Detection of Gravitational Waves III. Practice

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Overview of 3 Lectures

I. Principles (Fri 7 Aug)
- nature of gravitational waves
- experimental principles

II. Strategies (Mon 10 Aug)
- resonant-mass detector systems
- interferometer systems

III. Practice (Today, Tues 11 Aug)
- real instruments
- What does the future hold?

Outline of Lecture III

LSU's ALLEGRO

Prototype interferometers

- MPQ's 30-m ifo
- LIGO's 40-m ifo
- LIGO's Phase Noise Ifo

LIGO

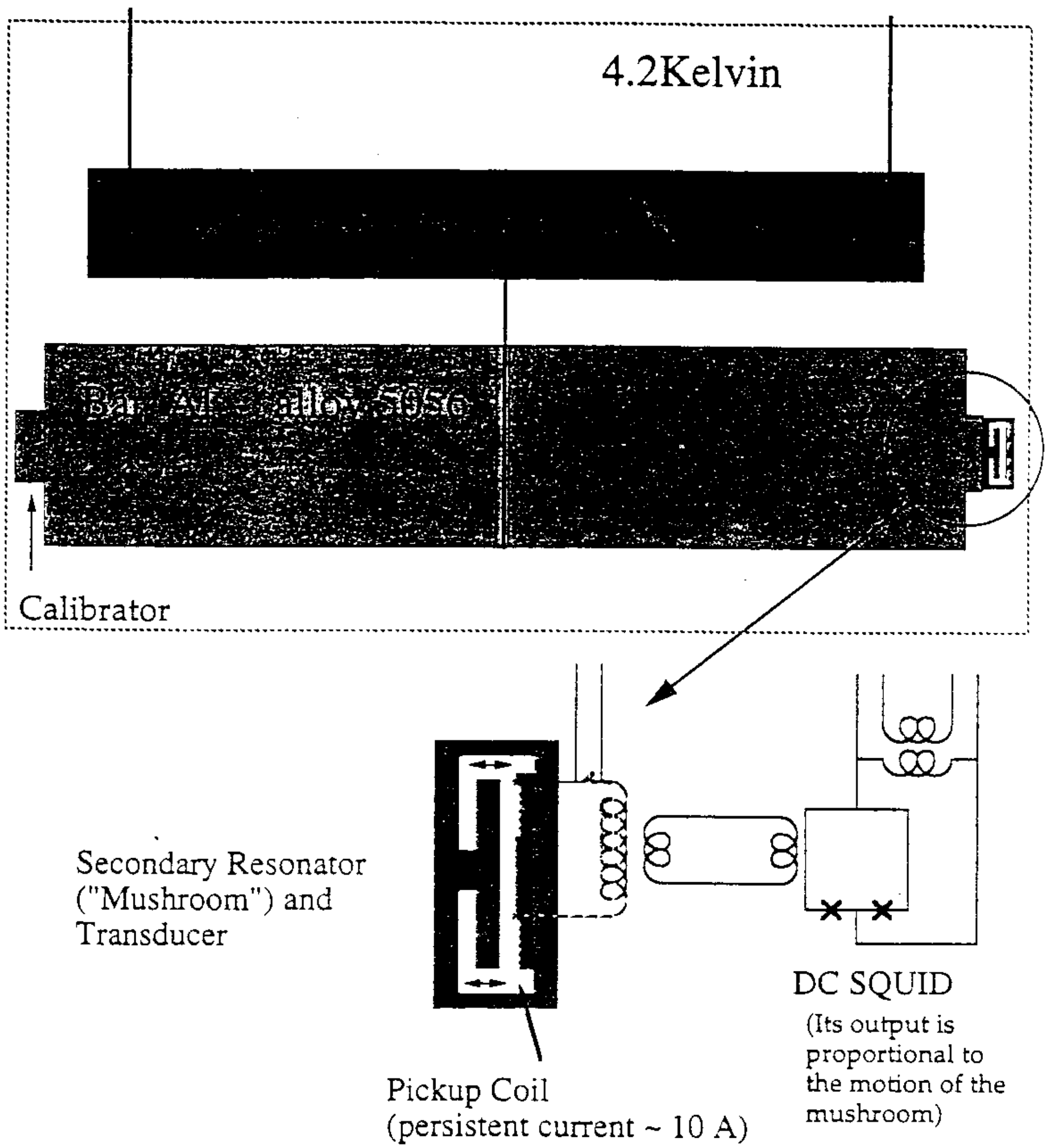
The future: large interferometer development, spheres, interferometers in space.

LSU's Allegro resonant-mass detector

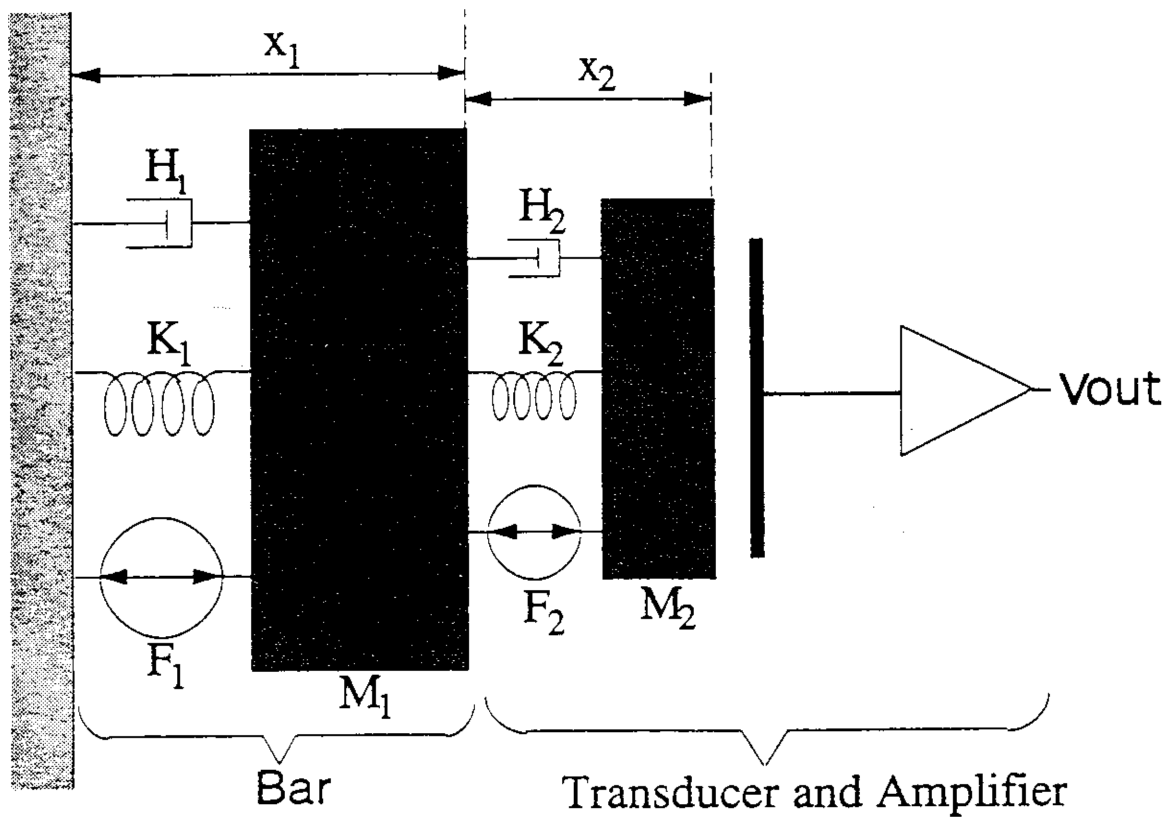
- State-of-the-art second generation detector
- $T = 4.2$ K, $f_0 = 913$ Hz
- cryogenics, vibration isolation have been well engineered for stable long-term operation
- ~1 event/day at levels equiv to

$$h > 2 \times 10^{-18}$$

Allegro antenna schematic



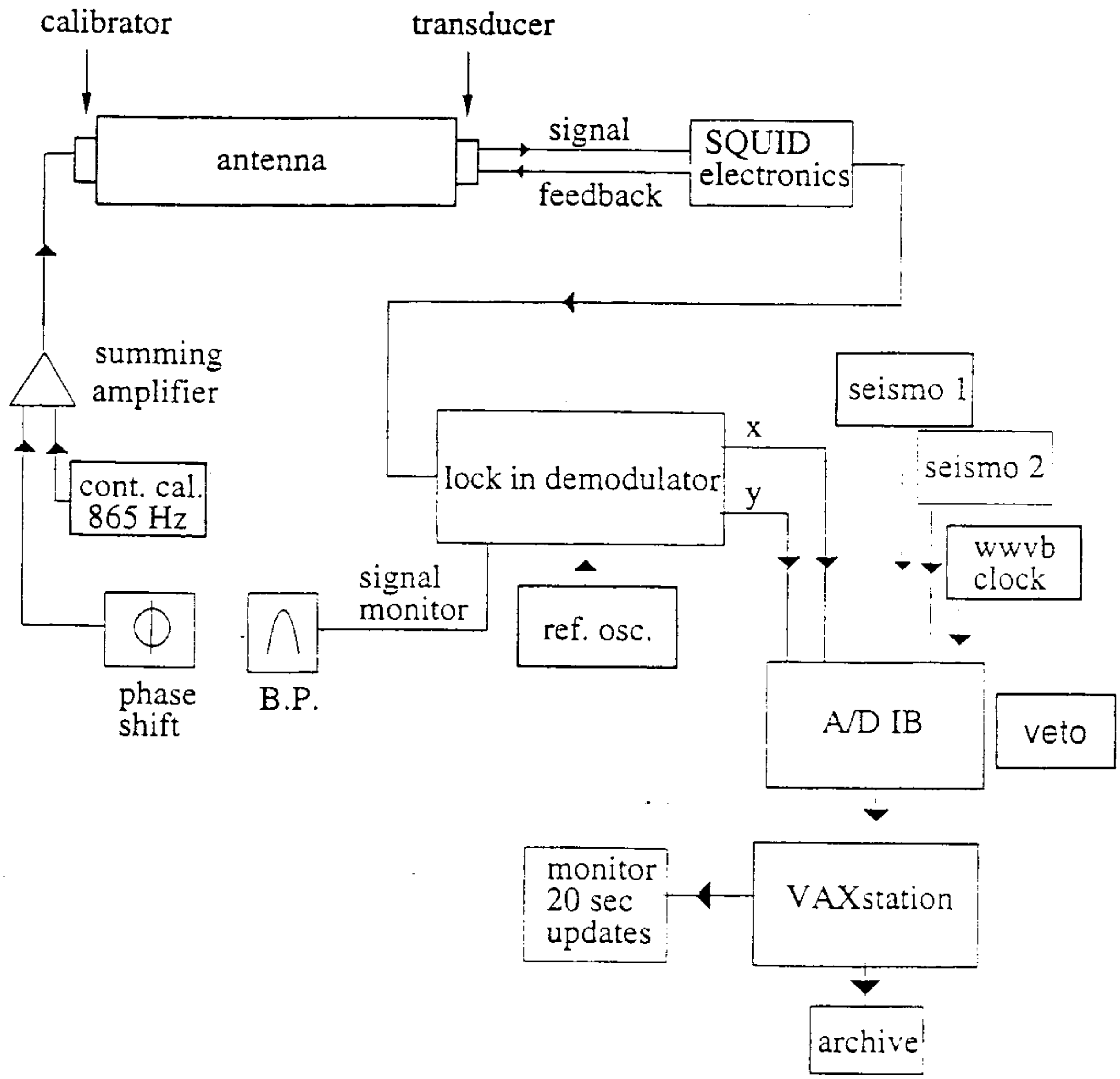
Allegro antenna model



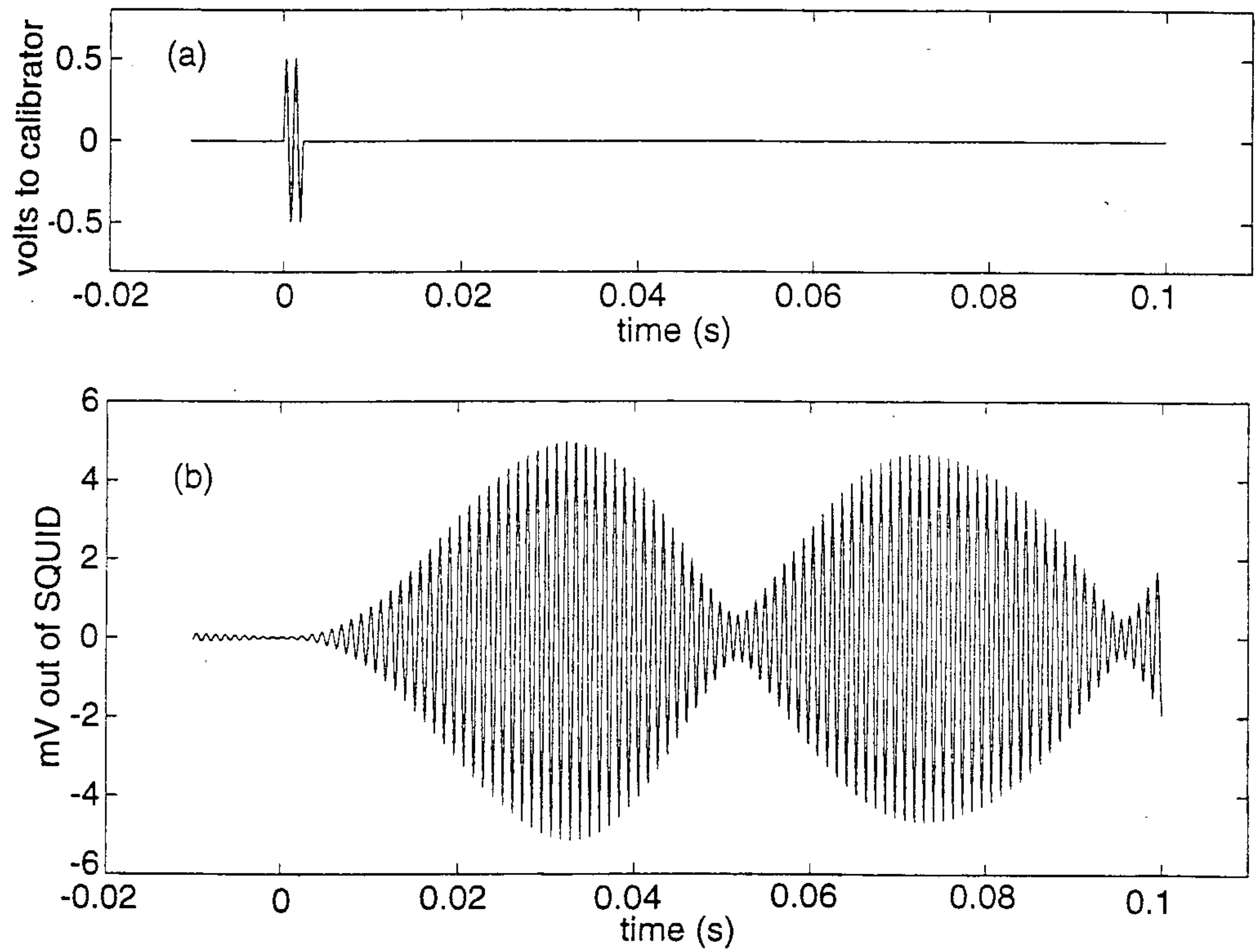
$$M_1\ddot{x}_1(t)+H_1\dot{x}_1(t)+K_1x_1(t)-H_2\dot{x}_2(t)-K_2x_2(t)$$
$$=F_1(t)-F_2(t)+F_T(t)+\frac{1}{2}M_1L_1\ddot{h}_{xx}(t) \qquad (1)$$

$$M_2[\ddot{x}_2(t)+\ddot{x}_1(t)]+H_2\dot{x}_2(t)+K_2x_2(t)=F_2(t)-F_T(t). \qquad (2)$$

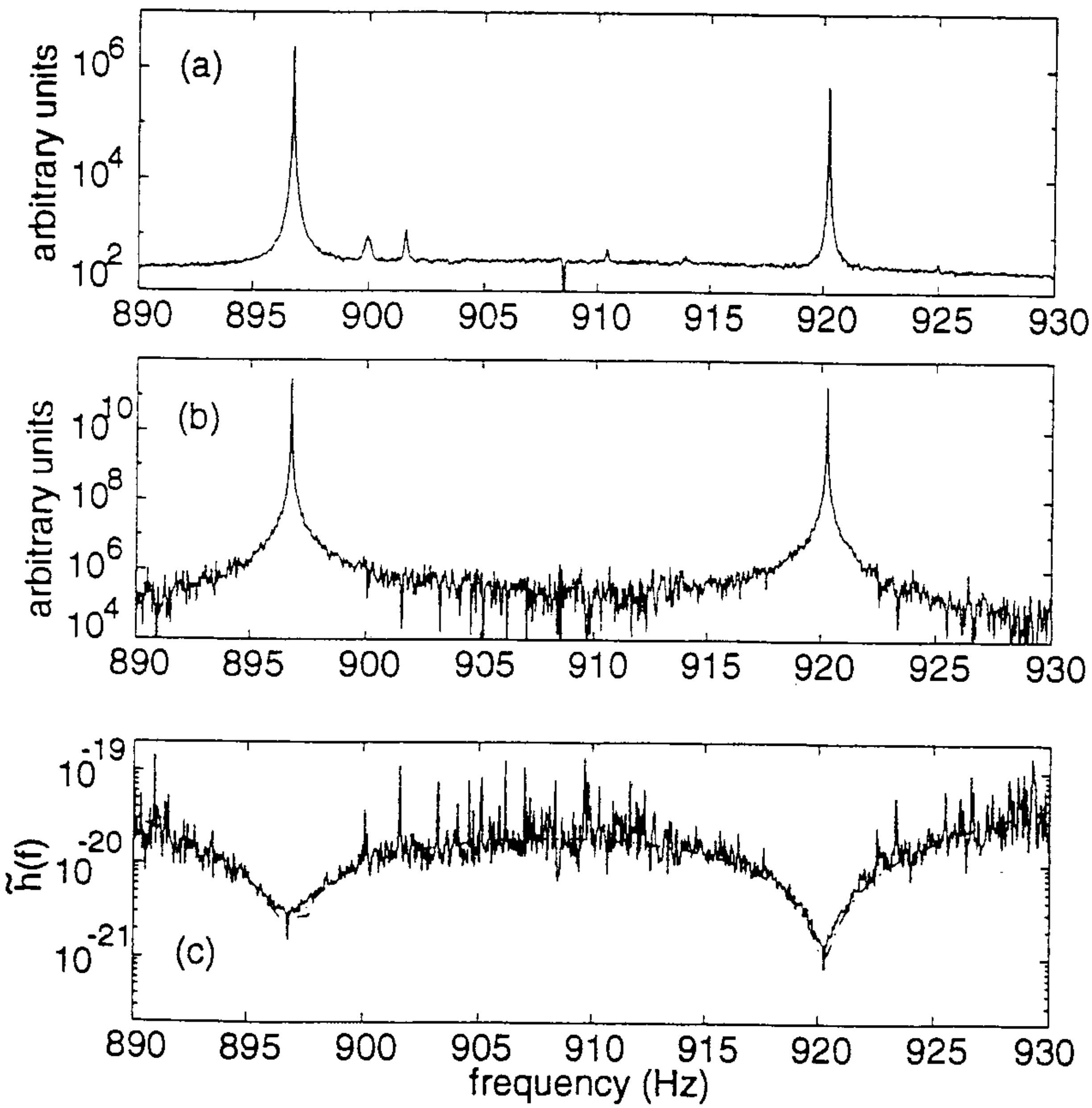
Allegro DAQ system



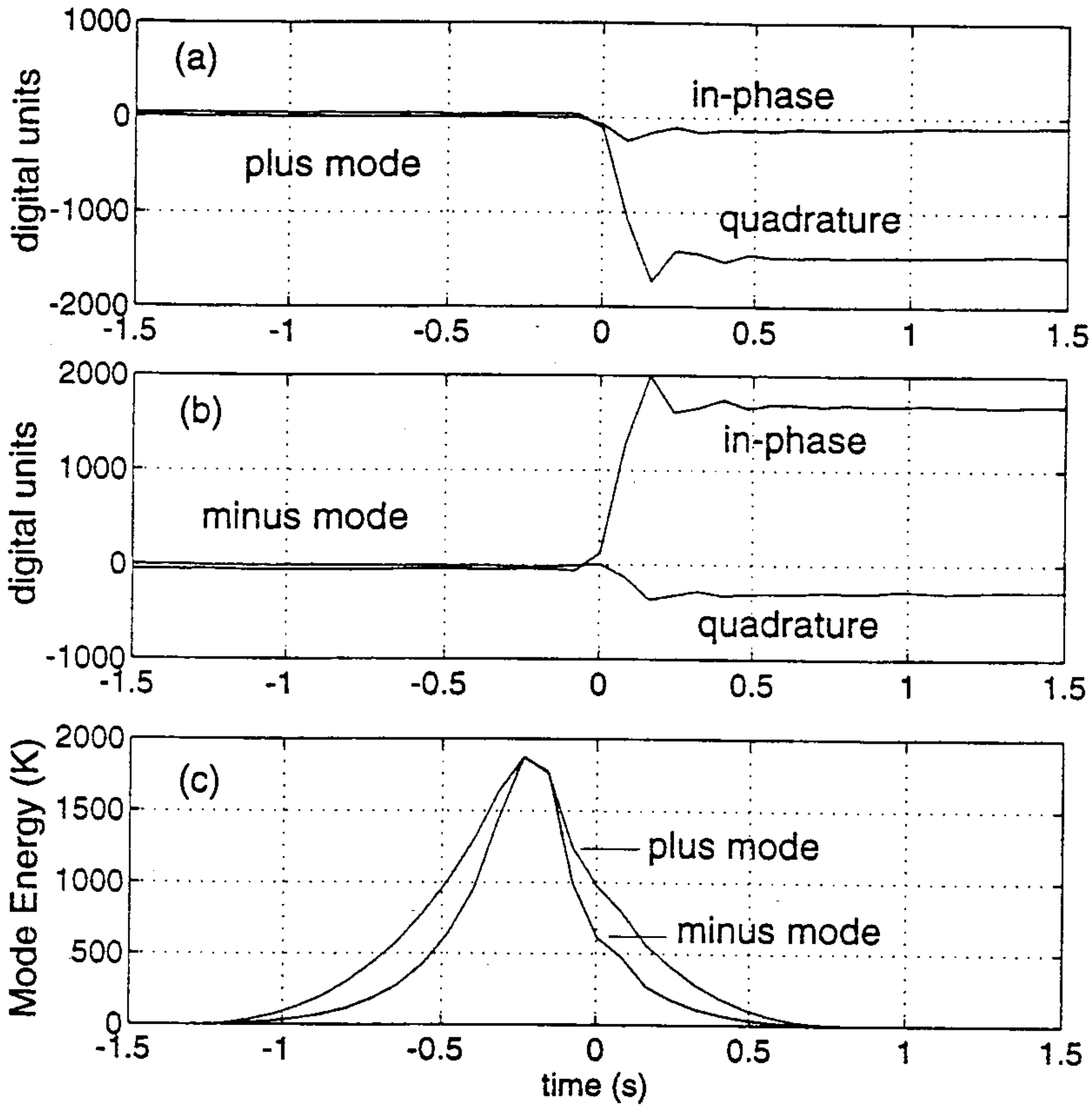
Allegro burst response



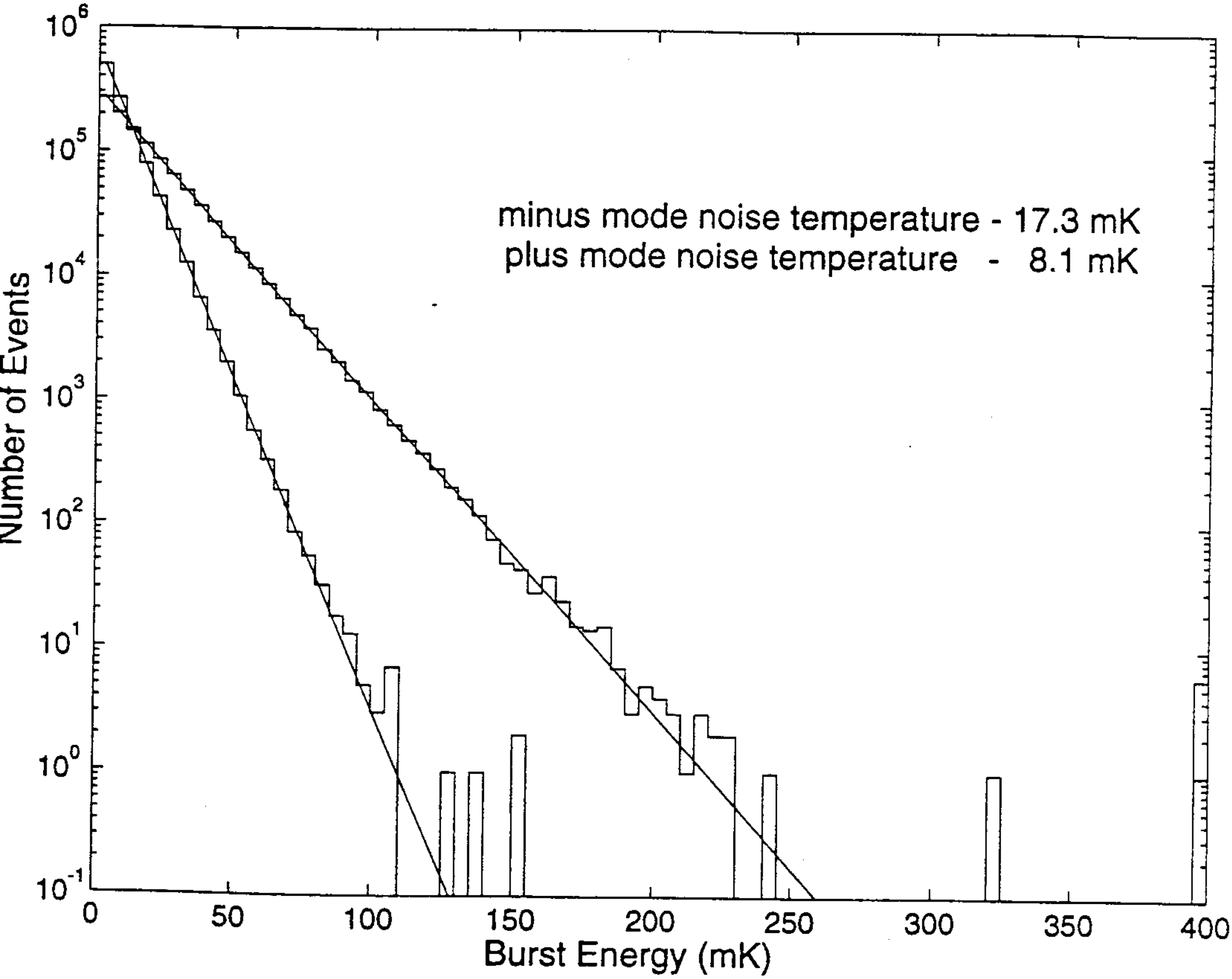
Allegro noise spectrum



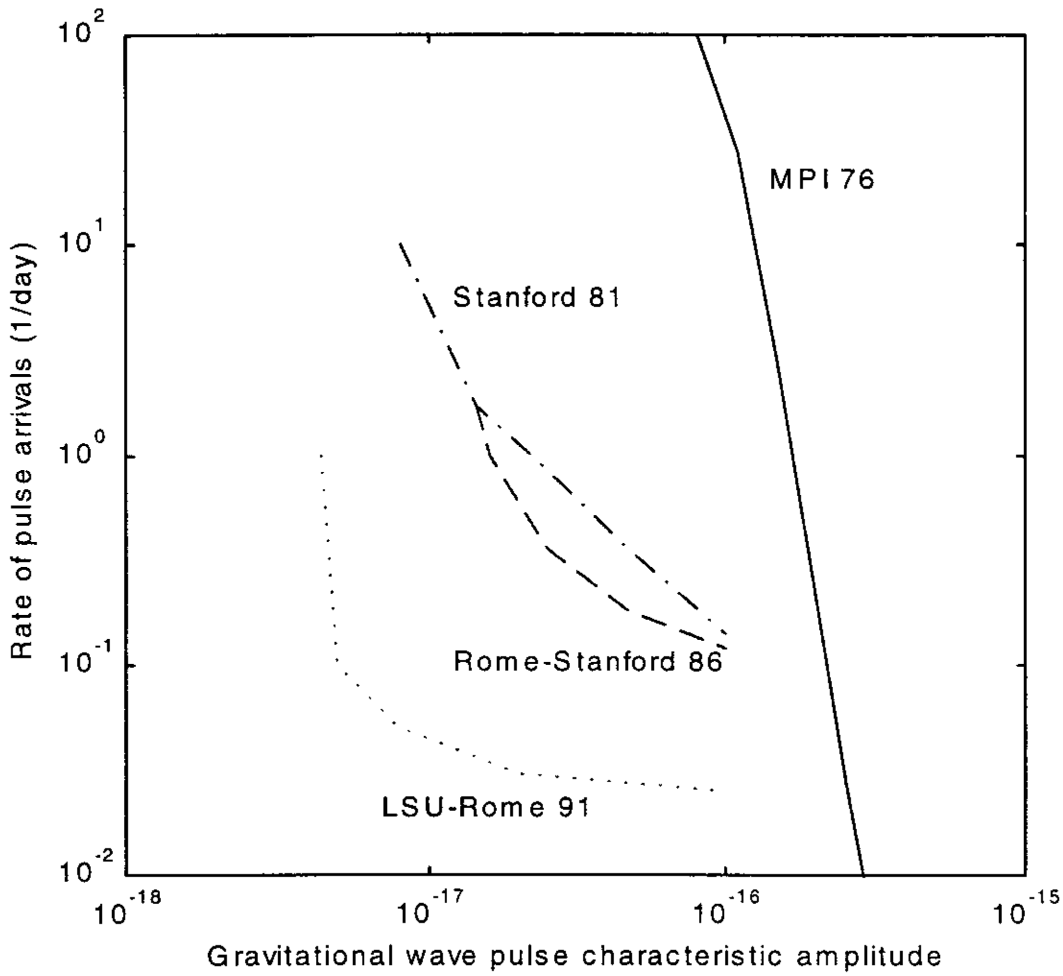
Allegro optimal filtering



Allegro event histogram



GW search w/ cryogenic resonant-mass detectors



3rd generation resonant-mass detectors

- Use ^3He-^4He dilution refrigerator to reach $T \sim 50$ mK.
- Two detectors now being shaken down:
  NAUTILUS (Frascati) and
  AURIGA (Legnaro).
- Early sensitivity should be near $h_{rms} \sim 10^{-19}$.
- With better preamps, $h_{rms} \sim 10^{-20}$.

Prototype Interferometers

- Designed to support design of large interferometers
  - proof of principle
  - tests of noise models
  - engineering tests
  - search for unpredicted problems
- Only briefly used as scientific instruments

  but noise levels have approached those of best resonant detectors

Real interferometer vs. *gedanken* interferometer

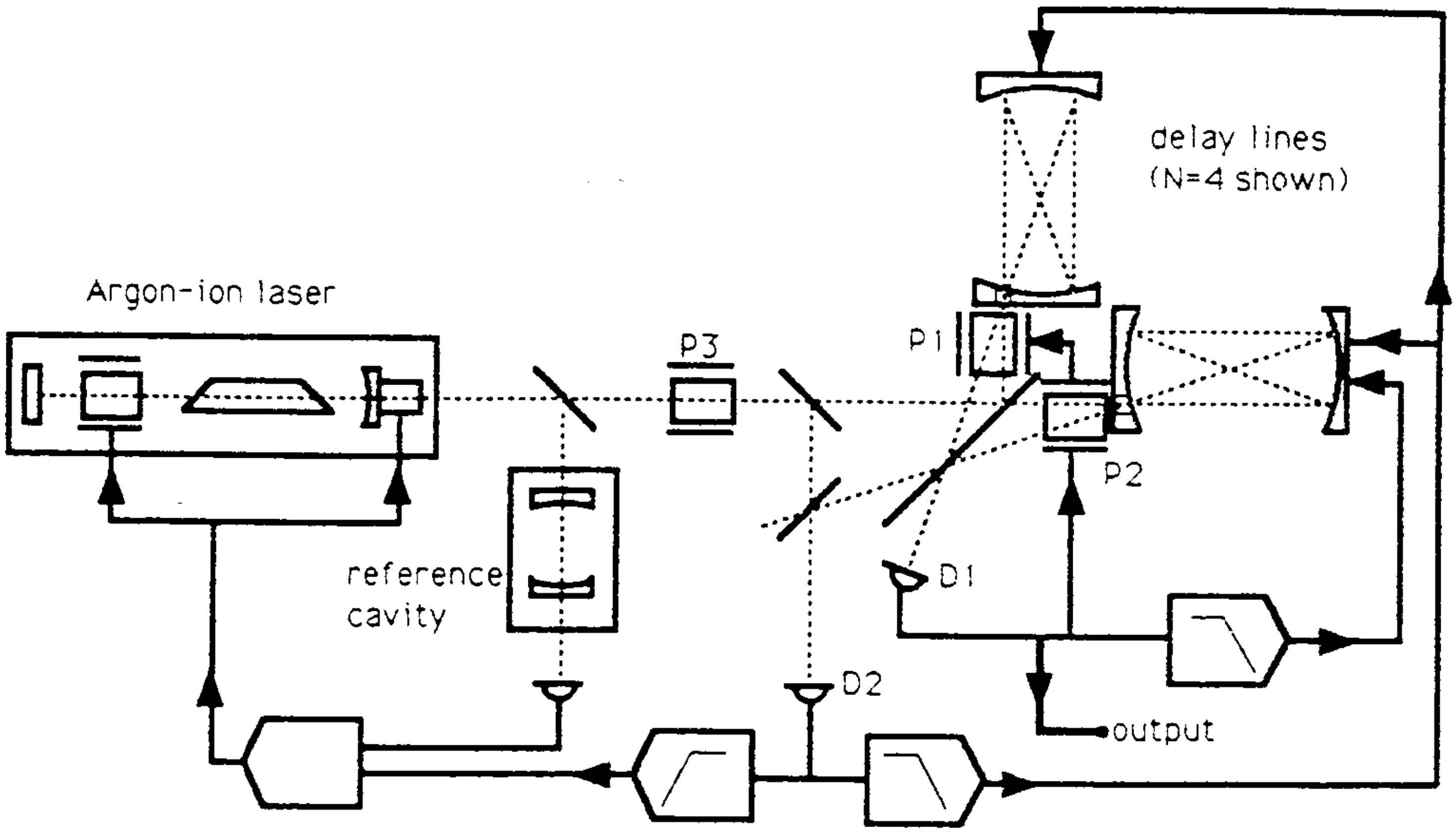
- In vacuum
- Servosystems control many degrees of freedom
  - orientation of mirrors
  - laser wavelength
  - interferometer arm lengths
  - arm length difference (= h)
- Held at "dark fringe" output

  RF modulation readout
- Add'l noise sources possible!

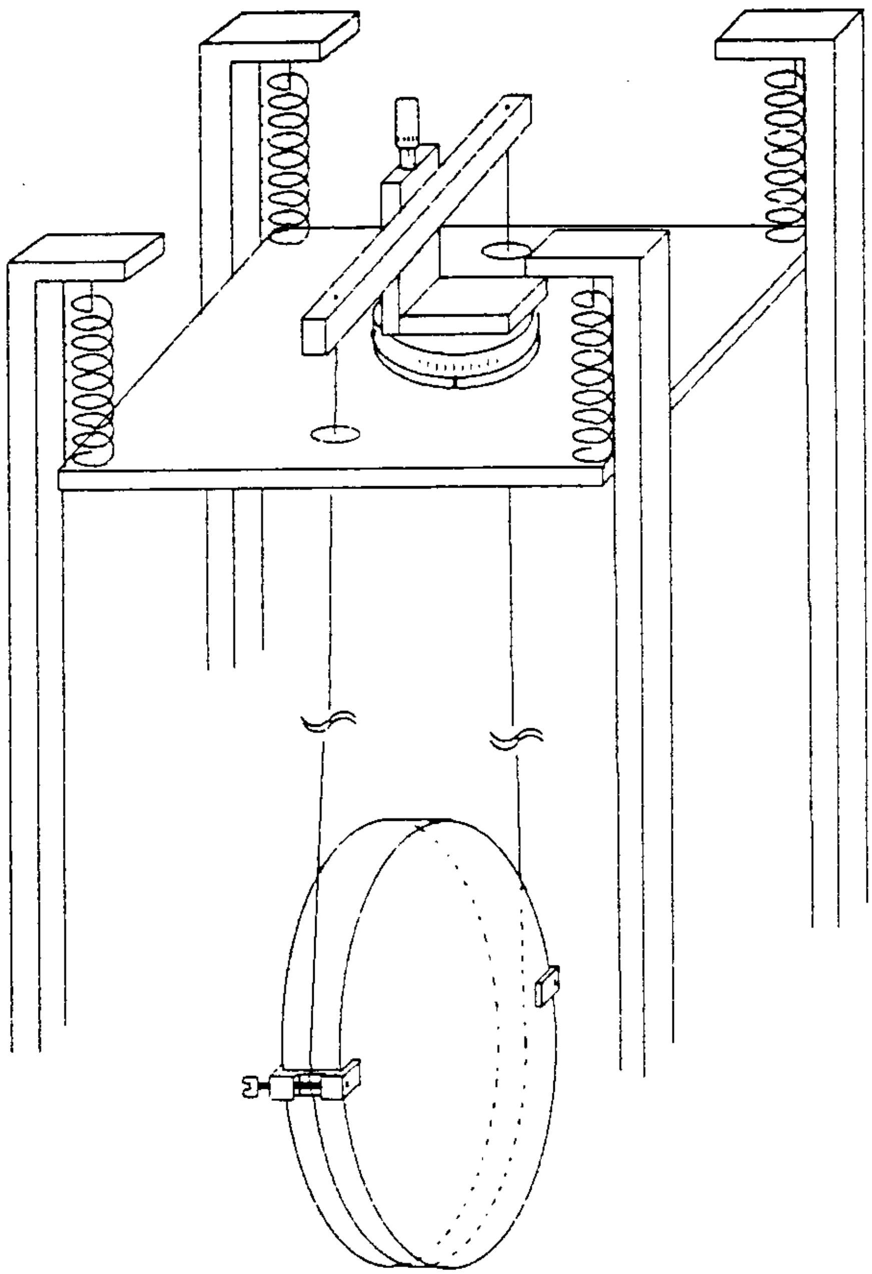
MPQ 30-meter interferometer

- 30 meter arms
- Argon laser, 230 mW
- delay lines with 45 round trips
  light travel time of 9 μs
- Noise spectrum carefully studied
- Easy and robust servo lock

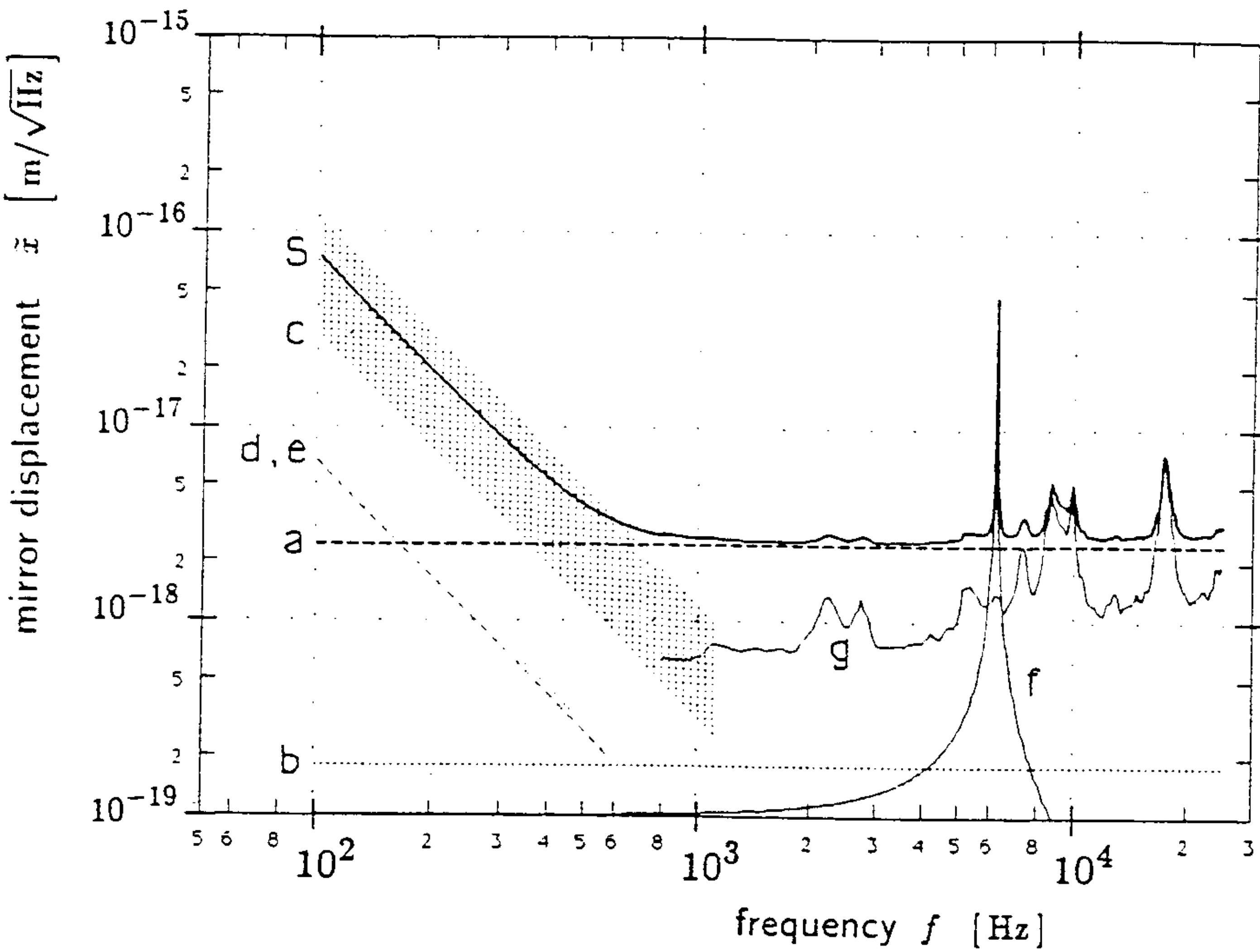
MPQ 30-m interferometer schematic



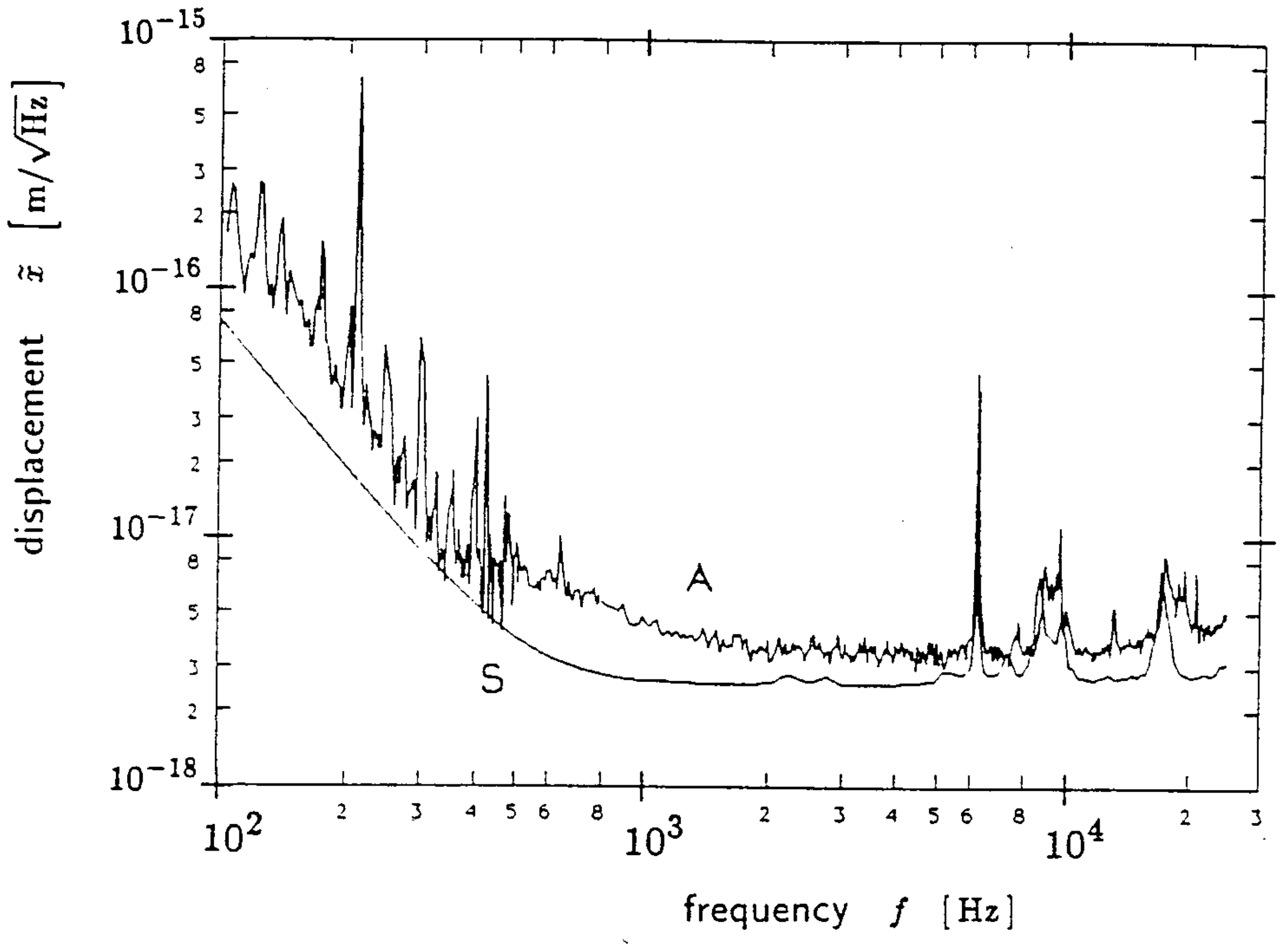
MPQ isolation system



MPQ noise spectrum model



MPQ noise spectrum: model vs. actual



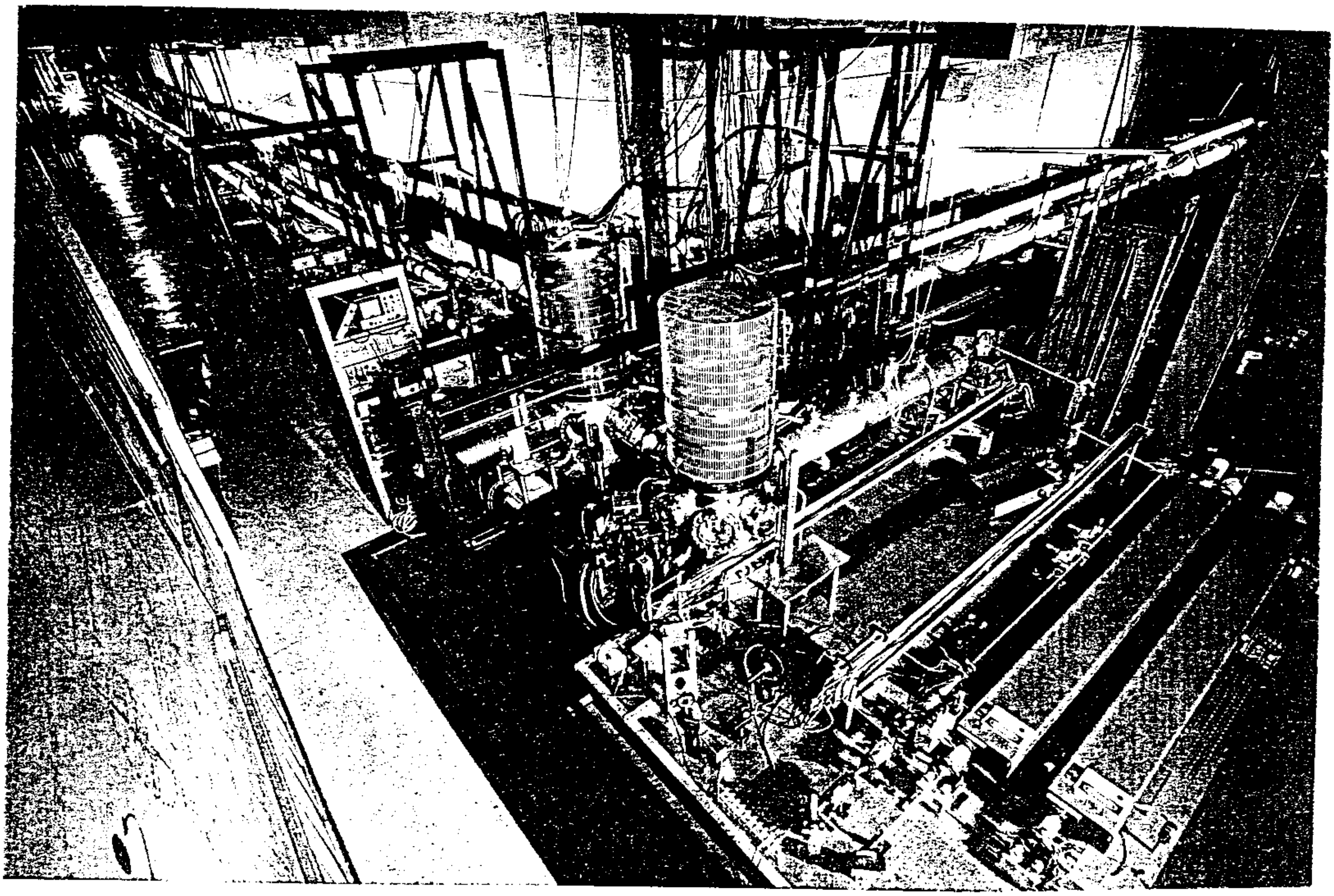
LIGO 40-m interferometer

- 40 meter long arms
- Argon laser, P = 150 mW
- FP cavity finesse of 15,000

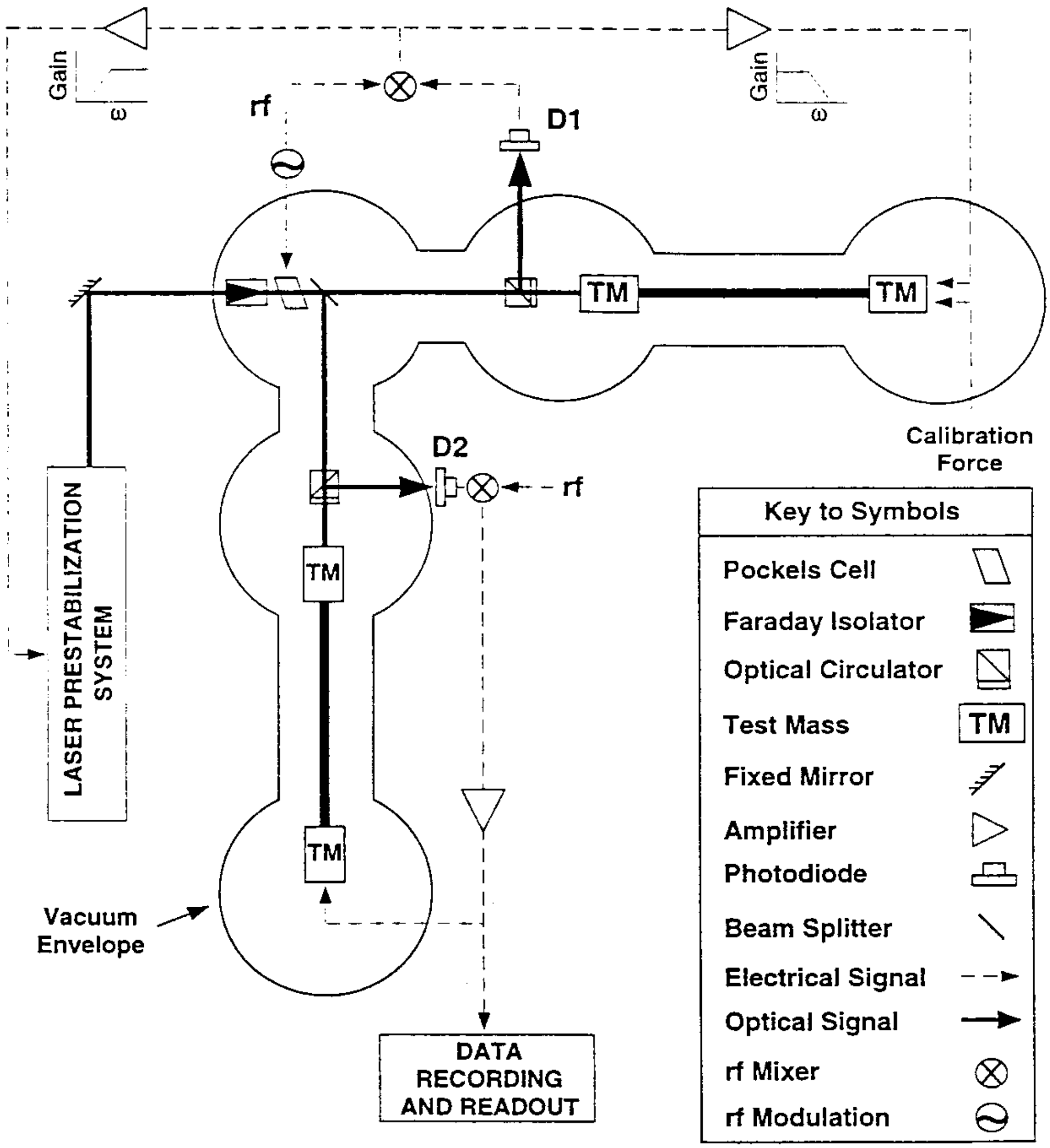
  storage time 0.6 ms
- Demonstrated Fabry-Perot cavity technology
- Record displacement sensitivity

  proof of principle: no prohibition on reaching LIGO I $x(f)$

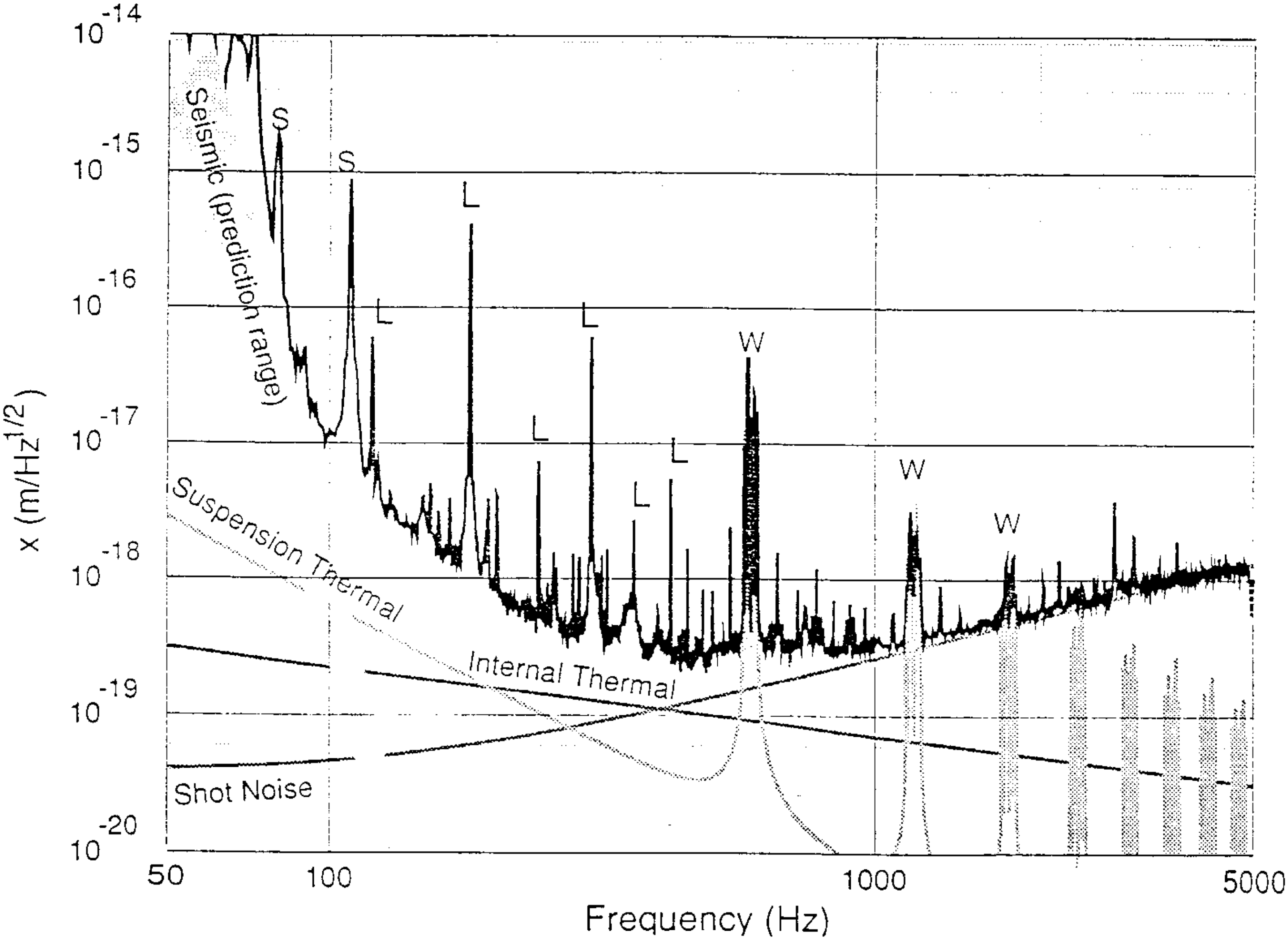
LIGO 40-m interferometer



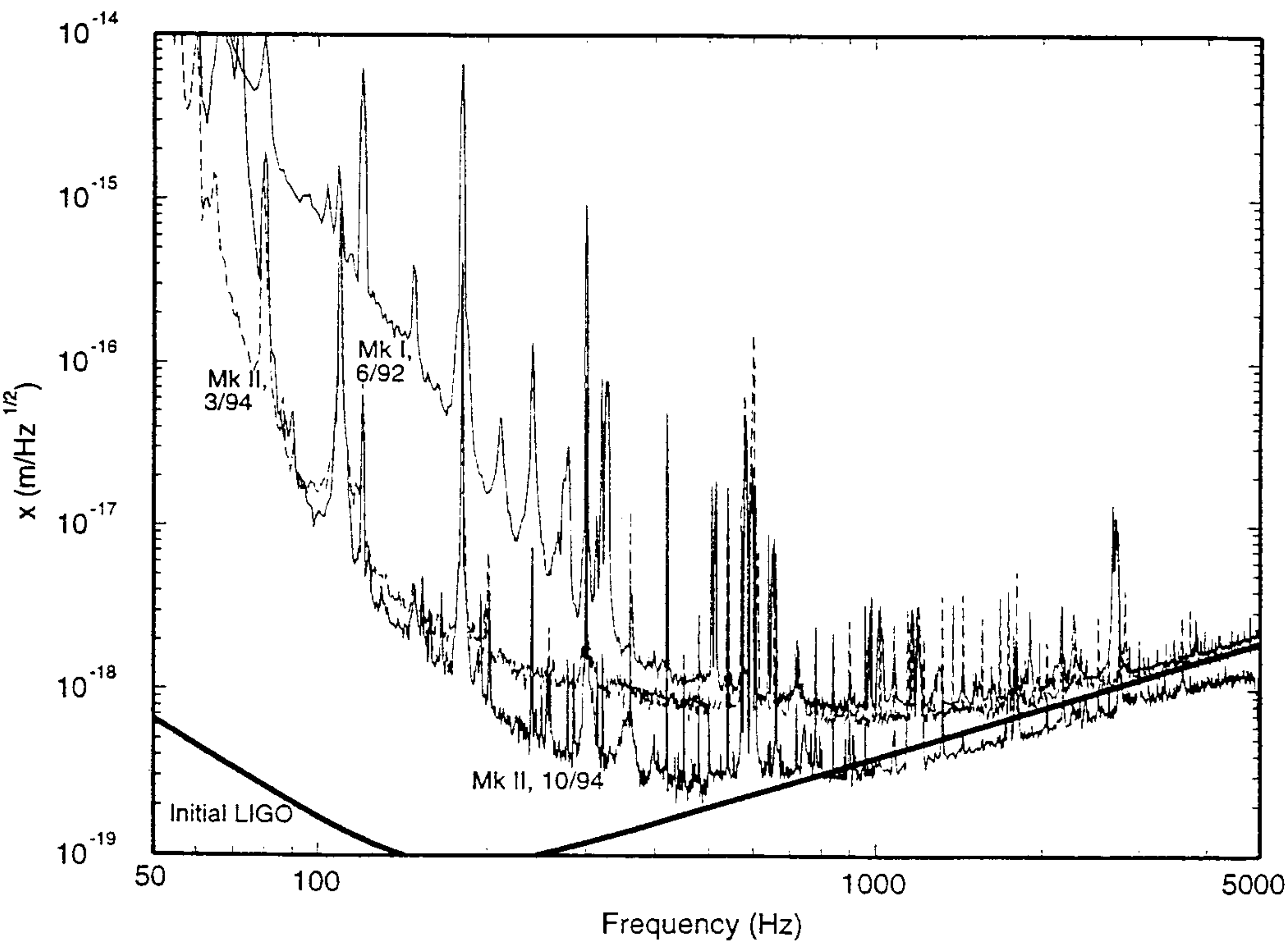
LIGO 40-m schematic



LIGO 40-m noise model



LIGO 40-m noise spectrum history

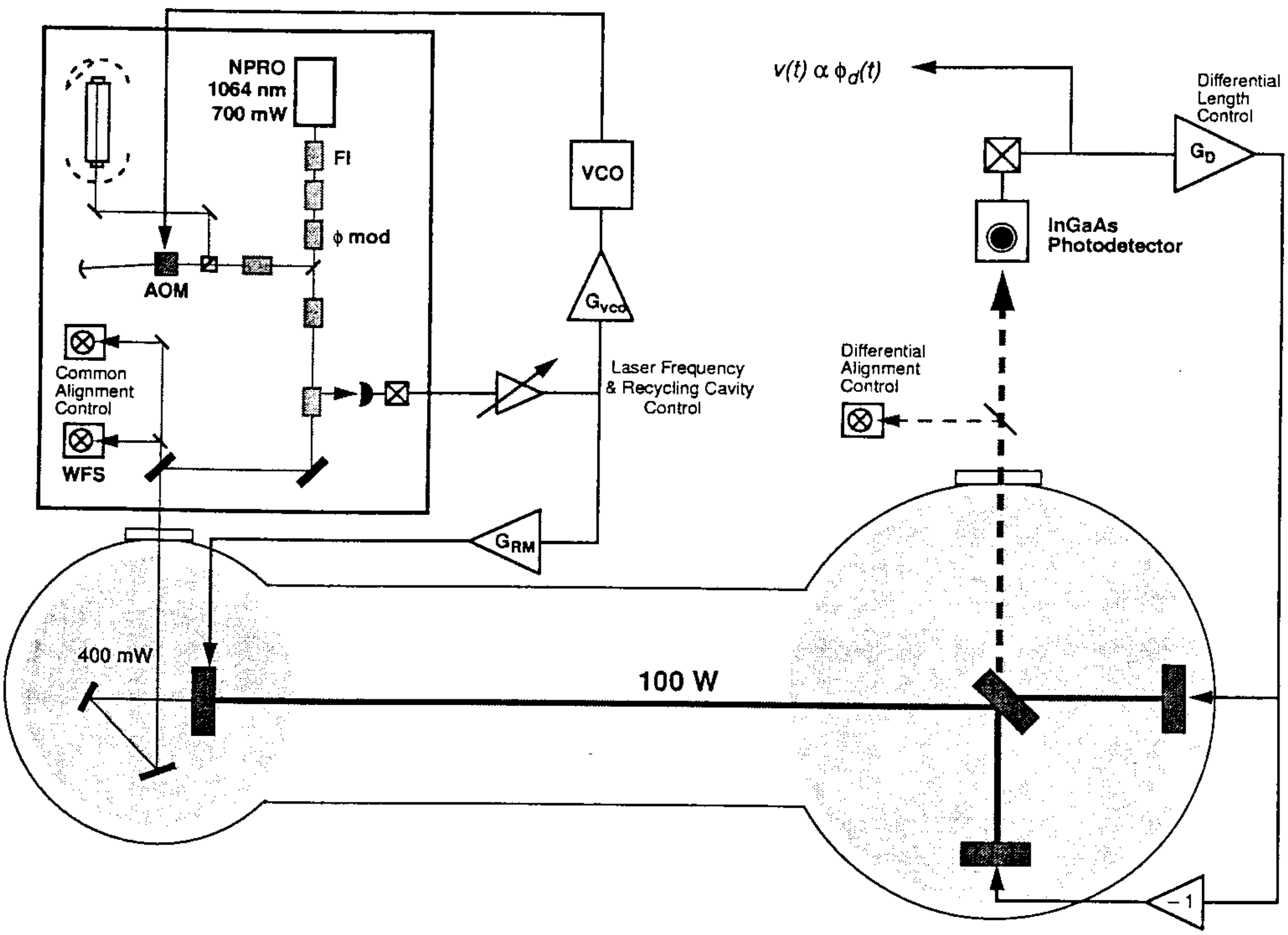


LIGO Phase Noise Interferometer

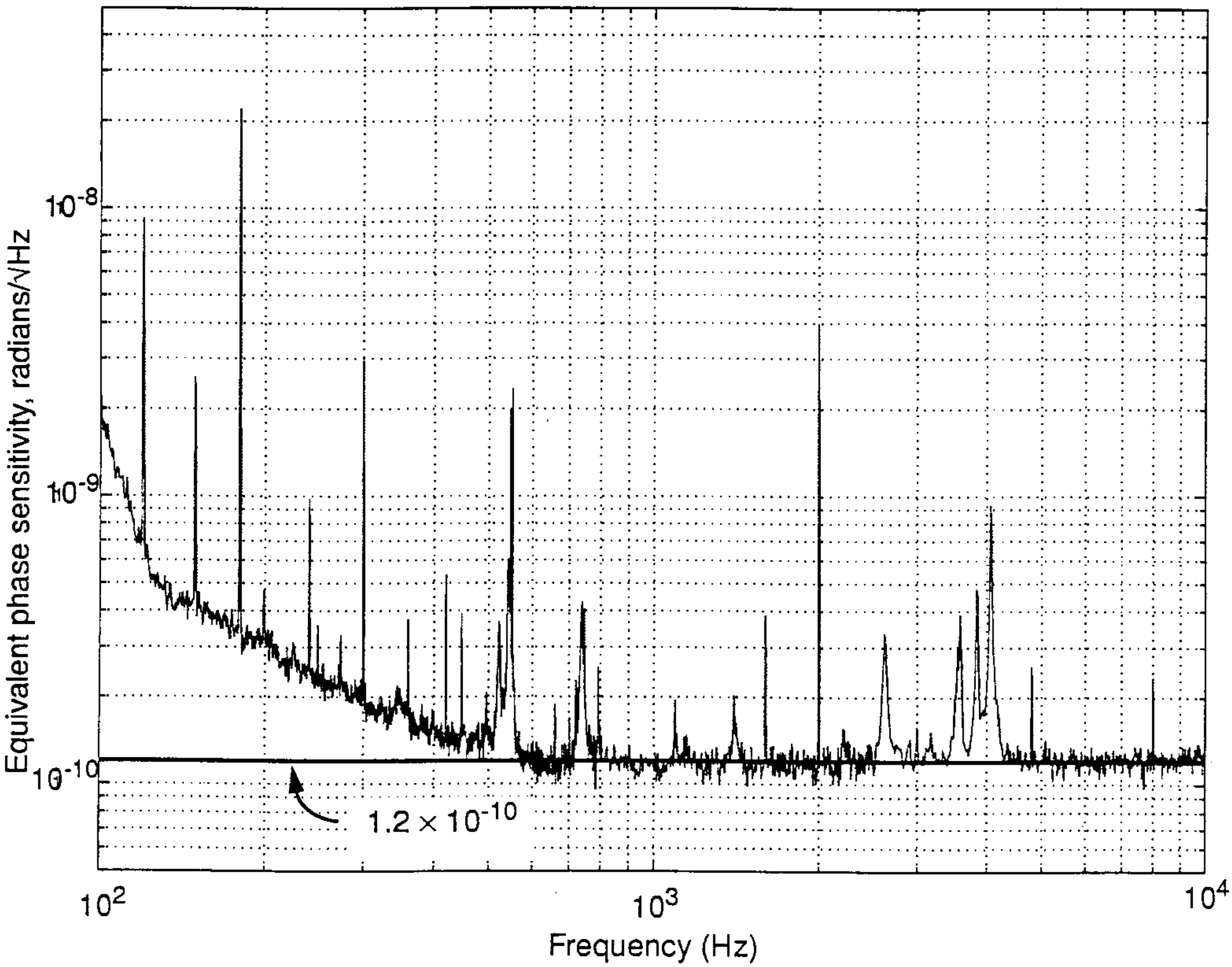
- short arms (~ 1 m), without delay lines or FP cavities
- Nd:YAG laser, 400 mW
- used *power recycling* to make this laser power equivalent to 100 W
- shot noise limited above 600 Hz
- Record phase sensitivity

  proof of principle: no prohibition on reaching LIGO I $\phi(f)$

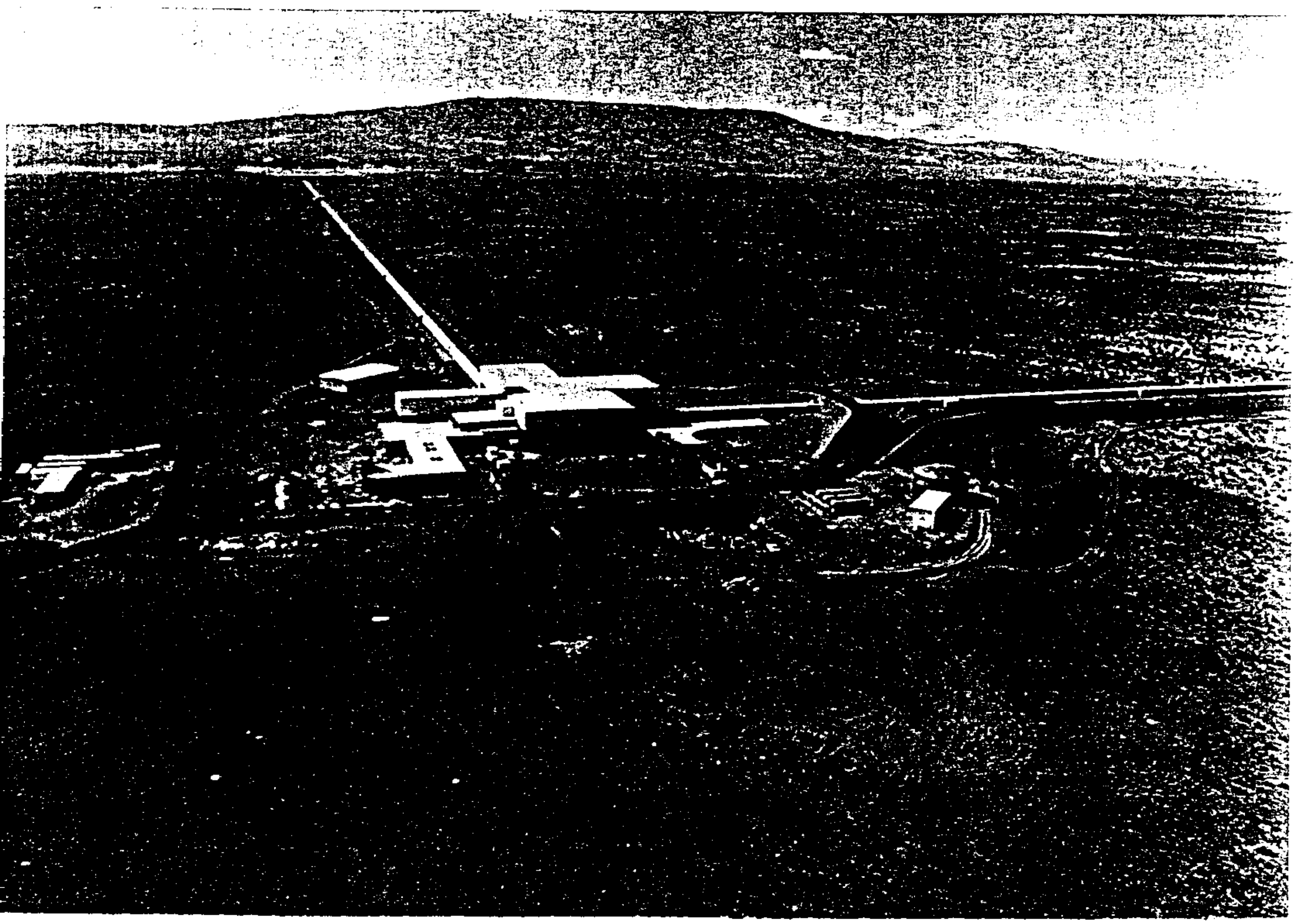
LIGO Phase Noise Interferometer schematic



PNI noise spectrum



Laser Interferometer Gravitational-Wave Observatory



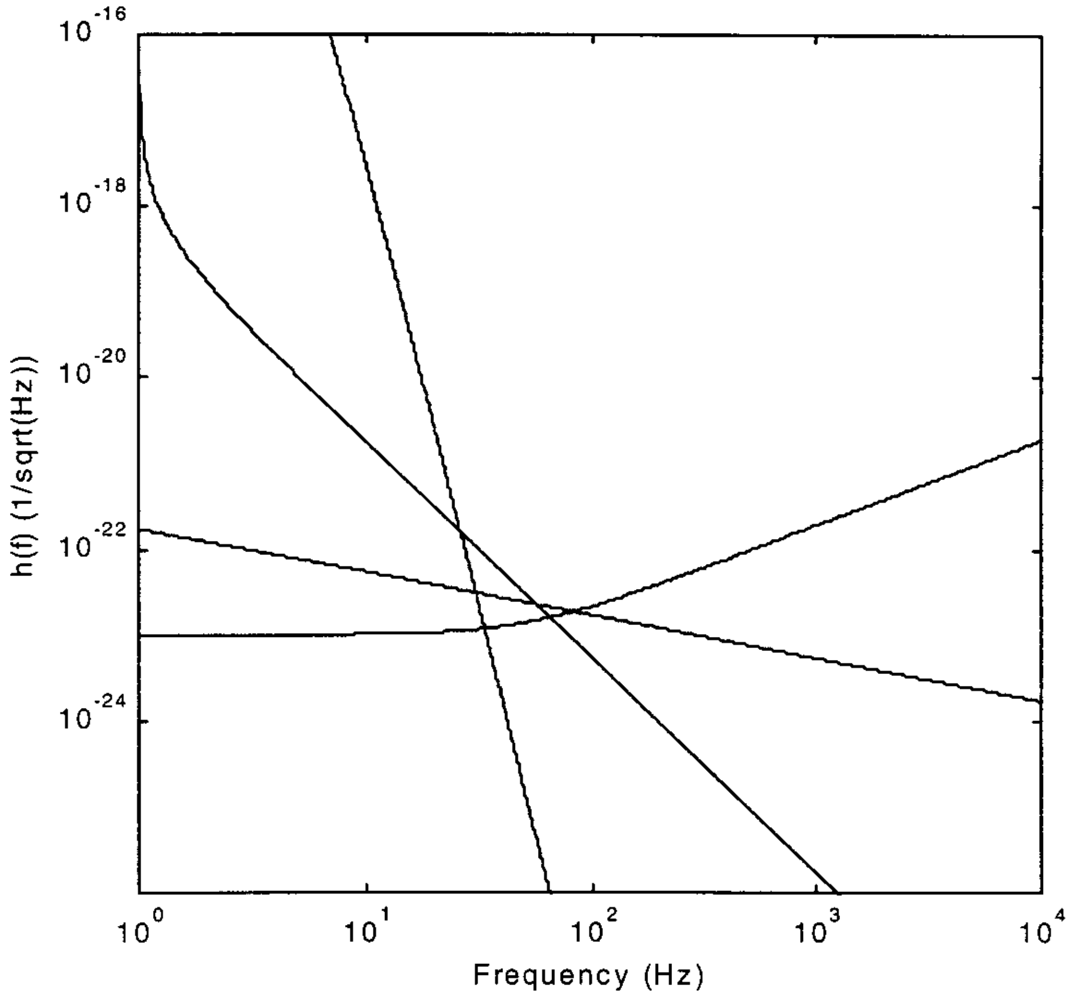
LIGO's key features

- 2 facilities with 4 km arms
  - 1 site has 2nd 2-km ifo
- widely separated, but under common management
  - Hanford WA and Livingston LA
  - coincident operation
- 1 meter (clear aperture) vacuum pipes, $P < 10^{-6}$ torr
- large vacuum chambers hold test masses, isolation systems

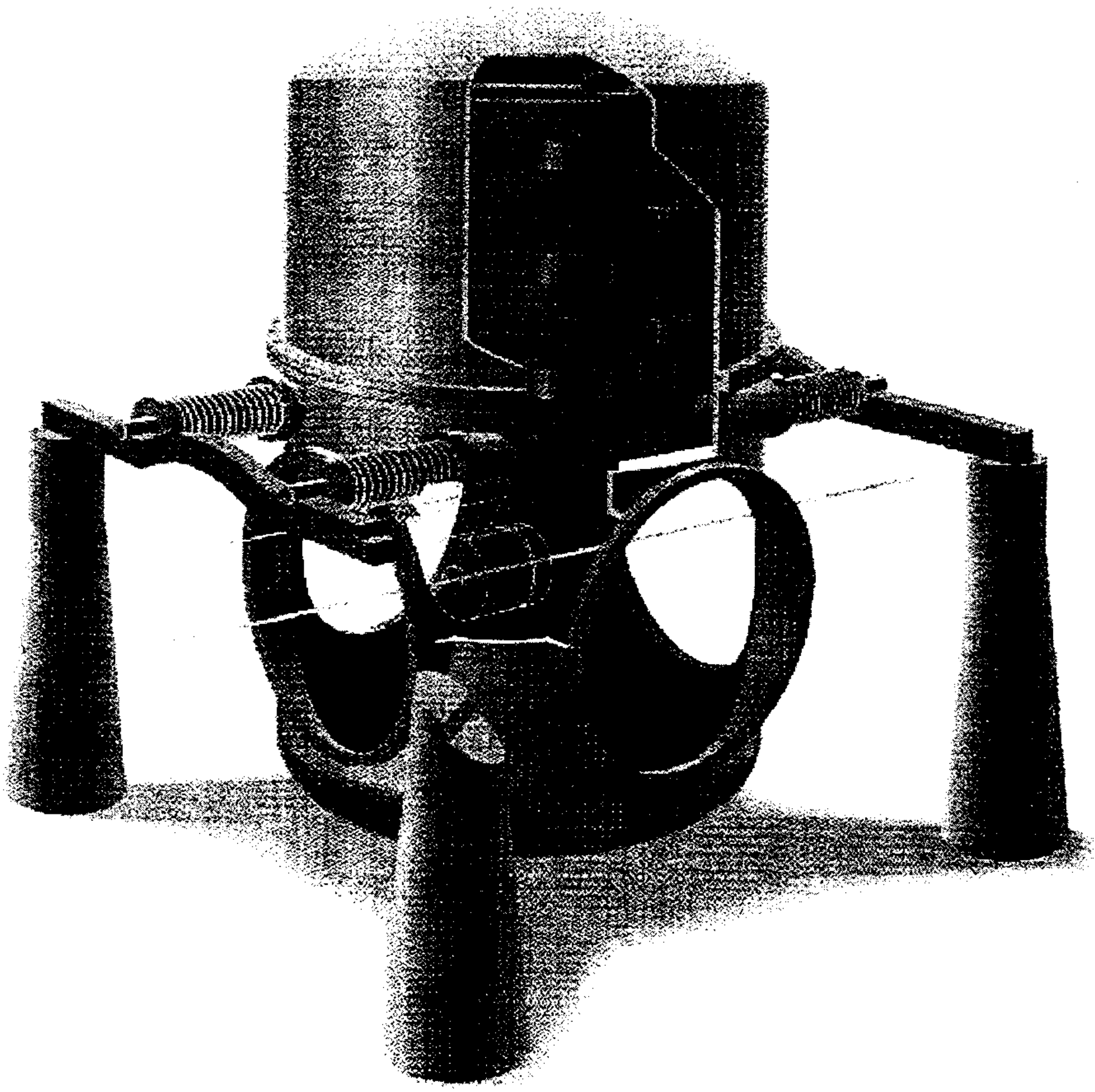
LIGO I Interferometers

- 2 @ 4 km, 1 @ 2 km
- Nd:YAG laser, $P = 6$ W
- Power recycling to 180 W
- Arms are FP cavities with storage time of 0.88 ms
- Design sensitivity $h_{rms} = 10^{-21}$.
- Two year data run 2002-3.

LIGO I noise spectrum



LIGO vacuum system



Other interferometers under construction

- VIRGO, 3 km, near Pisa
  (French-Italian collaboration)
- GEO 600, 0.6 km, near Hannover
  (British-German collaboration)
- TAMA 300, 0.3 km, near Tokyo
  (plans to upgrade to 3 km)
- ACIGA, near Perth
  (just approved for initial phase)

LIGO interferometer upgrades

- Upgrades planned after 2002-3 data run (and again ~2008.)
- 1st upgrade possibilities: lower thermal noise suspension, 60 W laser, …
- Would push sensitivity into range where neutron star binary signals might be expected.

4th generation resonant-mass detectors

Several groups studying resonant-mass detectors of spherical form, greater mass/length.

(For ex: 3 meters, 100 tons)

Would have better SNR, omni-directional.

Ultra-cryogenic sphere with quantum-limited preamp could see $h \sim 10^{-21}$.

Space interferometers (e.g. LISA)

Interferometers in space could

- have very long arms (5×10^6 km)
- avoid seismic noise entirely
- avoid suspension thermal noise
- be shielded from small buffeting by drag-free technology.

SNR > 10^3 possible for massive black hole binaries at the Hubble distance.

Guaranteed to see white dwarf binaries.

When will gravitational waves be detected?

Maybe tomorrow -- cryogenic resonant-mass detectors are on line now.

Odds start to improve dramatically ~ 2002, when LIGO and other large interferometers go on line; odds become excellent as their performance improves.

A space interferometer at design sensitivity will surely see them.