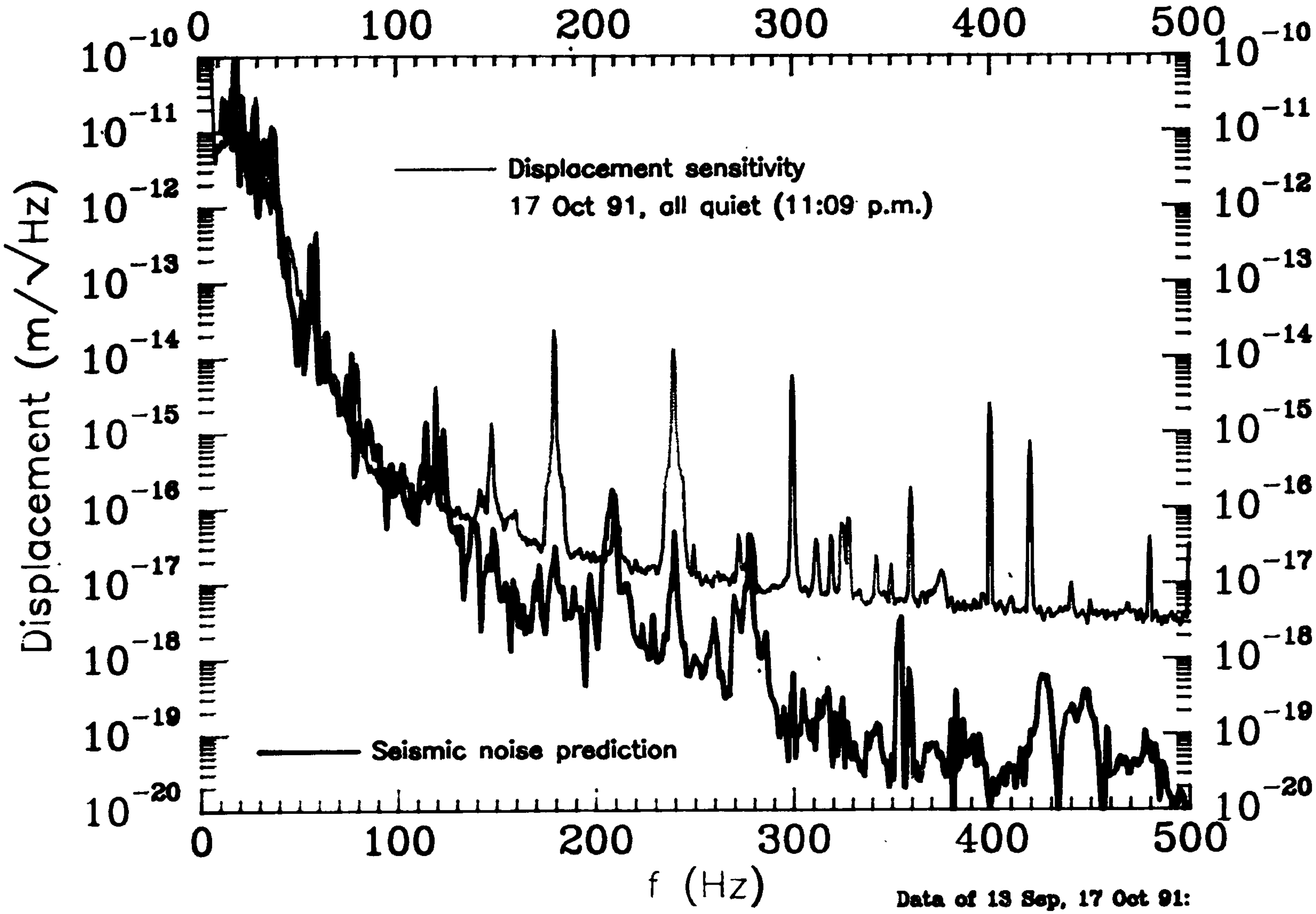
- EACH ADDITIONAL LAYER INCREASES THE ROLL-OFF BY f^2.



Simple Model of Mark 2 Stack Isolation (vertical)

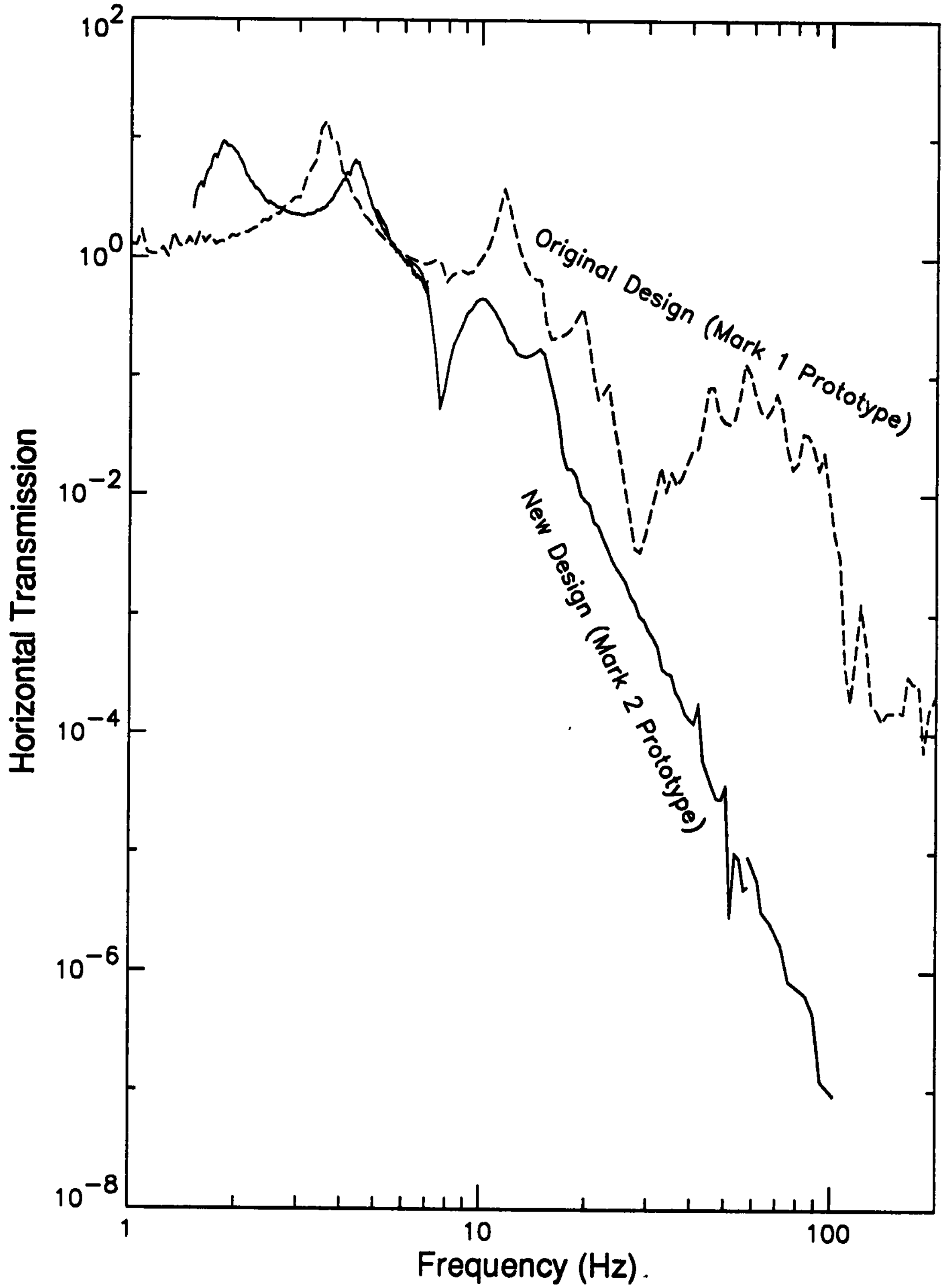


SEISMIC NOISE CONTRIBUTION---VERTICAL (H)
Input excitation measured by accelerometer



Data of 13 Sep, 17 Oct 91:
shv1, shv4, shv2, shv8, late, late1; sepspv.sm

COMPARISON OF VIBRATION ISOLATION STACK PERFORMANCE



Thermal Noise

LIGO

Thermal Fluctuations of a Damped Harmonic Oscillator

- **Thermal agitation results in random fluctuations:**

$$\tilde{x}_T^2(f) = \frac{4k_BT}{\omega}\,\frac{k\phi(\omega)}{(k - m\omega^2)^2 + k^2\phi^2(\omega)}$$

complex spring constant = $k[1 + i\phi(\omega)]$

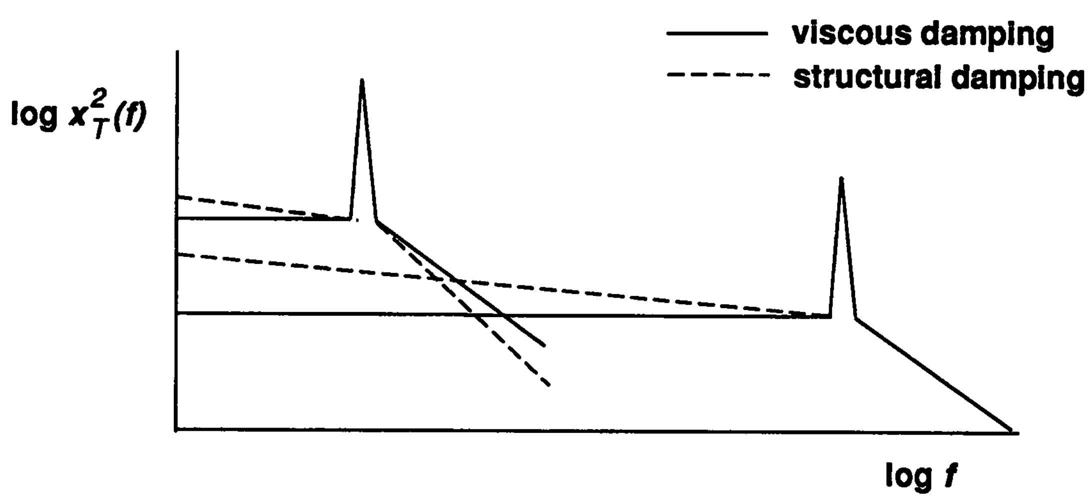
- **Reasonable parameterizations for** $\phi(\omega)$**:**

Viscous Damping

$$F_d = -2\gamma v \rightarrow \phi(\omega) = \frac{2\gamma\omega}{k}$$

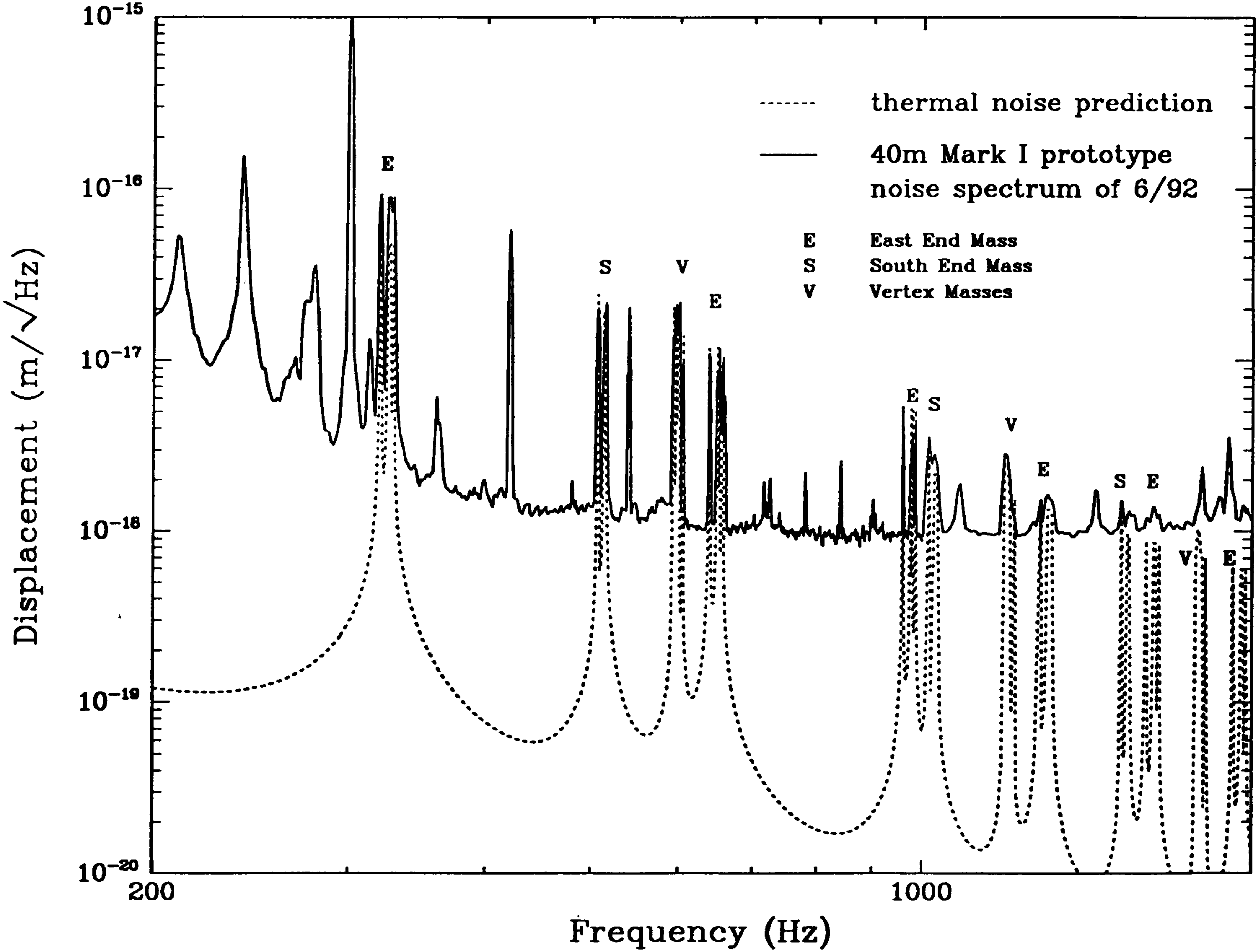
Structural Damping

$$\phi(\omega) \;=\; \text{constant} \;=\; 1/Q$$

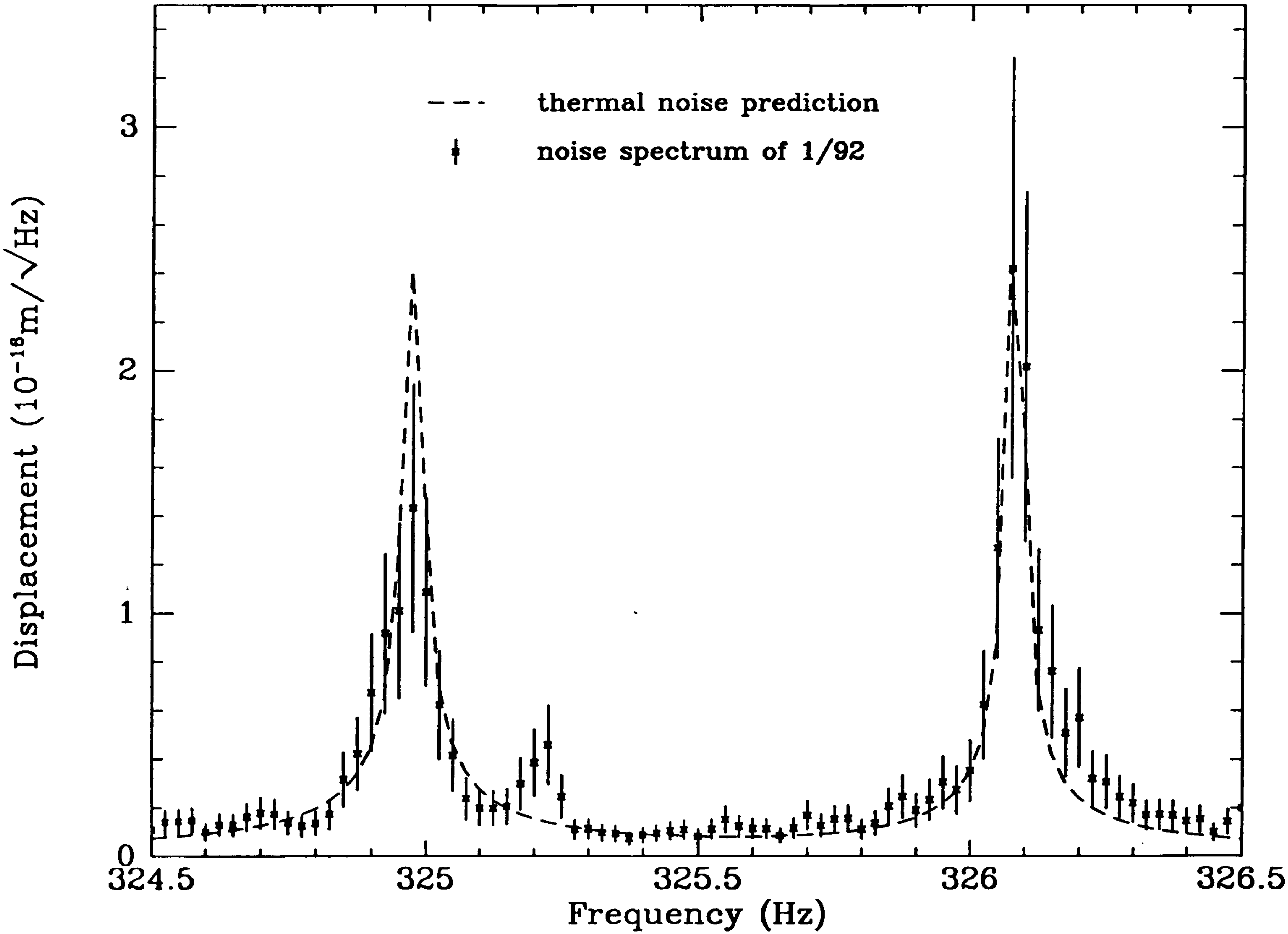


LIGO

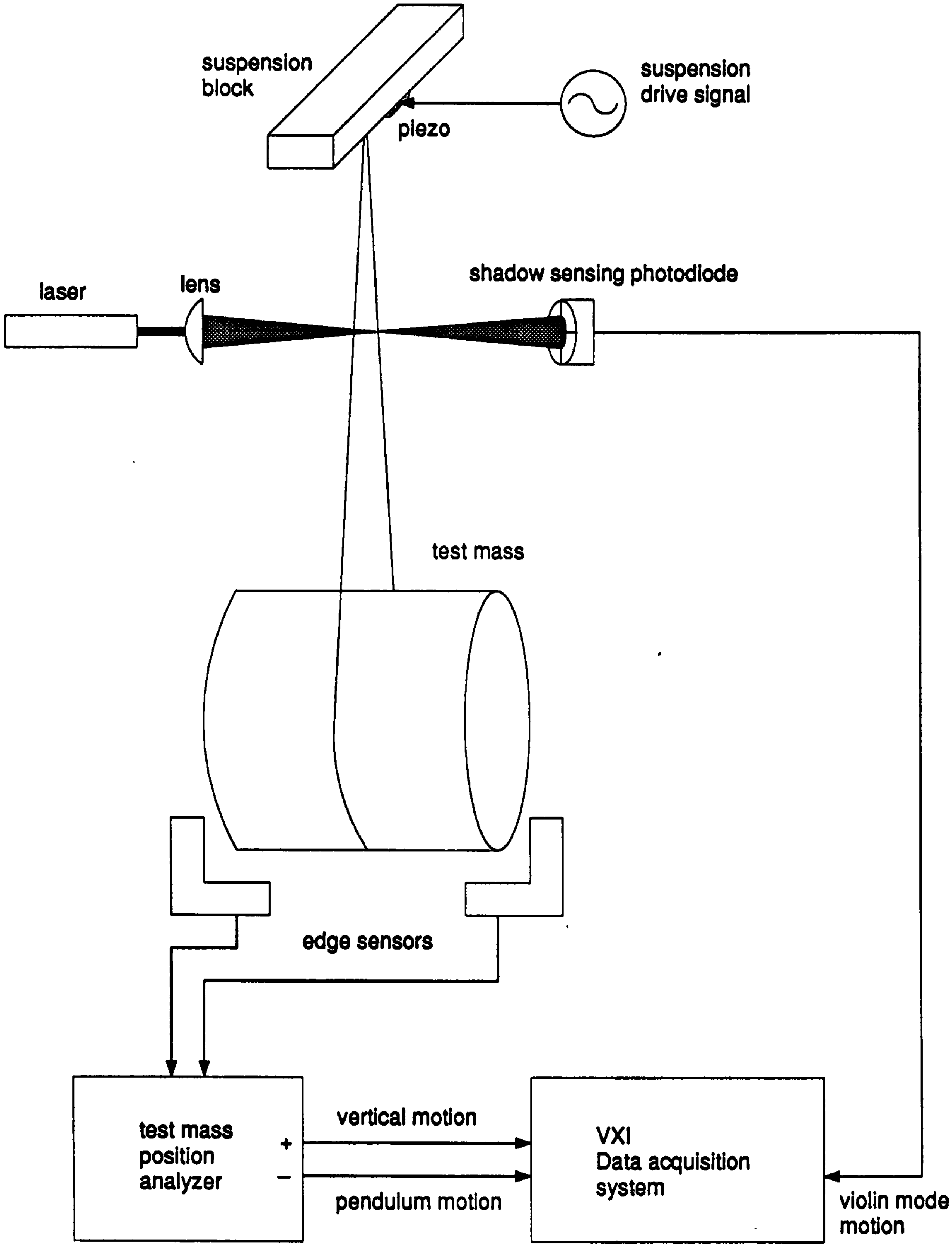
Suspension Thermal Noise, 40m Mark I Prototype

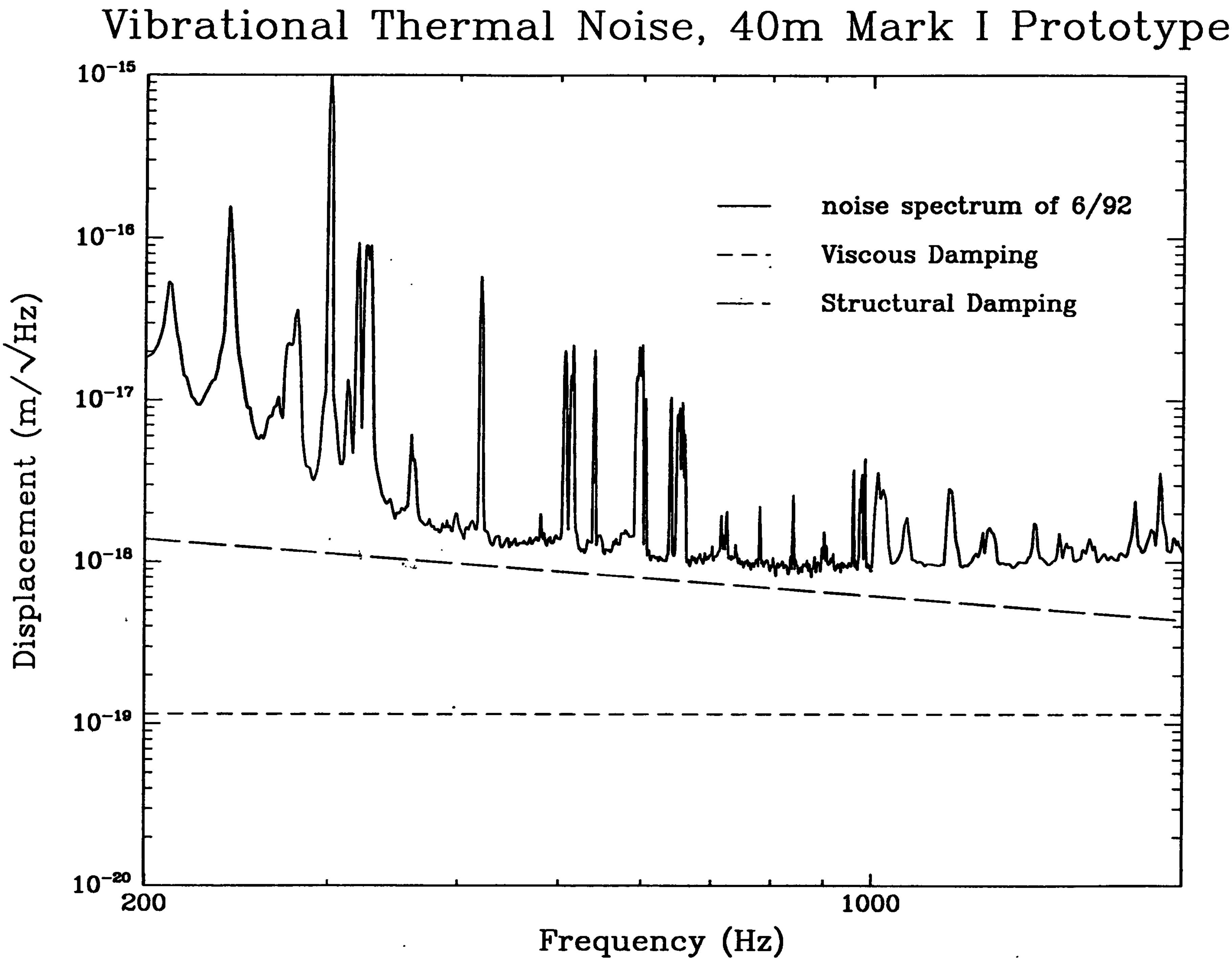


East End Mass Violin Resonances



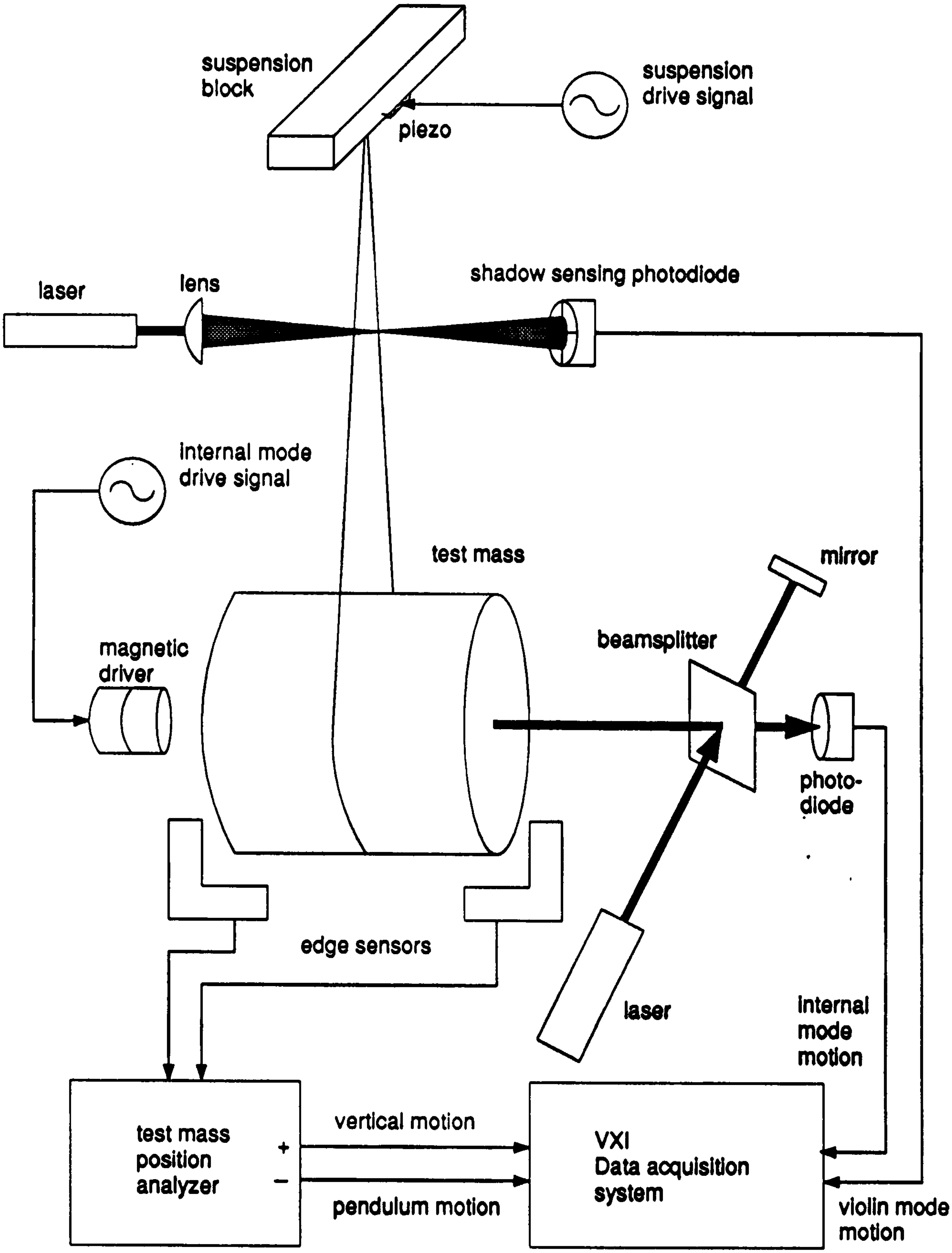
Suspension Development Apparatus





Vibrational Thermal Noise, 40m Mark I Prototype
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
Displacement (m/√Hz)
200
1000
Frequency (Hz)
noise spectrum of 6/92
Viscous Damping
Structural Damping

Suspension Development Apparatus



Optics Development and Testing

Optics Development

- Stringent Requirements for:
  - Optical figure
  - Substrate homogeneity
  - Low loss coatings

- Optics which meet the requirements are presently available on smaller diameter optics.

- Present concentration:
  - Developing the proper specifications to insure good interferometer performance.
  - Satisfying these specifications on 25 cm diameter mirrors.
  - Need to insure that the optical characteristics of the mirrors are not degraded by their environment.

LIGO

Mirror Characterization

- Parameters to be measured:
  - Reflectivity
  - Transmission
  - Scattering
  - Absorption
- Presently have "single location" capabilities for all parameters
- Position-dependent measurements of these parameters will allow characterization of the entire mirror surface and numerical modeling of LIGO interferometer performance.
- Position-dependent transmission apparatus is operational.
- Position-dependent reflectivity and scattering apparatus is partially operational.
- Absorption experiments are ongoing
- Plan to develop metrology using 1" diameter optics then upgrade positioning equipment to handle 25 cm optics (15 cm $\times$ 15 cm scan area).

Power Testing

- Purpose is to determine the high power (CW) performance characteristics of mirrors and transmissive optics.

- Mirror Testing

    - Lock Ar^+ ion laser to a cavity made of test mirrors.

    - Monitor optical losses in the cavity as a function of hours locked.

    - Measurement accuracy was ± 2 ppm.

    - After 100 locked hours, increase to next higher power level.

    - No changes in the initial optical losses were seen on mirrors at highest power setting (4 kW circulating power) after 100 hours (100 times initial LIGO intensity, same as initial LIGO power level).

- Transmissive Optics (for Input Beam Conditioning)

    - Pass beam of variable power through optic.

    - Look for dependence of spot size in far field as a function of power.

    - No serious optical distortions were observed at initial LIGO power (4 watts CW).

Contamination Testing

- Test materials for use inside the LIGO vacuum system.

- Materials which are normally considered "vacuum compatible" may actually contaminate the mirror surfaces to unacceptable levels.

- Test for possible mirror degradation caused by long term exposure to a material specimen.

    - Introduce specimen into clean vacuum system containing an optical cavity.

    - Monitor cavity losses over months.

    - RTV and Viton caused less than 0.4 ppm per week of additional losses.

- Test for possible mirror degradation caused by simultaneous exposure to various material specimens and high laser intensities.

    - Subject an optical cavity with a material specimen in the vacuum to mirror power test.

    - No damage was detected to the mirrors when exposed to either RTV or Viton at laser intensities of 400 KW/cm^2 (8 times initial LIGO intensities) for 100 hours.

Summary of Noise Investigations

- Most Fundamental Noise Source Models Verified (Theoretical Formulation Correct, Parameters and Scaling Properties Known)
  - Shot Noise
  - Seismic Noise
  - Residual Gas

- Substantial Progress toward Understanding Thermal Noise
  - Use of Wire Modes to Determine Damping Parameters at Relevant Frequencies
  - Preliminary Results Indicate Suspension Thermal Noise Goals Achievable
  - Systematic Investigation of Thermal Noise from Test Mass Modes Underway

- Numerous Non-fundamental ("Technical") Noise Sources Diagnosed and Controlled

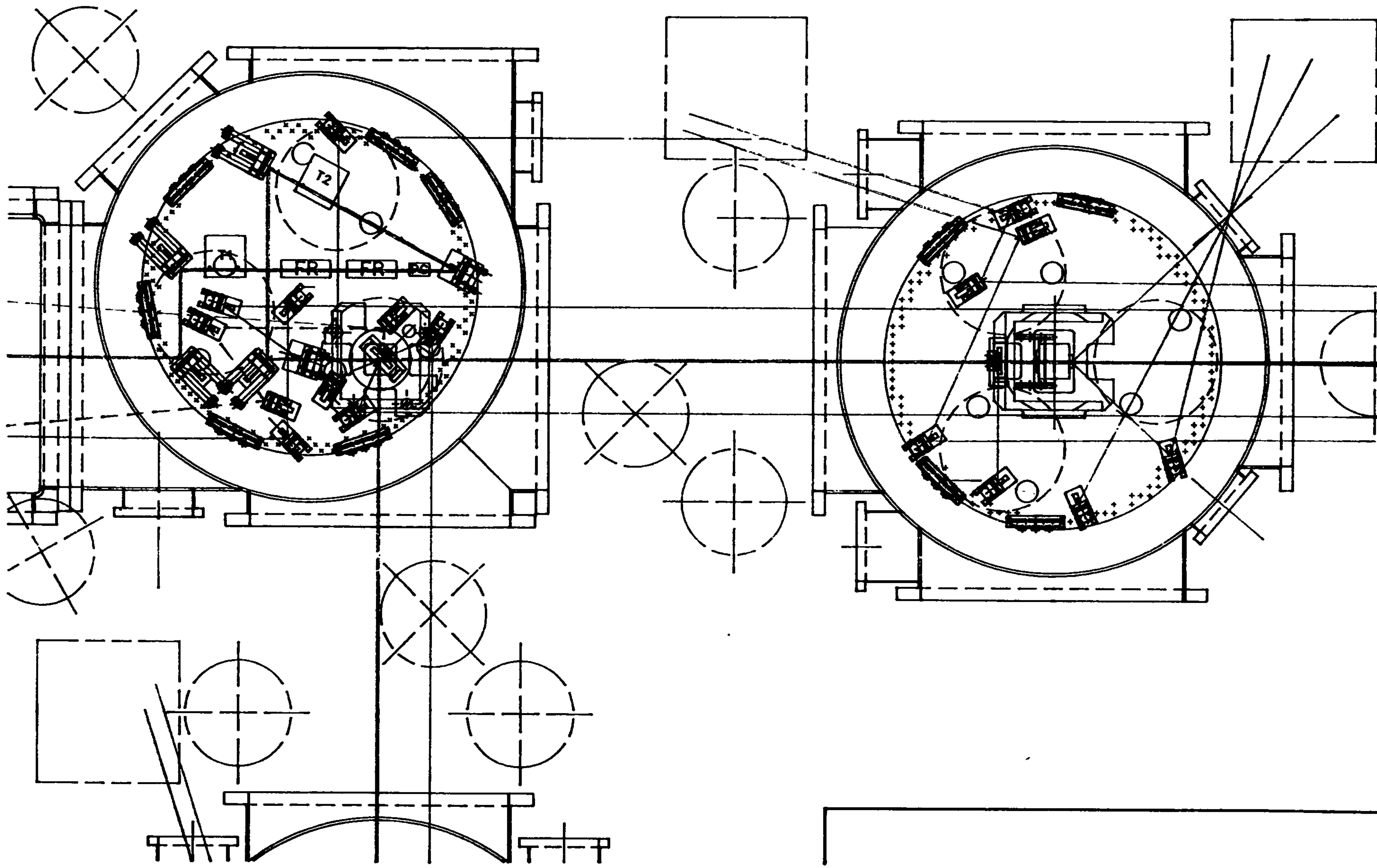
Limitations of Mark I 40 m Interferometer

- Optical Topology is Not LIGO Compatible
  - No Recombination or Recycling
  - Vacuum System Too Small to Accommodate LIGO Topologies
- Seismic Isolation Insufficient Below 300 Hz
  - Existing Isolation System Not Scalable
  - Chambers Too Small to Accommodate LIGO-like Isolation Stacks
- Vacuum System Contaminated with Organics
  - Prevents Operation of Interferometer at High Laser Power

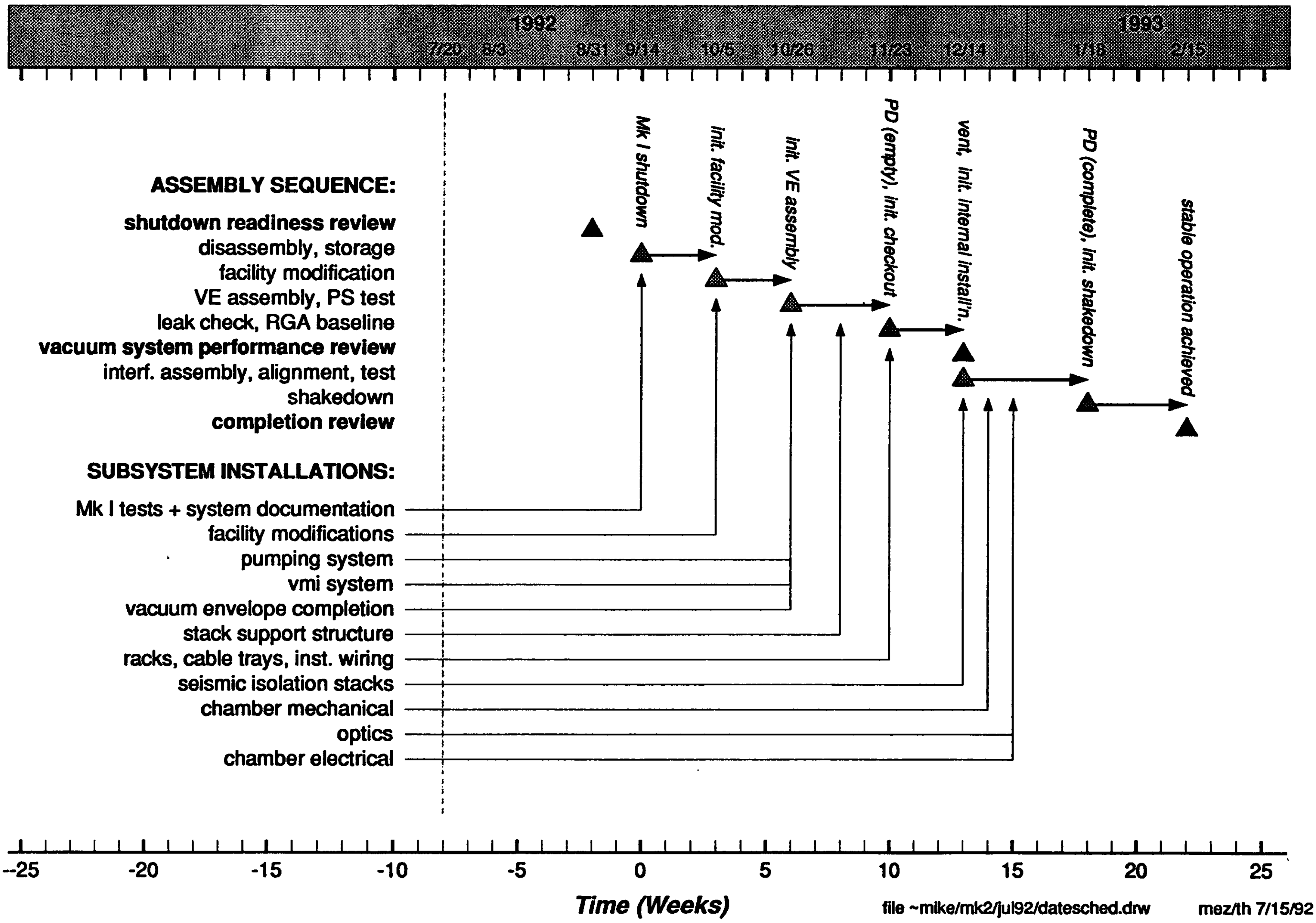
Mark II 40 m Interferometer

- Provide a Larger Vacuum System to Facilitate Future Experiments with Alternative Optical Topologies
  - Test Mass Chambers: 18″ → 48″
  - Beam Tube: 8″ → 24″
- Install Improved Seismic Isolation Stacks
  - LIGO Type and Scale
  - $>10^3$ Improvement at 100 Hz
- Provide a Clean Vacuum Environment for Long Term Operation Of Supermirrors
  - Strict Qualification and Control of All Materials Used
  - Allow Full Laser Power Operation of Interferometer
  - Test of Long-term Degradation Effects Before LIGO Installation
- Minimal Changes to Remainder of Interferometer to Give Continuity of Baseline Performance
  - Optical Topology
  - Suspensions and Controls
  - External Optics
  - Mode-Cleaner

BS & VERTEX TM CHAMBERS



Mk II Prototype: Revised Assembly Schedule



Experiments Planned for Mark II Interferometer

- Verify Improved Seismic Isolation
- Install and Test New Mode Cleaner
- Install and Test New Monolithic Test Masses and Suspensions
- Operate in Recombined and Recycled Optical Configuration