Gravity Wave Experiments

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HEPAP Subpanel
Non-Accelerator Session
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LIGO-G970172-00-M

General Theory of Relativity

- Newtonian Gravity has instantaneous action at a distance

- Einstein showed fluctuating fields give gravitational waves
  - transverse, like radio waves
  - propagate at speed of light
  - two polarizations are at 45^{O}

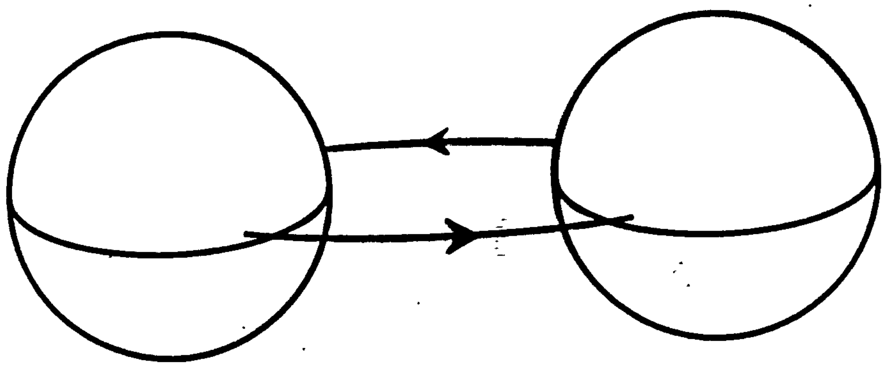
- Lowest order radiation term: quadrupole
  - field proportional to $\ddot{Q}$,
  - second derivative of non-spherical part of kinetic energy
  - dimensional analysis leads to $h \approx \frac{G}{c^4}\frac{\ddot{Q}}{r}$

- passing GW leads to change in proper distance

  $\delta l \approx \left(\frac{1}{2}h(t)\right)L$ between points separated by L

Gravitational Waves

Sources and Detection



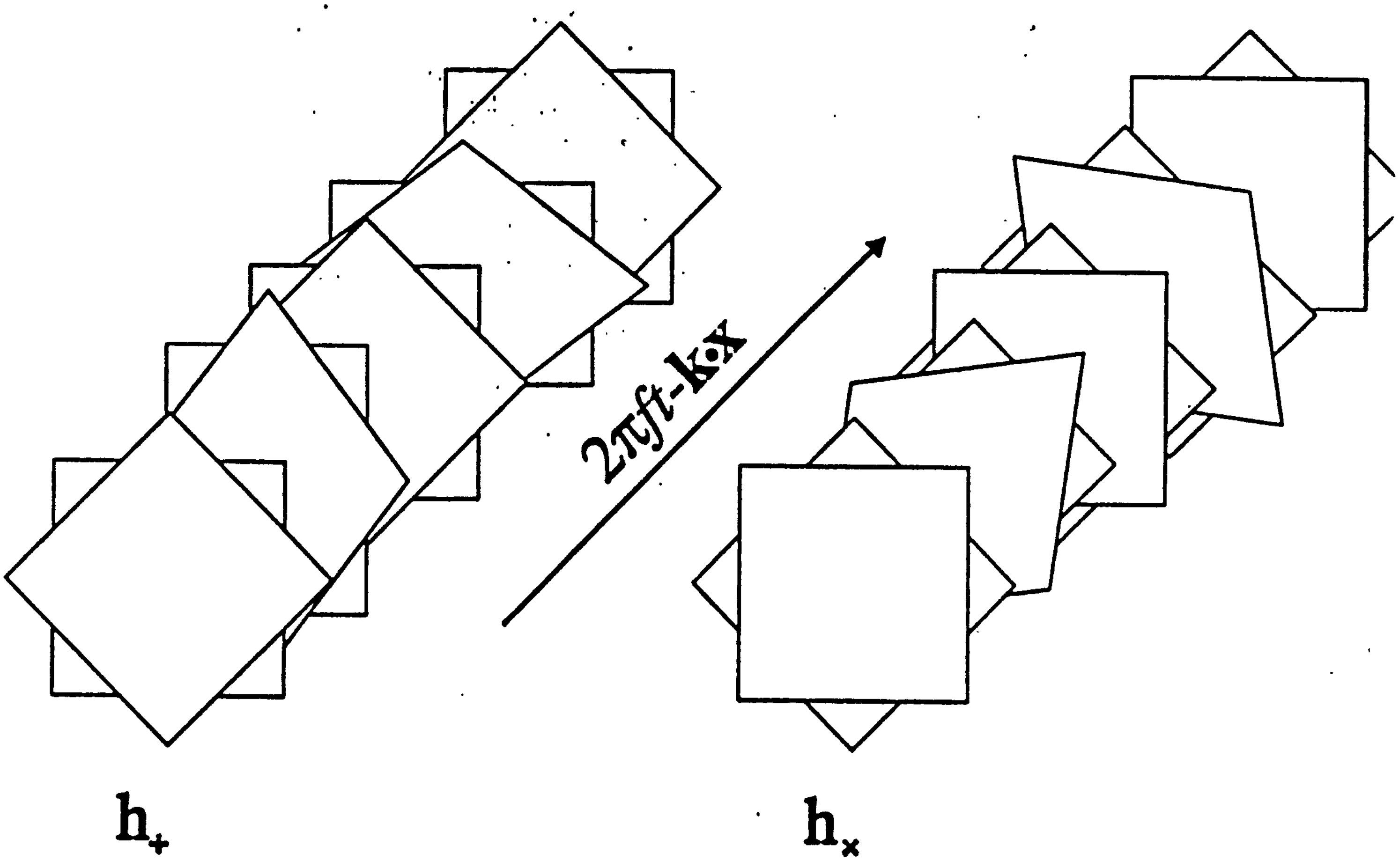
- binary star system

Sources	Frequency	h	Event Rate	Detection
Coalescing Binary Neutron Stars (200 Mpc)	10~1000 Hz	10^{-22}	~3/year	Interferometer +Template
Supernovae (in our Galaxy)	~1 kHz	10^{-18}	~3/century	Interferometer, Resonant
Supernovae (in Virgo)	~1 kHz	10^{-21}	several/year	Interferometer
Generation of Large Black Holes	~1 mHz	10^{-17}	1/year	Interferometer in Space
Pulsars	10~1000 Hz	10^{-25}	periodic	Interferometer, Resonant
Cosmic Strings	10^{-7} Hz	10^{-15}	stochastic	Pulsar Timing

- sources and detection

Gravitational Waves

Two Polarizations



LIGO

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III

Gravitational vs E.M. Waves

	EM WAVES	GRAV. WAVES
Nature	Oscillation of EM Fields Propagating Through Spacetime	Oscillations of the "fabric" of spacetime
Emission Mechanism	Incoherent superposition of waves from molecules, atoms, particles	Coherent emission by bulk motion of energy
Interaction with Matter	Strong absorption and Scattering	Essentially None!
Frequency Band	$f > 10^7$Hz	$f < 10^4$Hz

- Implications
  - Most gravitational sources not seen as electromagnetic (and vice versa)
  - Potential for great surprises
  - Uncertainty in strengths of waves

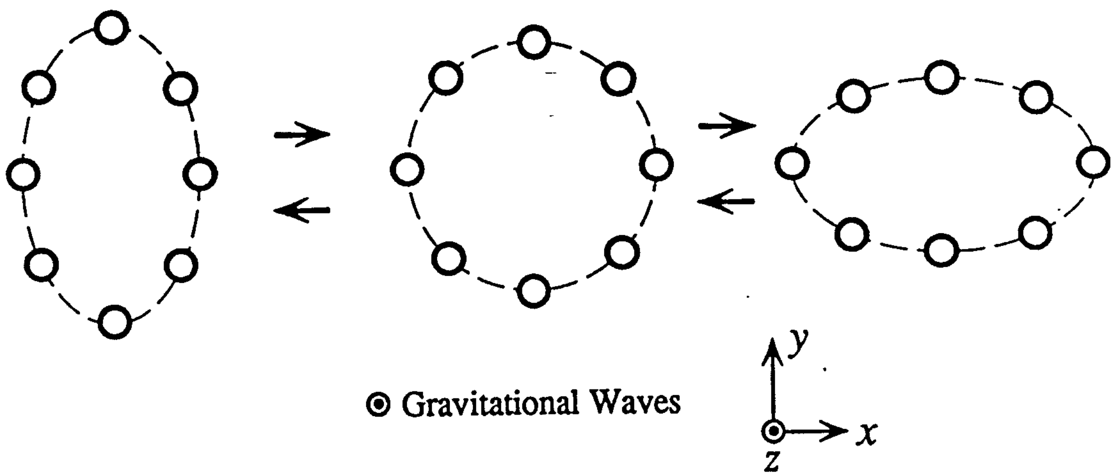
LIGO
Scientific Mission

- Direct Detection of Gravitational Waves
  - Benchmark Source: Neutron Binary Coalescence
    - Detect the last 15 minutes of Hulse/Taylor type binary system (eg. 100 million years)
    - Sensitivity -- detection rate >3 year
  - Other Sources

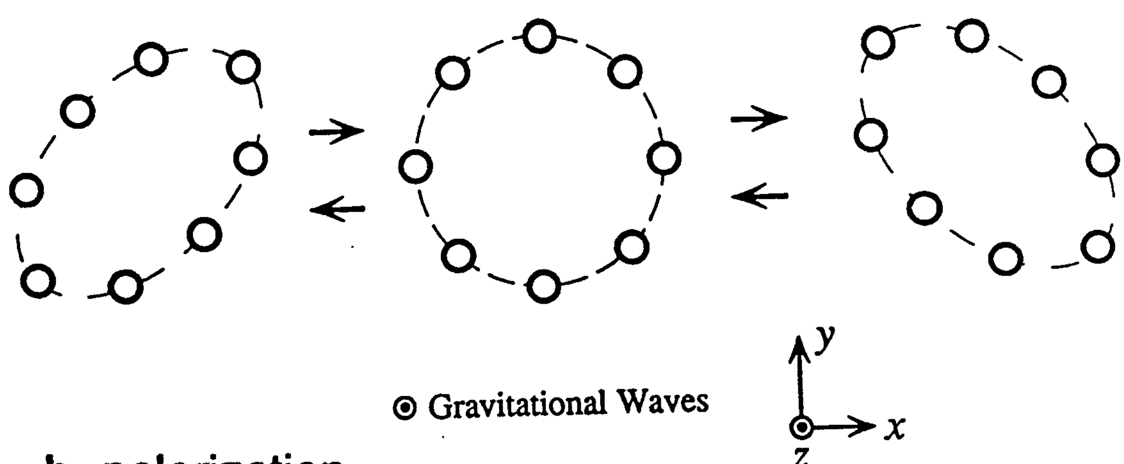
- Fundamental Physics (GR)
  - » Test General Relativity in Strong Field and High Velocity Limit
  - » Measure Polarization and Propagation Speed

Gravitational Waves
Effects

- Displacement of free particles



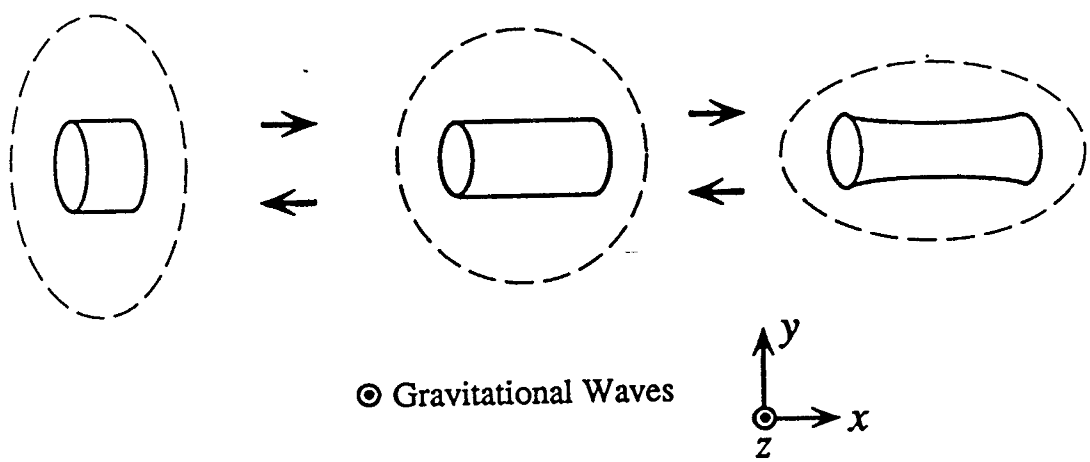
» h_+ polarization



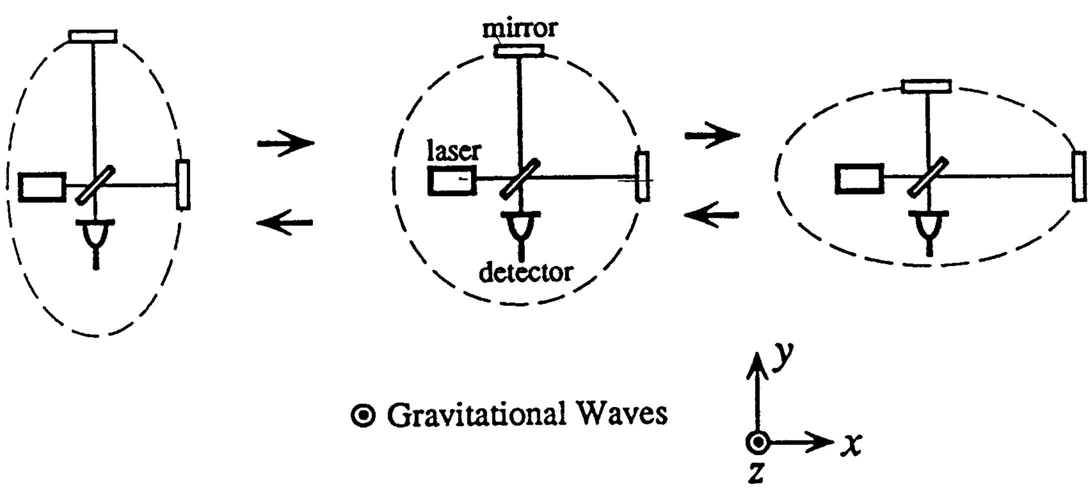
» h_x polarization

Gravitational Waves

Detection

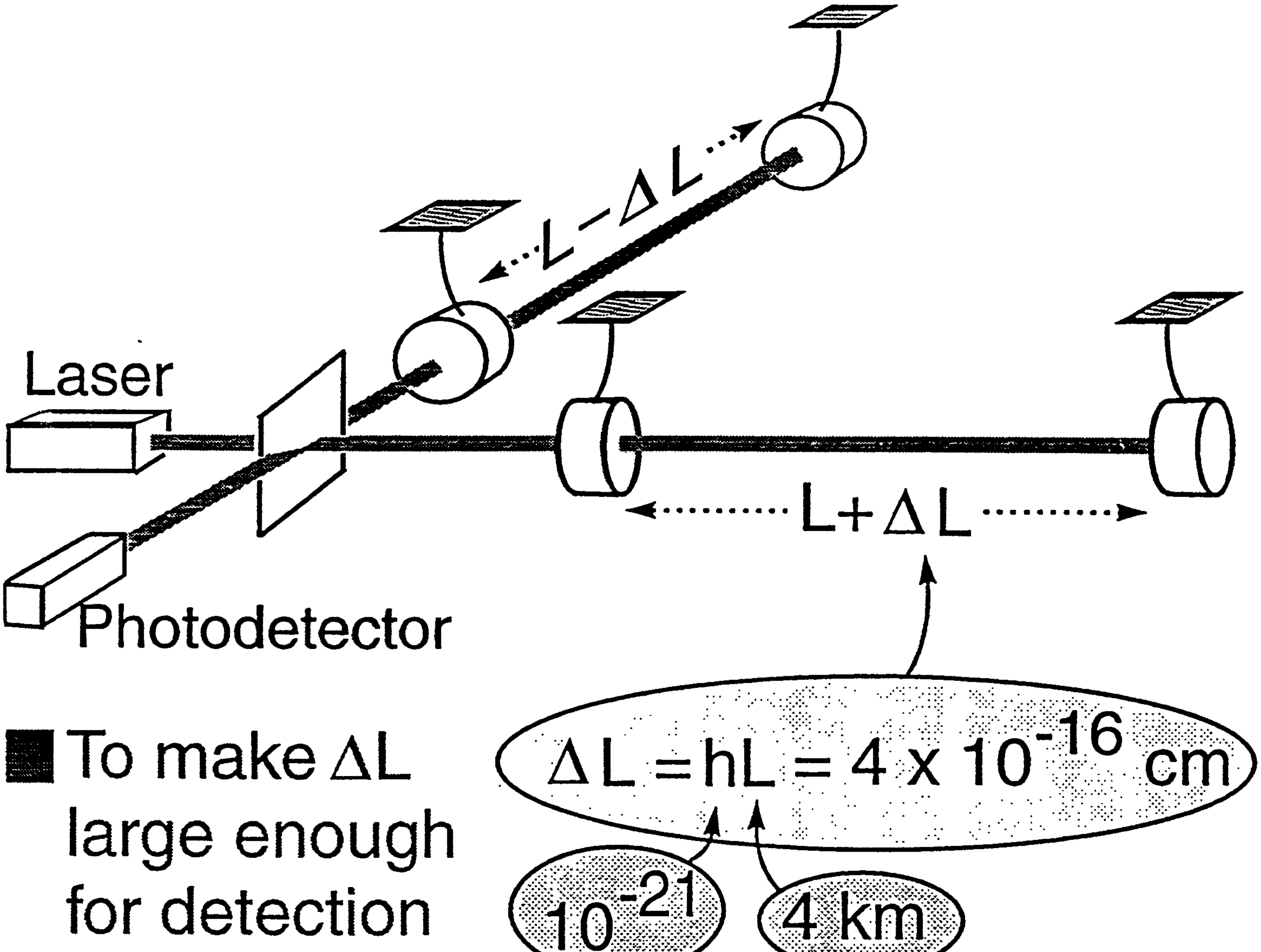


- Bar detector



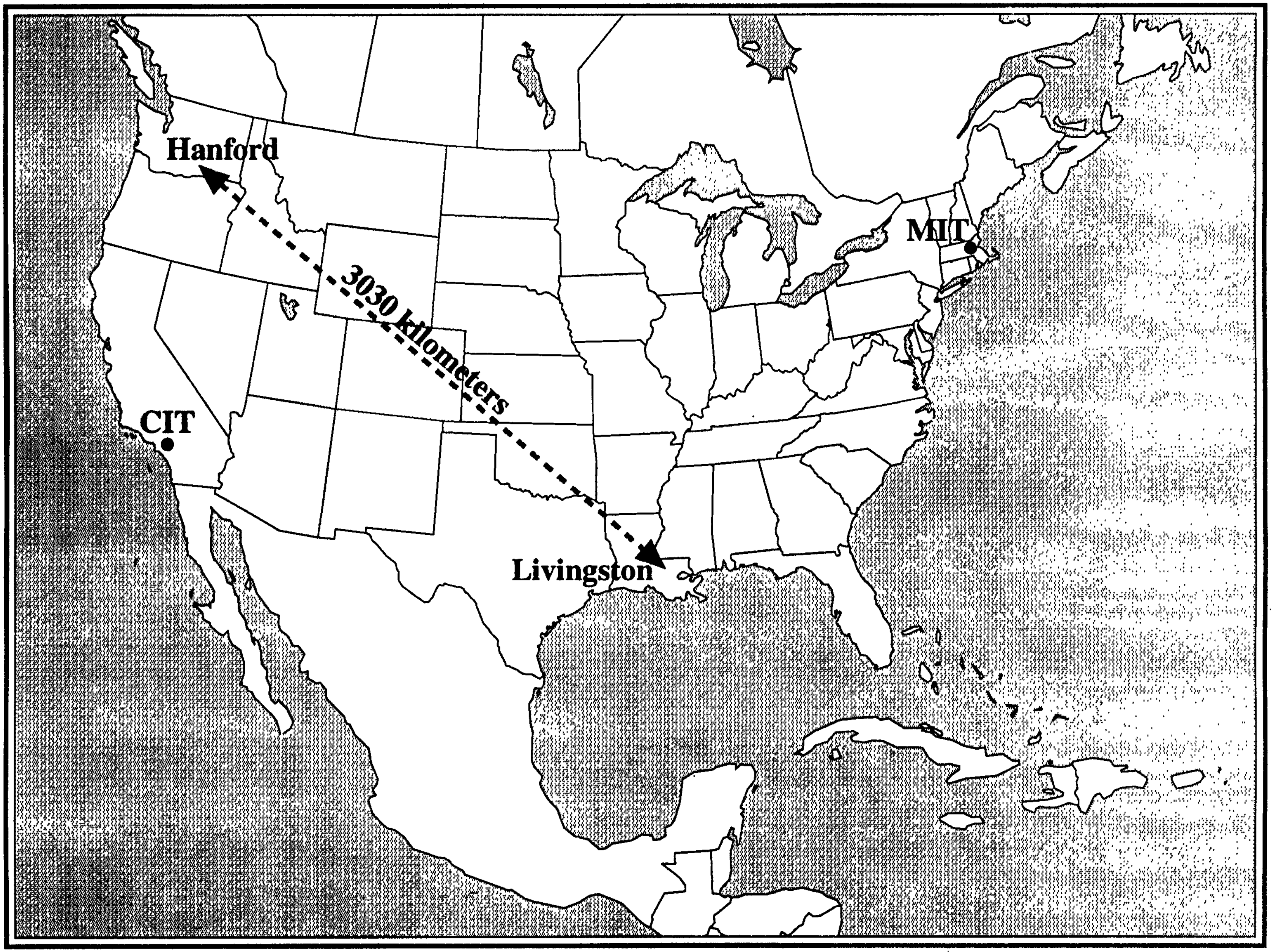
- Interferometer detector

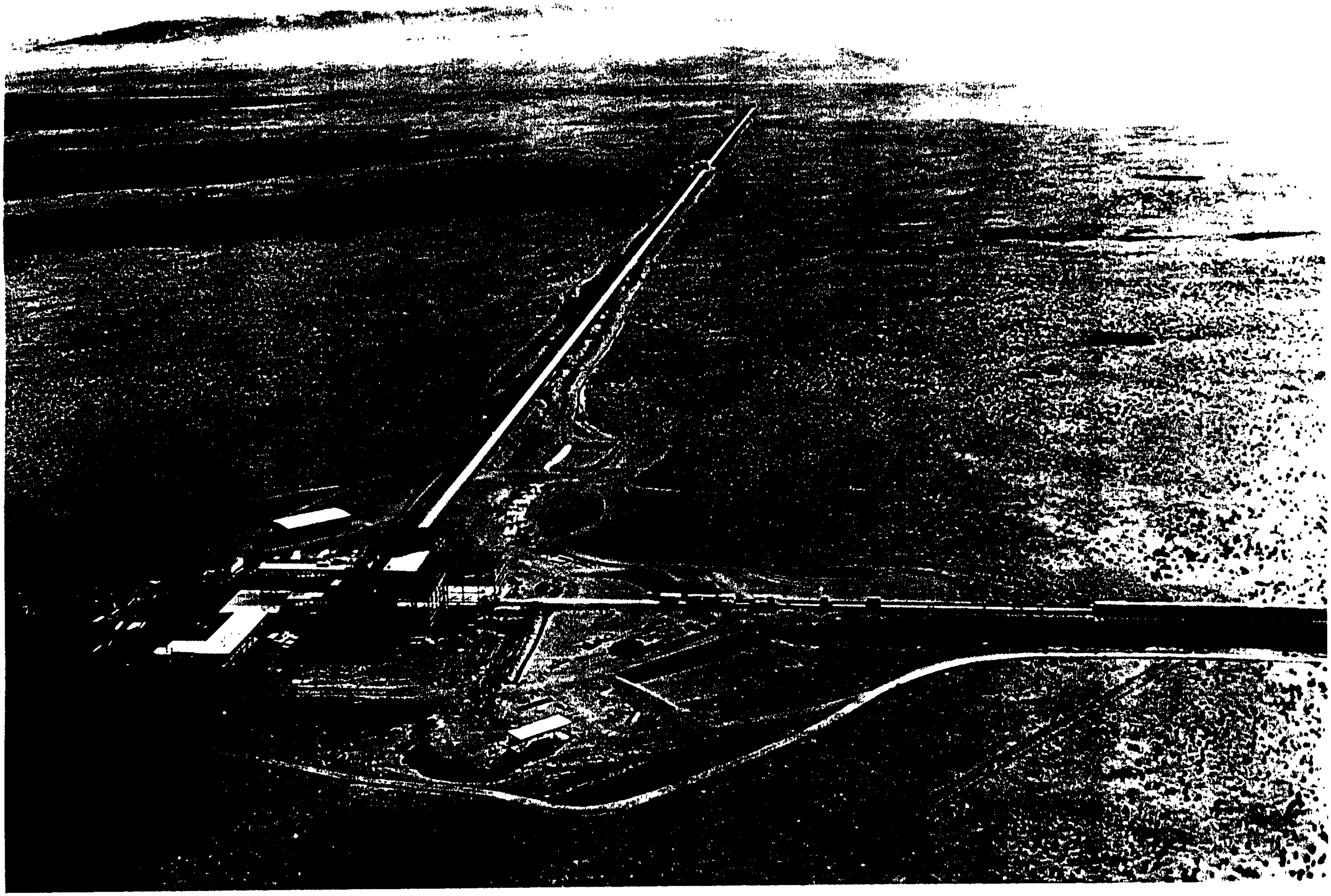
LIGO INTERFEROMETERS



- To make ΔL large enough for detection requires $L \gtrsim 4$ km

- Measured waveform, h(*time*) = $\Delta L/L$, is a linear combination of h_+ and h_x , which depends on interferometer's orientation


Hanford
3030 kilometers
MIT
CIT
Livingston



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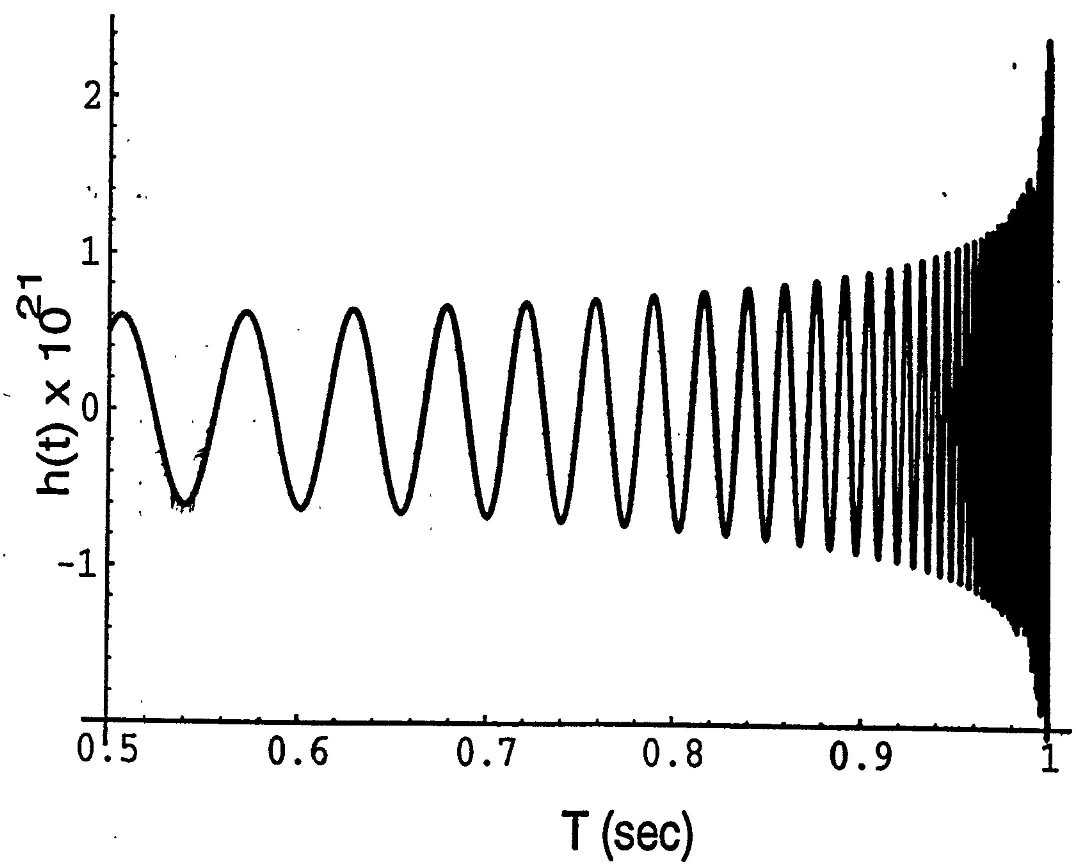
LIGO
Science Goals

- Final Inspiral of Binary Systems *(chirp)*
  - » Neutron Star/Neutron Star Inspiral
    - – Design Benchmark: last 15 min
20,000 cycles
600 MLyr
  - » Black-hole/Black-hole Inspiral and Coalescence
  - » Black-hole/Neutron Star Inspiral
- Supernovae *(burst)*
  - » Axisymmetric in our galaxy
  - » Non-axisymmetric ~300MLyr
- Periodic Sources *(track frequency)*
  - » spinning neutron stars
- Early Universe *(correlations)*
  - » Stochastic Background Radiation
- Unknown Sources

Neutron Binary Systems

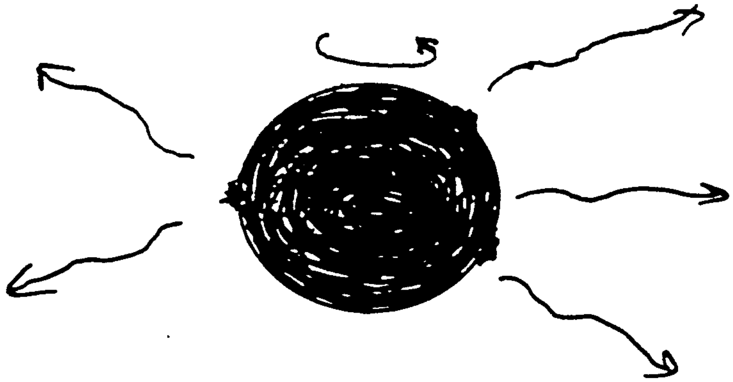
Inspiral

- LIGO frequency band
  - » last 15 minutes (~10^4 cycles)
- 'Chirp Signal'
- Detailed waveform gives masses, spins, distance, eccentricity of orbit, etc



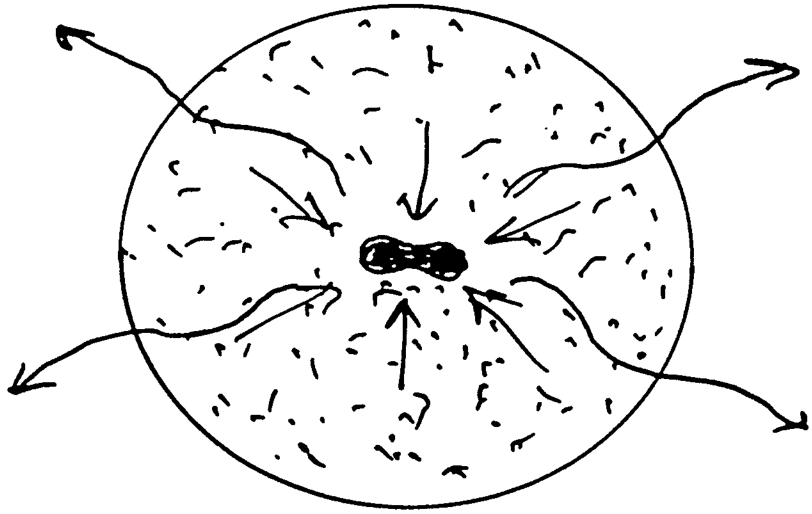
OTHER POSSIBLE SOURCES

SPINNING, "MOUNTAINOUS" NEUTRON STAR



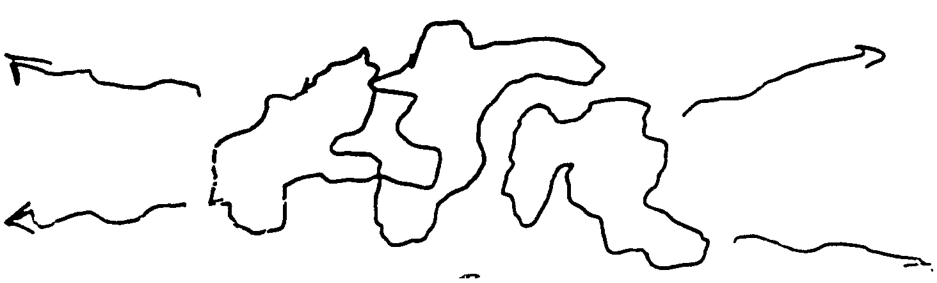
Periodic

IMPLOSION OF A STAR'S CORE — WHICH TRIGGERS A SUPERNOVA



Bursts

VIBRATING LOOPS OF COSMIC STRING



Stochastic

FIGURES

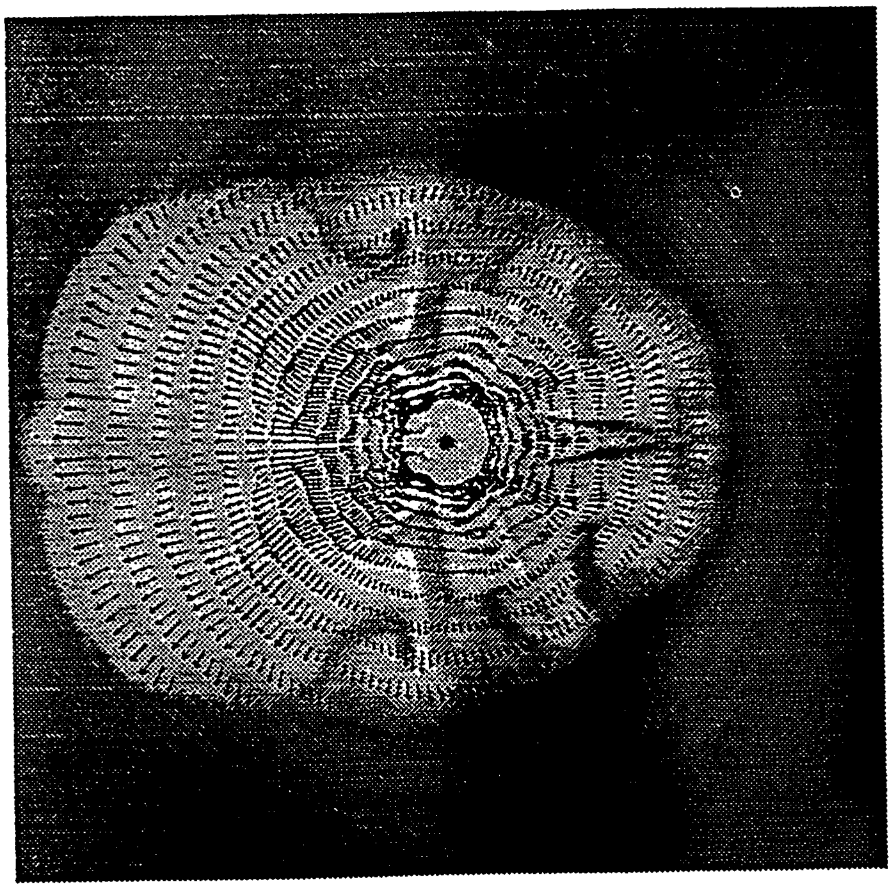
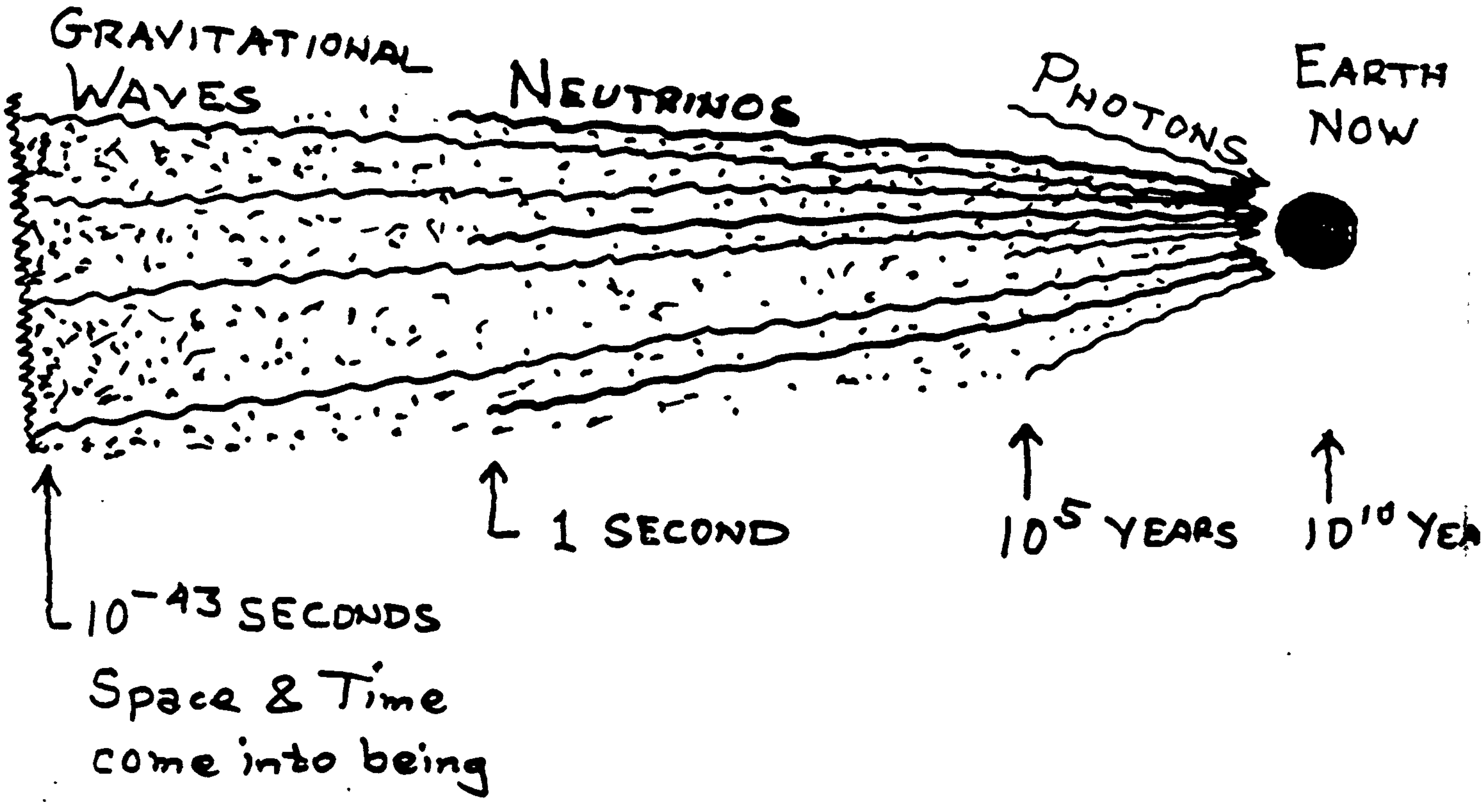


FIG. 1. A grey-scale rendering of the entropy distribution at the end of the simulation, about 50 milliseconds into the explosion. Note the pronounced pole–to–pole asymmetry in the ejecta and the velocity field (as depicted with the velocity vectors). The physical scale is 2000 km from the center to the edge. Darker color indicates lower entropy and $\theta = 0$ on the bulge side of the symmetry axis.

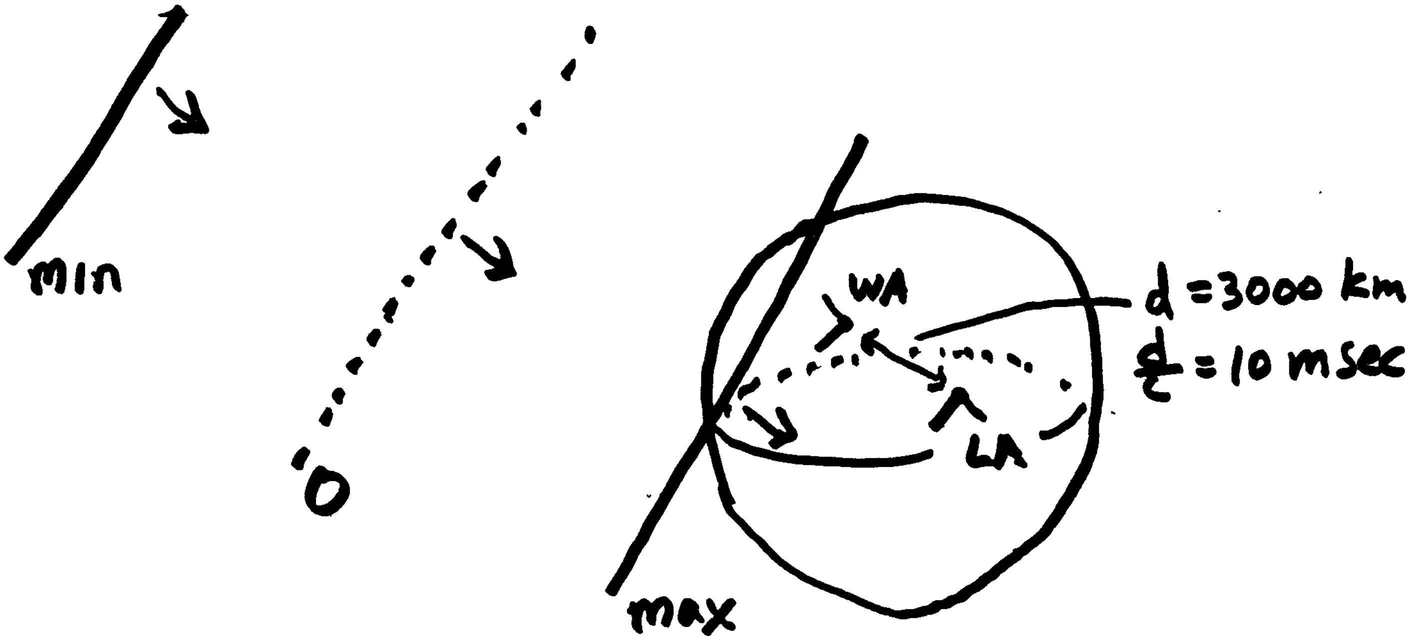
THE BIG BANG SINGULARITY

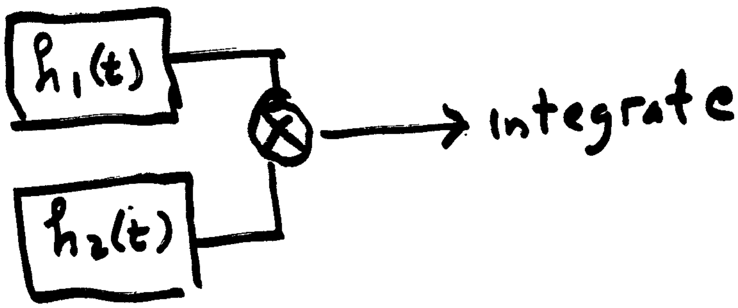


LIGO 10^{-22} sec Temp $\sim 10^6$ GeV
graviton $\sim$ 10 MeV

LISA (10^{-2} Hz) 10^{-14} sec Temp $\sim 10^2$ GeV (electrowk)
graviton $\sim$ 1 keV

How to detect Stochastic Background



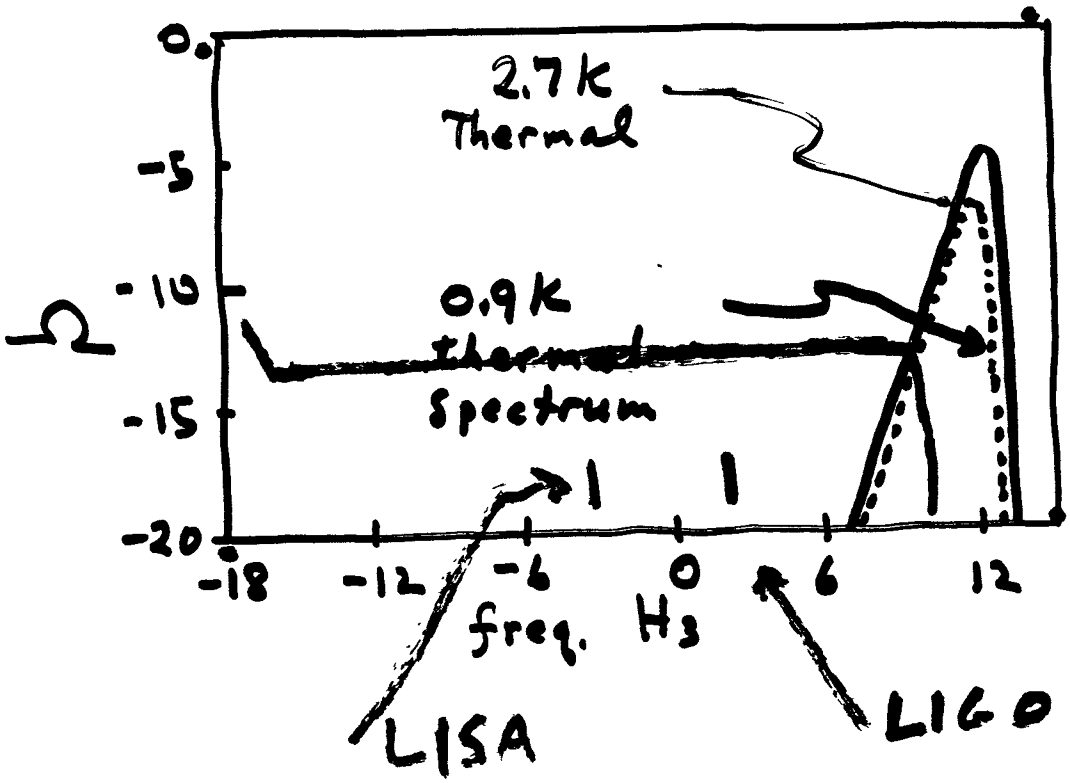


For waves with $\frac{\lambda}{2} > 3000$ km $\left(f \lesssim 50 \text{ Hz} \right)$
detector arms move in phase (together) so
average product $h_1(t) h_2(t) > 0$

In absence of background (and other signals)
average product $h_1(t) h_2(t) \to 0$

Michelson, Mon. Not. Roy. Astron Soc 227 (1987) 933.
Christensen, Phys. Rev. D46 (1992) 5250.
Flanagan, Phys. Rev. D48 (1993) 2389

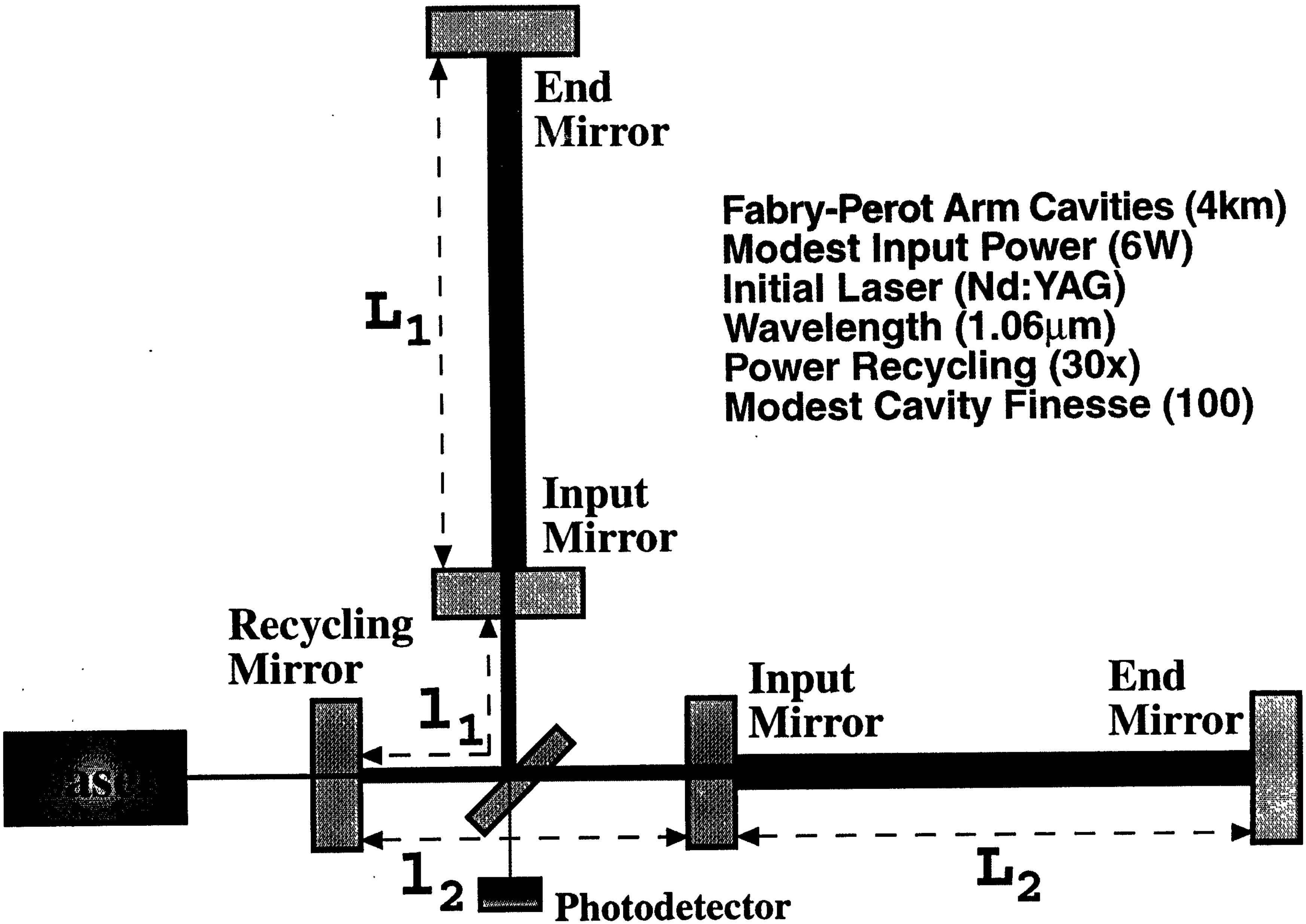
— inflation



- unlikely equilibrium was established since gravitational interactions so weak (time required longer than expansion time)

- useful benchmark

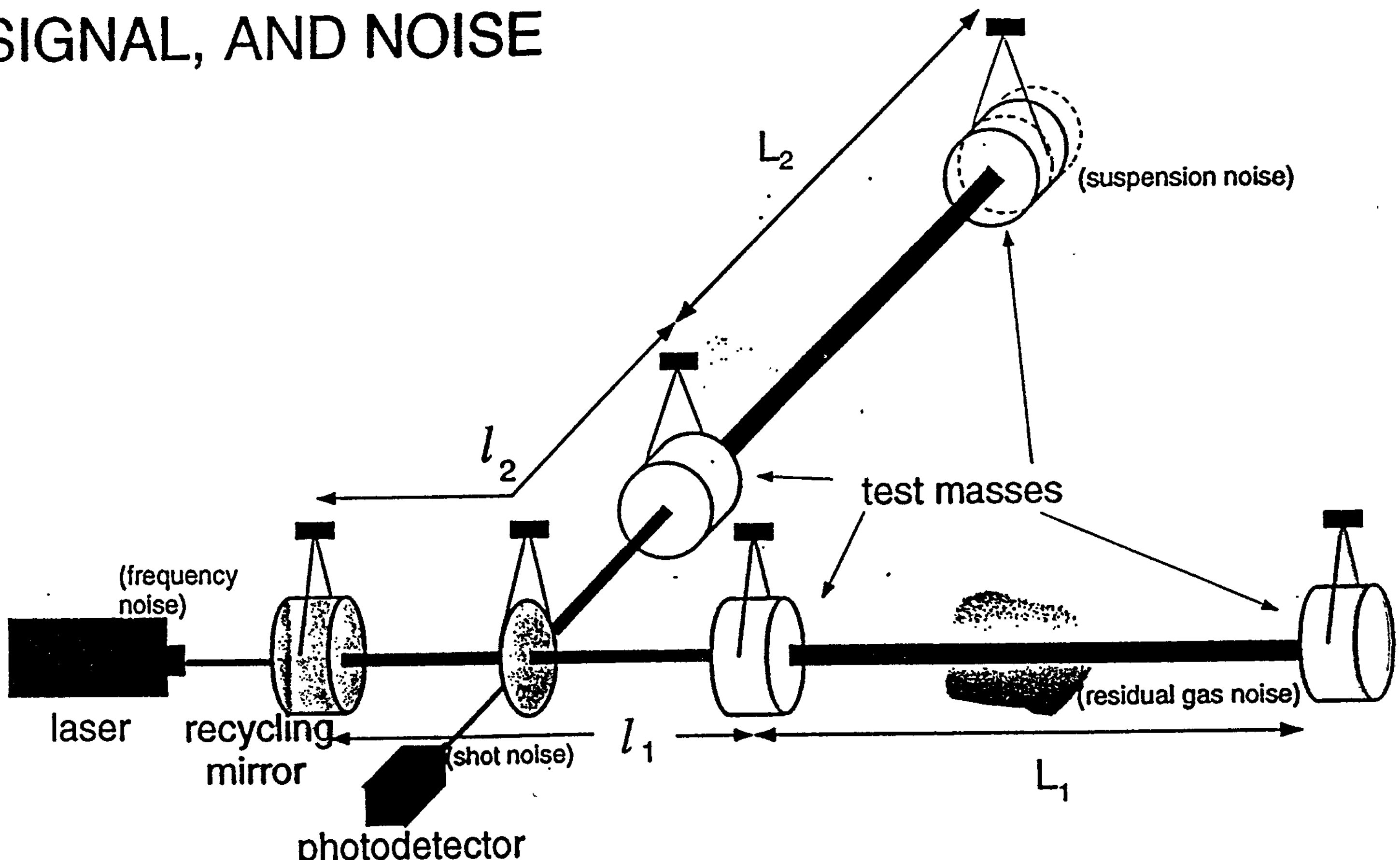
- detection
  correlate (anticorrelate) signals from different detectors
  (eg < 64 Hz LIGO detectors correlated)


End
Mirror
Fabry-Perot Arm Cavities (4km)
Modest Input Power (6W)
Initial Laser (Nd:YAG)
Wavelength (1.06μm)
Power Recycling (30x)
Modest Cavity Finesse (100)
L1
Input
Mirror
Recycling
Mirror
l1
Input
Mirror
End
Mirror
l2
Photodetector
L2

Interferometer

Noise Limitations

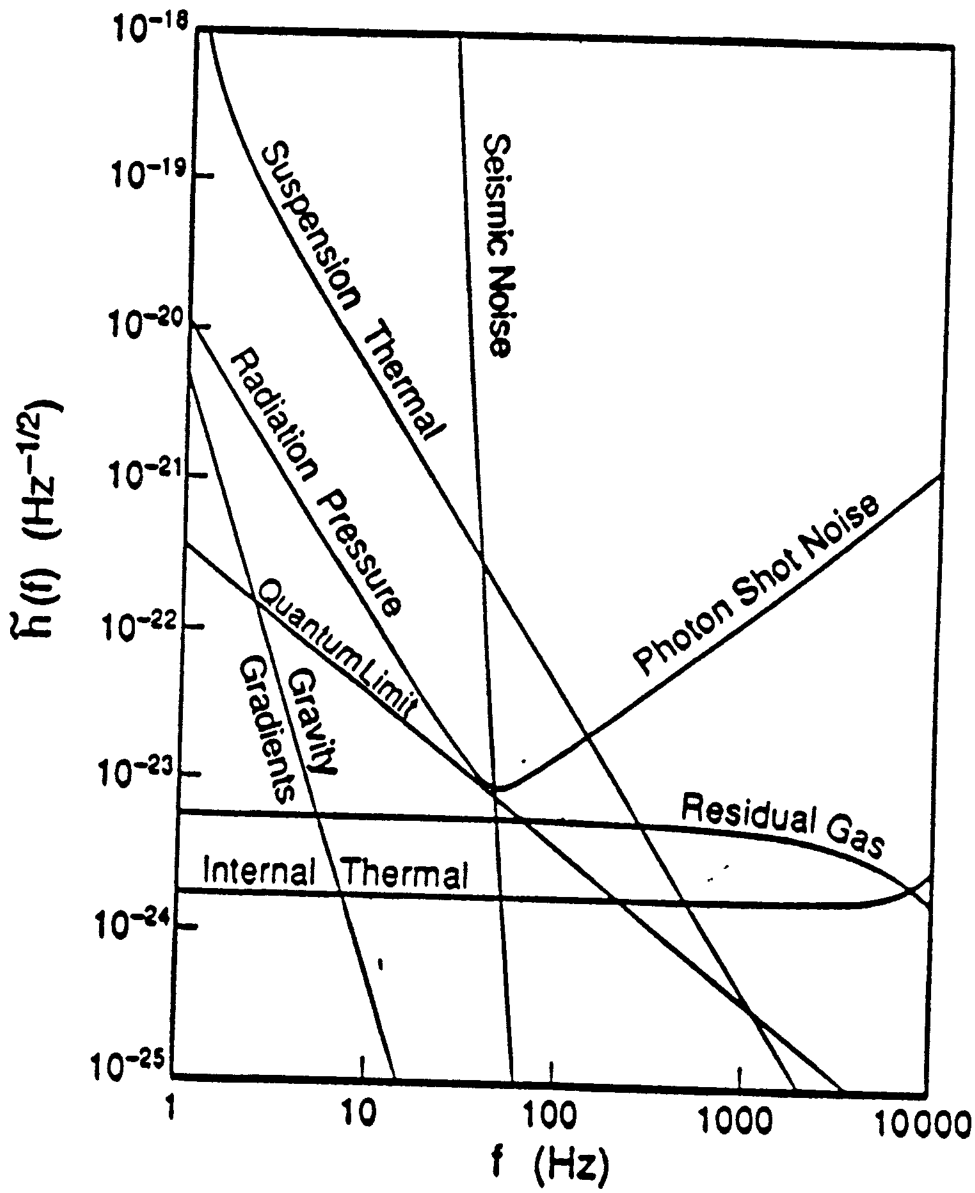
INTERFEROMETER, SIGNAL, AND NOISE



SIGNAL = $L_1 - L_2$

Noise Budget For First LIGO Detectors

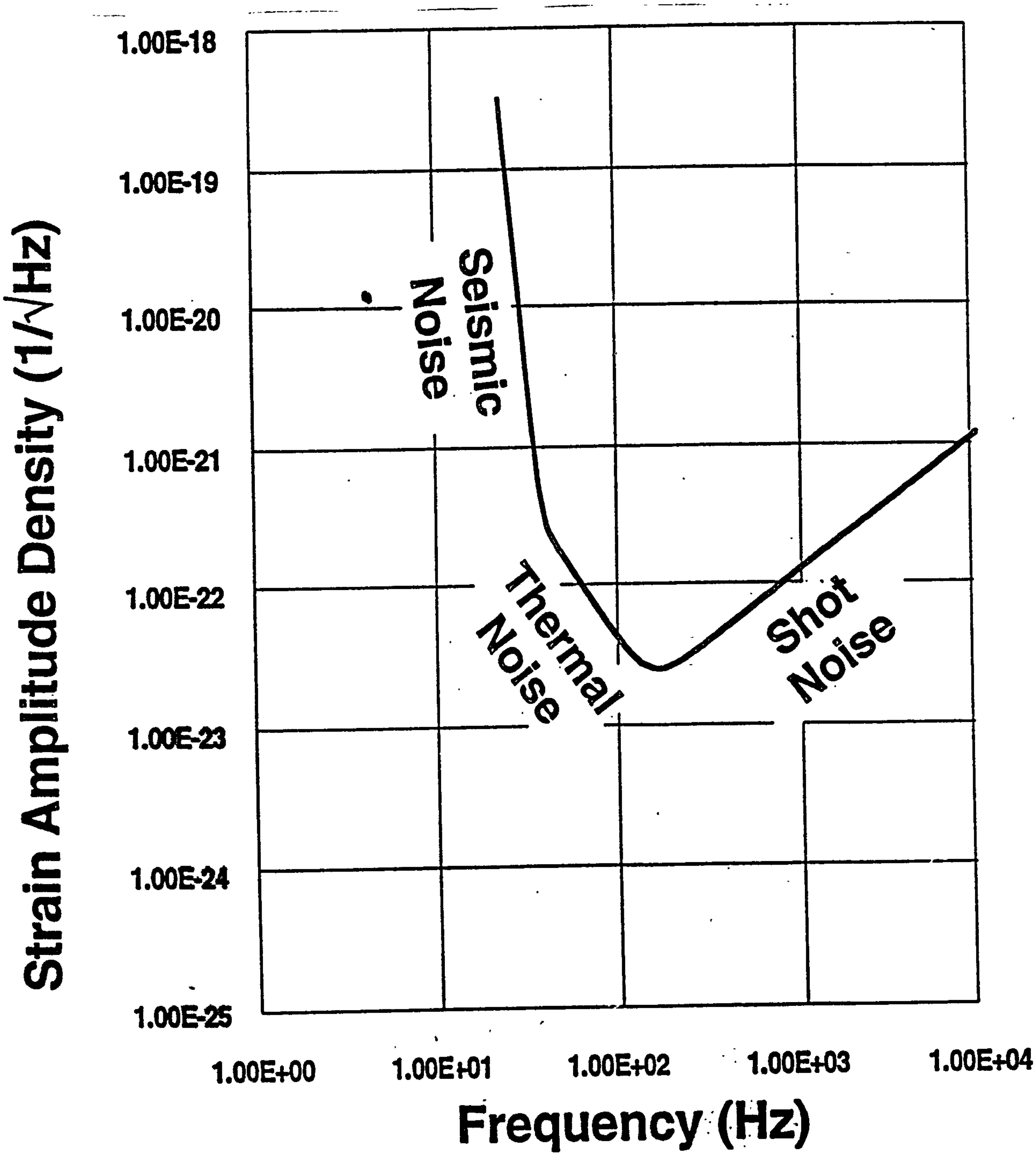
- **5 Watt Laser**
- **Mirror Losses 50 ppm**
- **Recycling Factor of 30**
- **10 kg Test Masses**
- **Suspension Q=10^7**



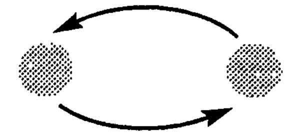
LIGO

Initial Interferometers

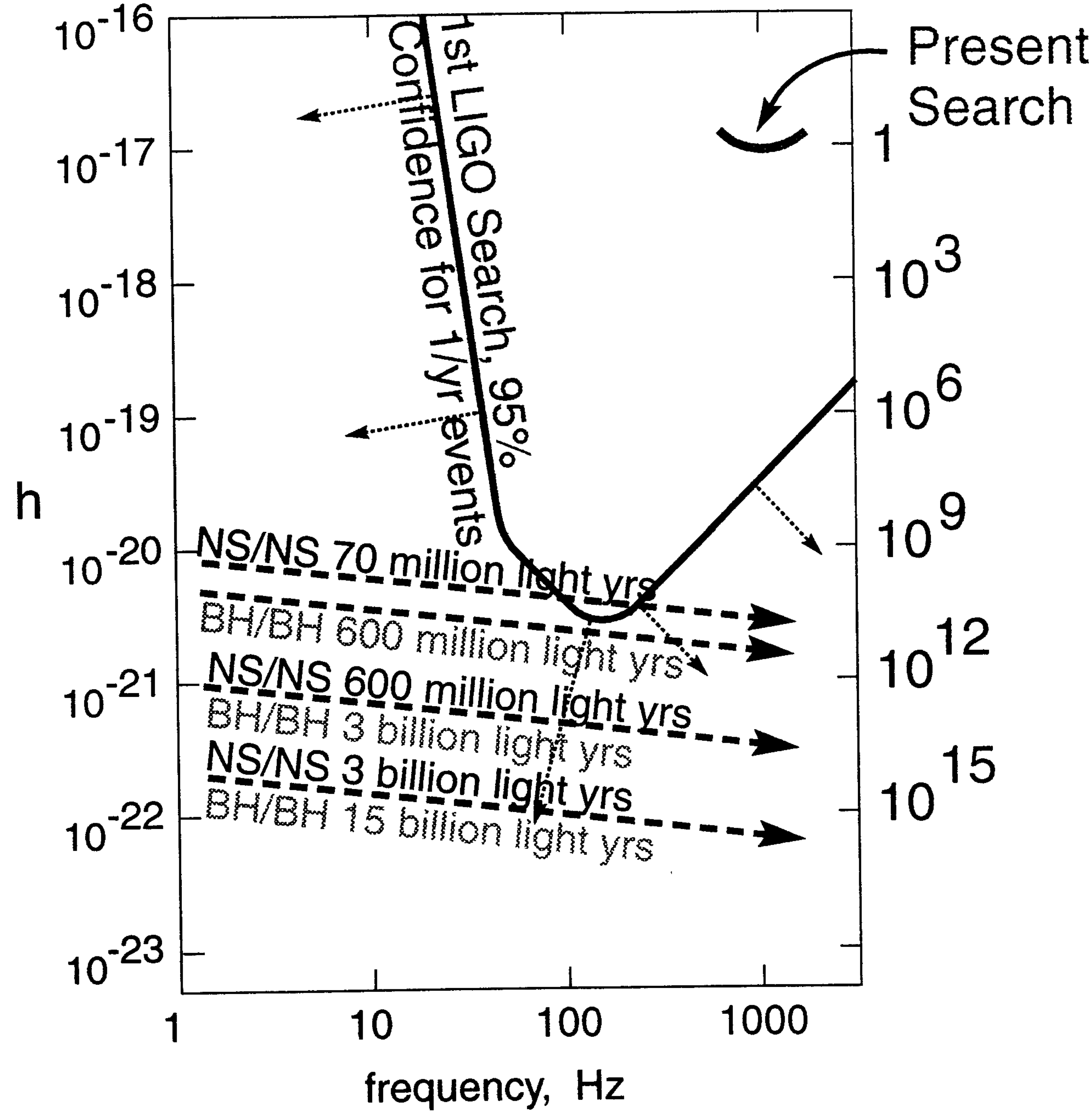
Noise Floor



NEUTRON STAR BINARIES

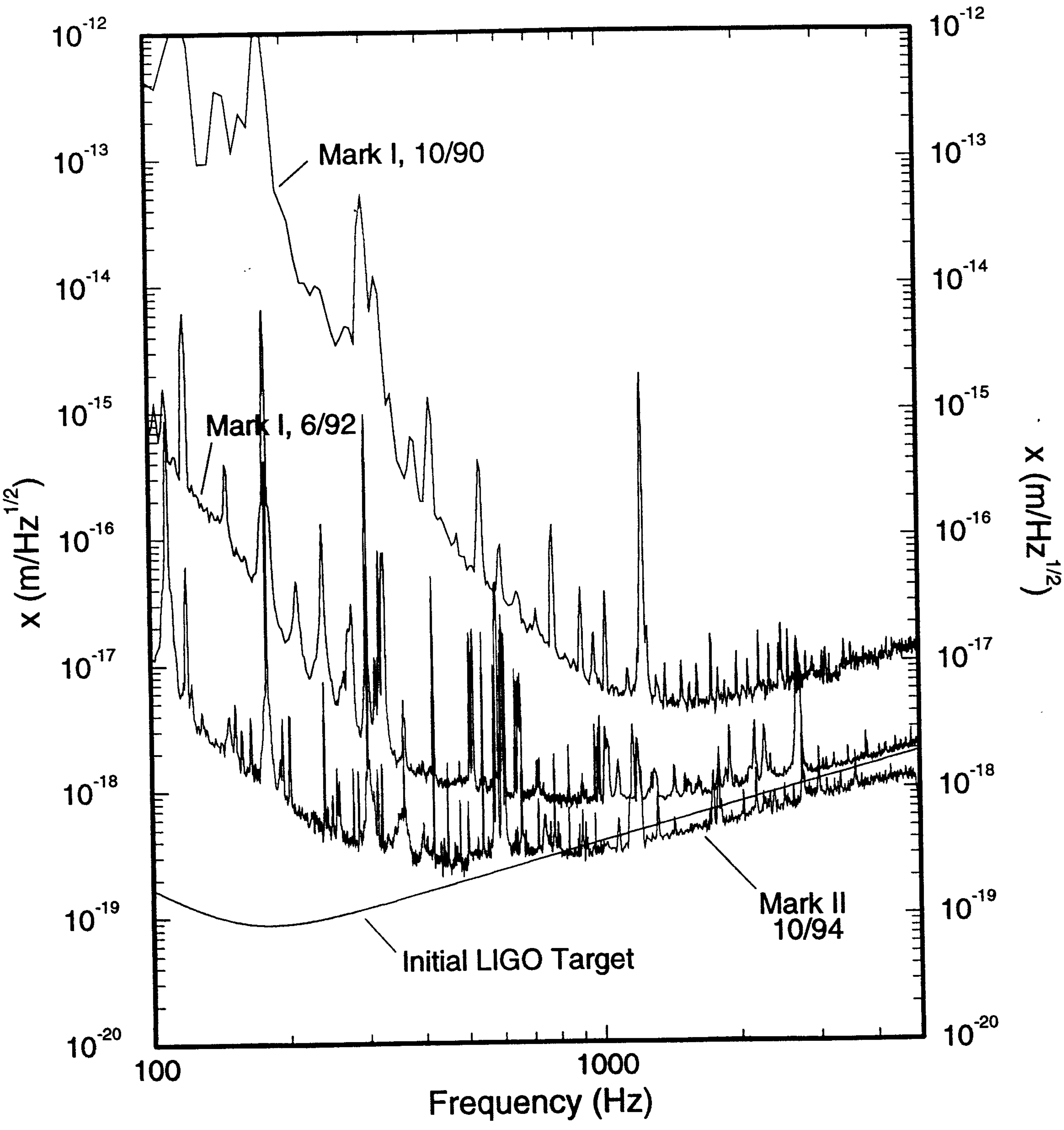


["Near-Guaranteed" source]



- *15 minutes &10,000 orbits in LIGO band*
- *Rich information in waveforms: masses, spins, distance, direction, nuclear equation of state*

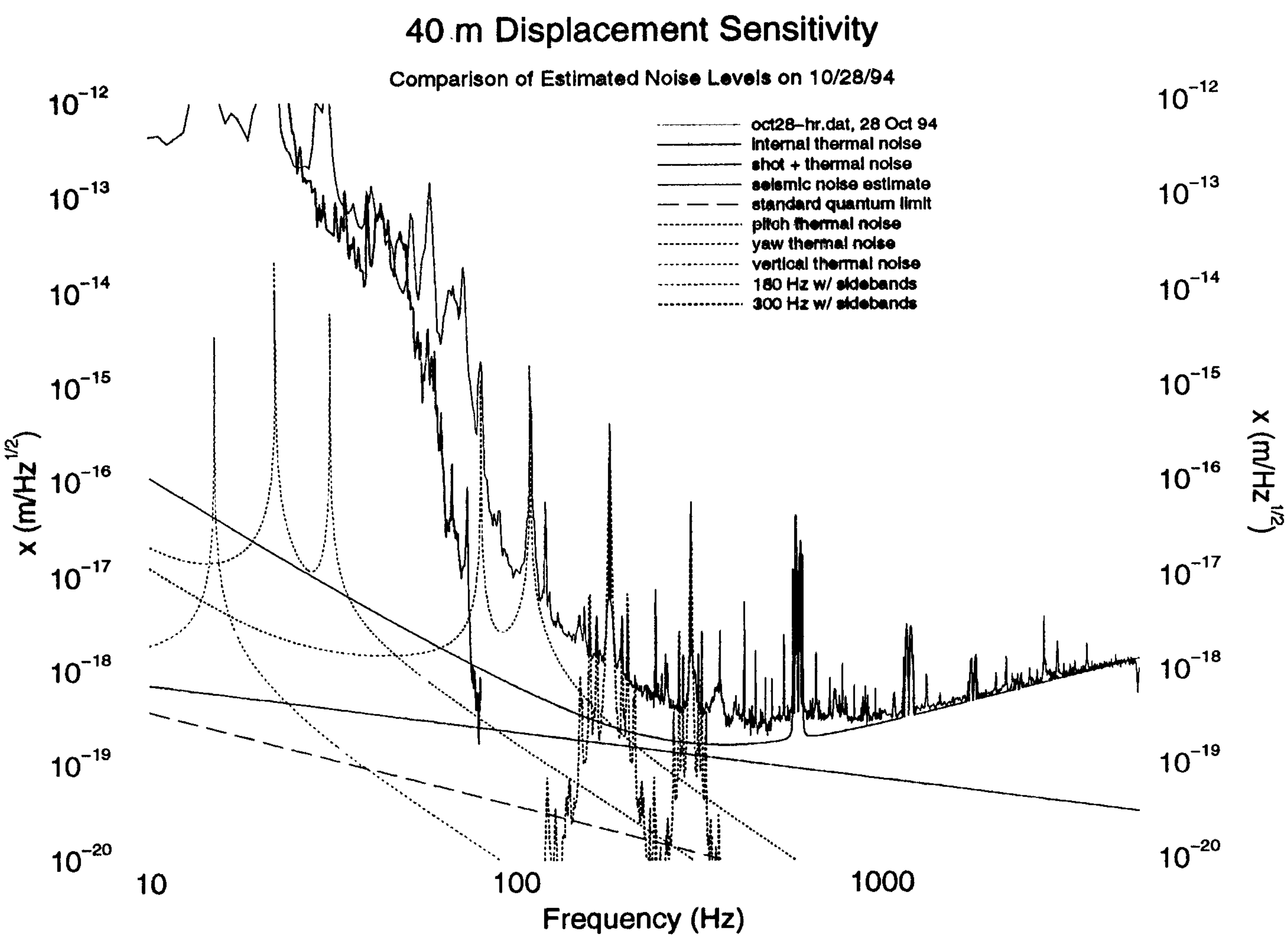
Displacement Sensitivity of 40-Meter Interferometer

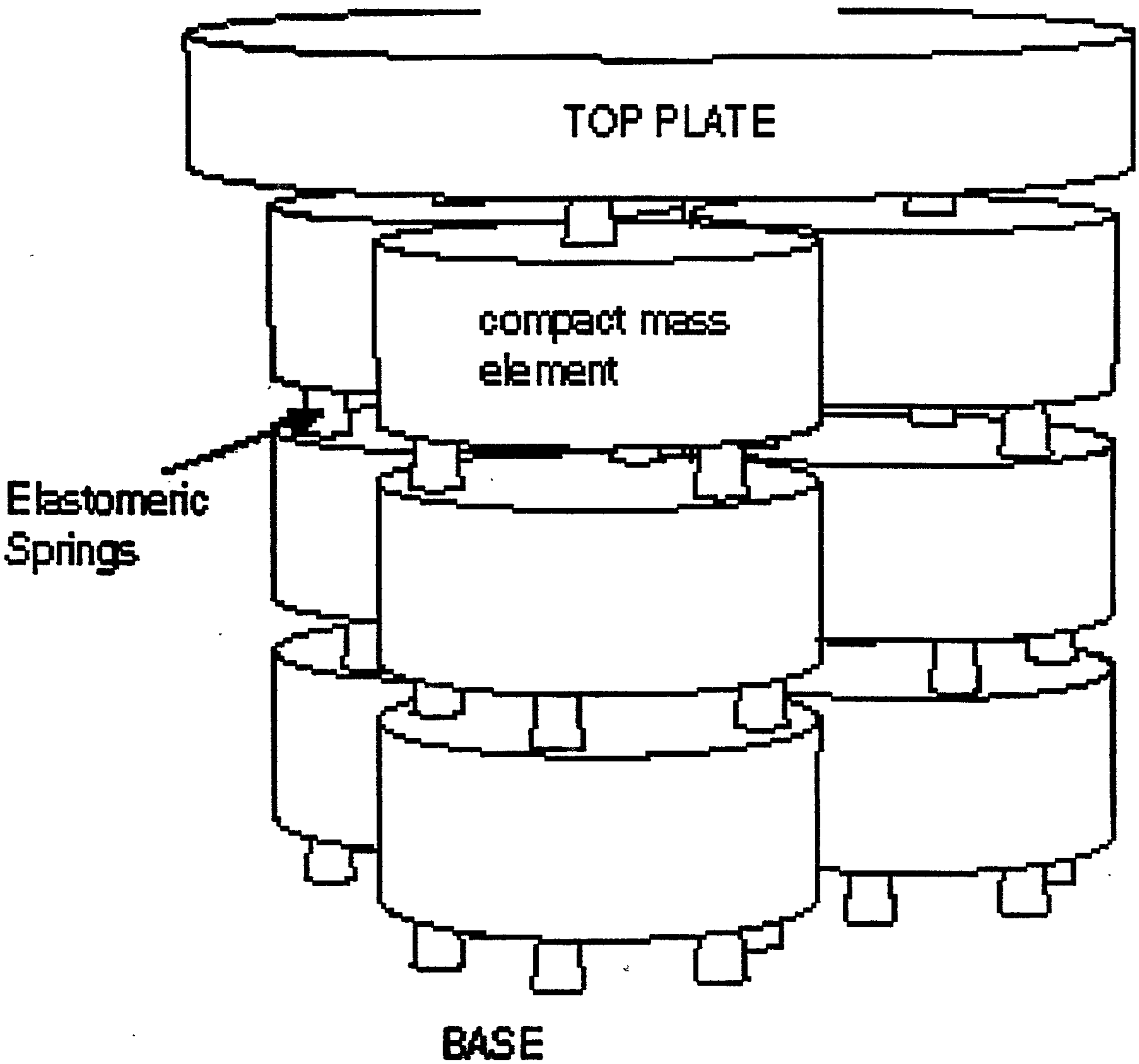


~fjr/fort/mk2/port_90_94.xvgr

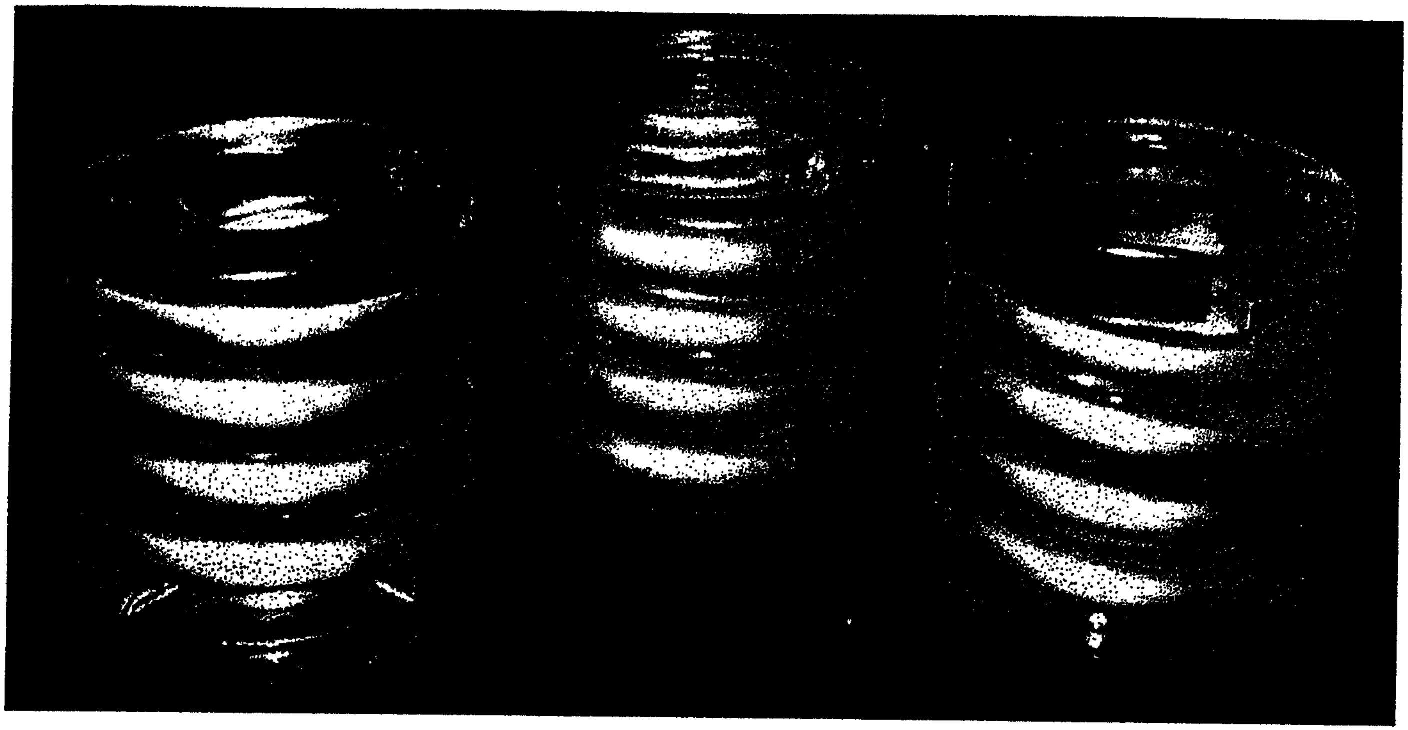
LIGO Systems Engineering and Integration

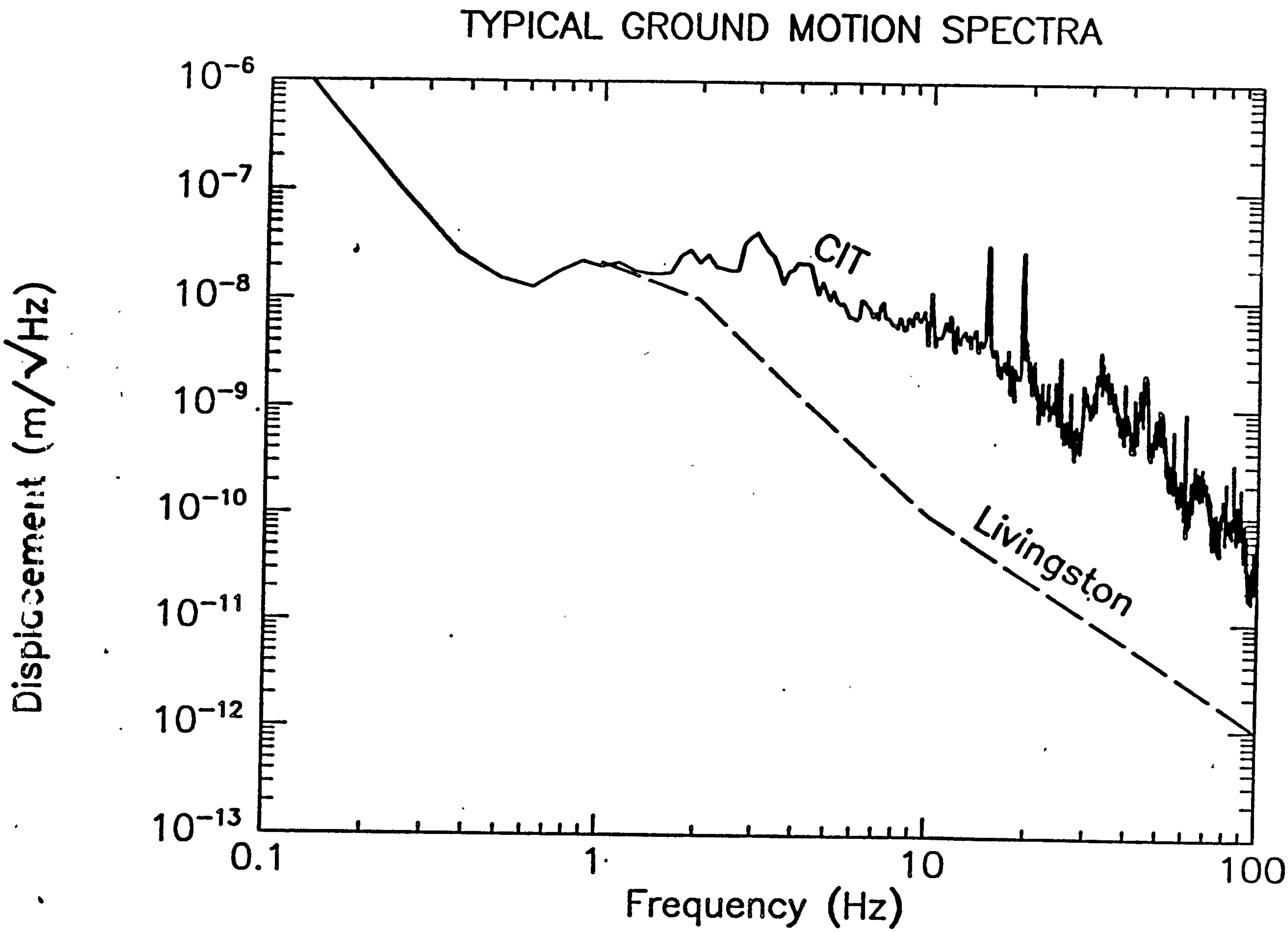
40 m Lab





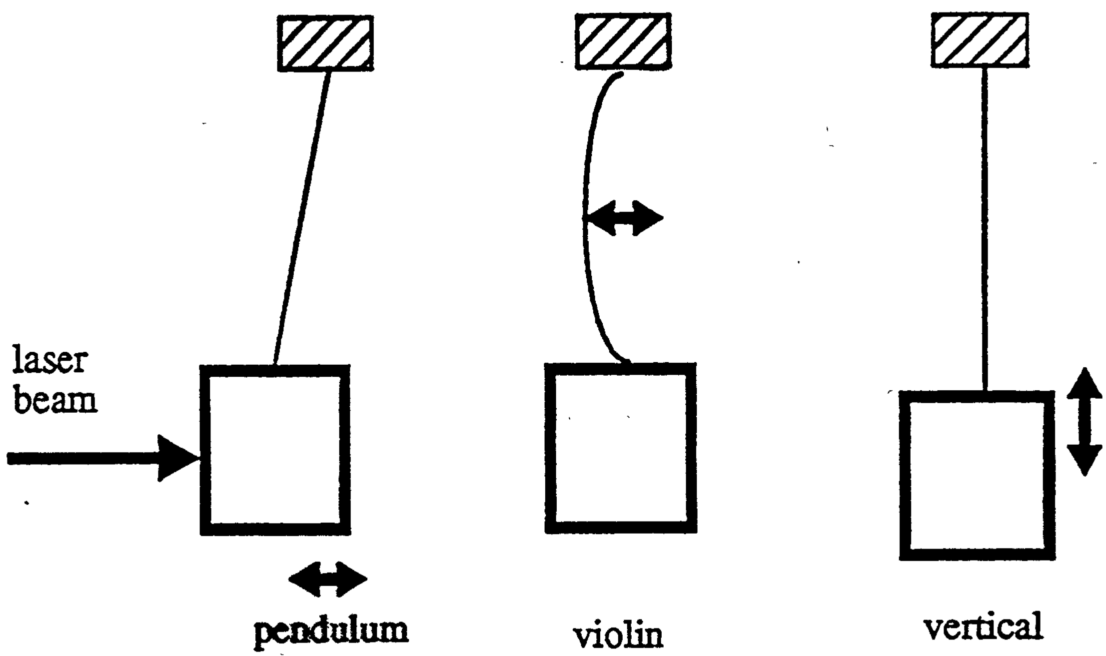
PROTOTYPE ISOLATION STACK





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

Interferometers
Mechanical Thermal Noise



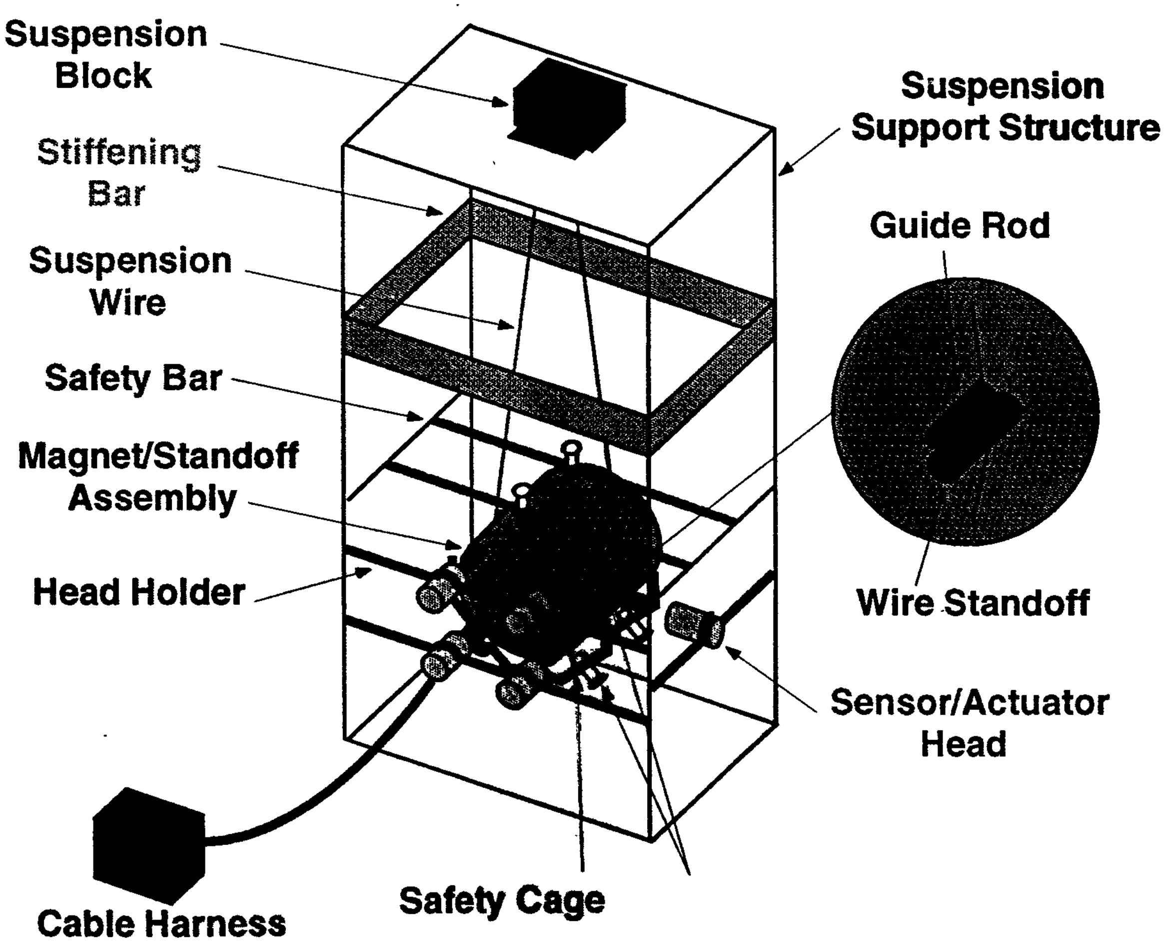
- pendulum noise
  - » $x_{rms} \sim 10^{-11}$ m, $f_0 \sim 1$ Hz
- violin mode
  - » $x_{rms} \sim 5\ 10^{-17}$m; $f_{0n} \sim 600n$ Hz
- test mass vibrational mode
  - » $x_{rms} \sim 5\ 10^{-16}$m, $f_0 > 10$ kHz

R&D: Suspension Research

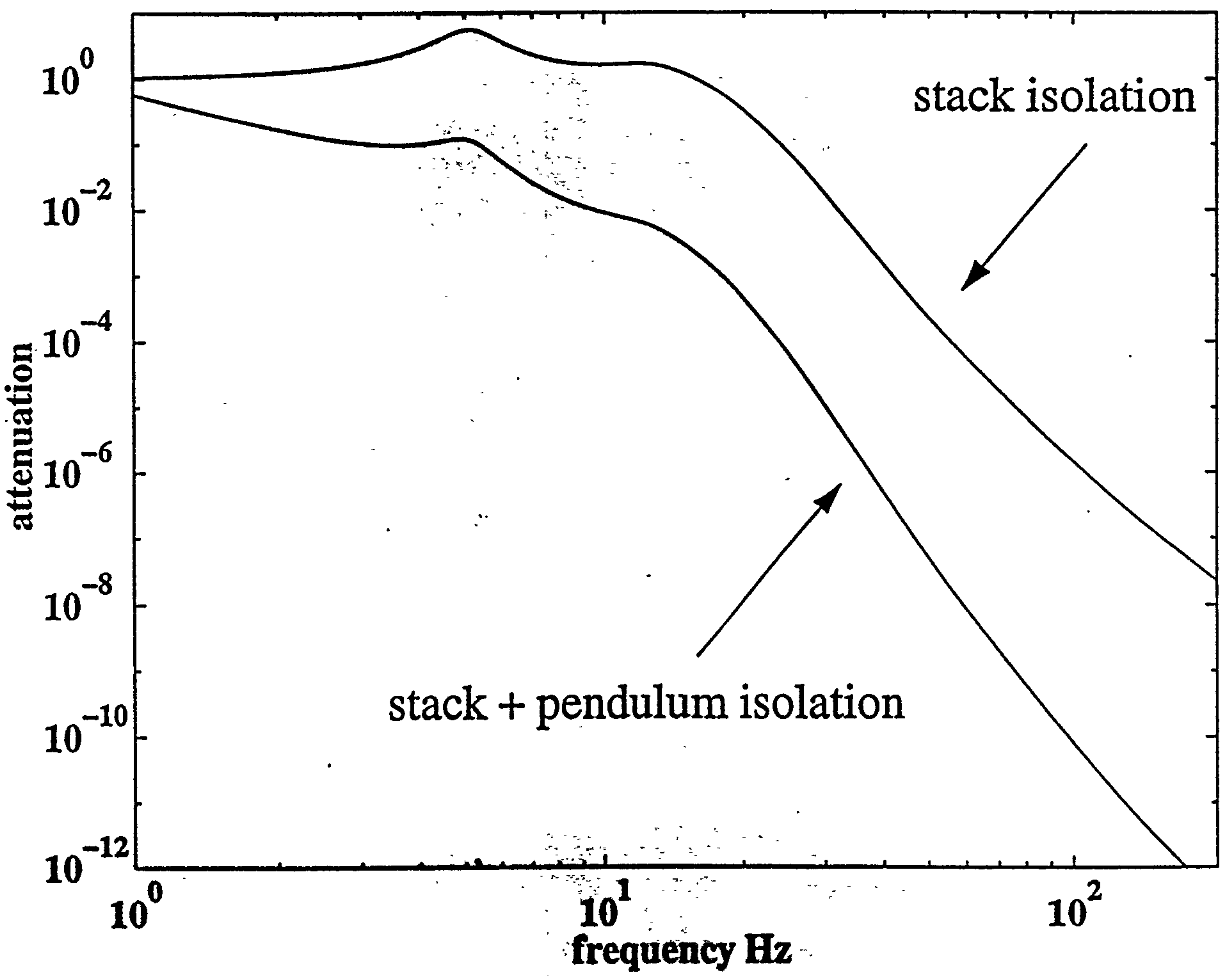
Pendulum suspension serves several purposes

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

Prototypes tested separately, and in, interferometers



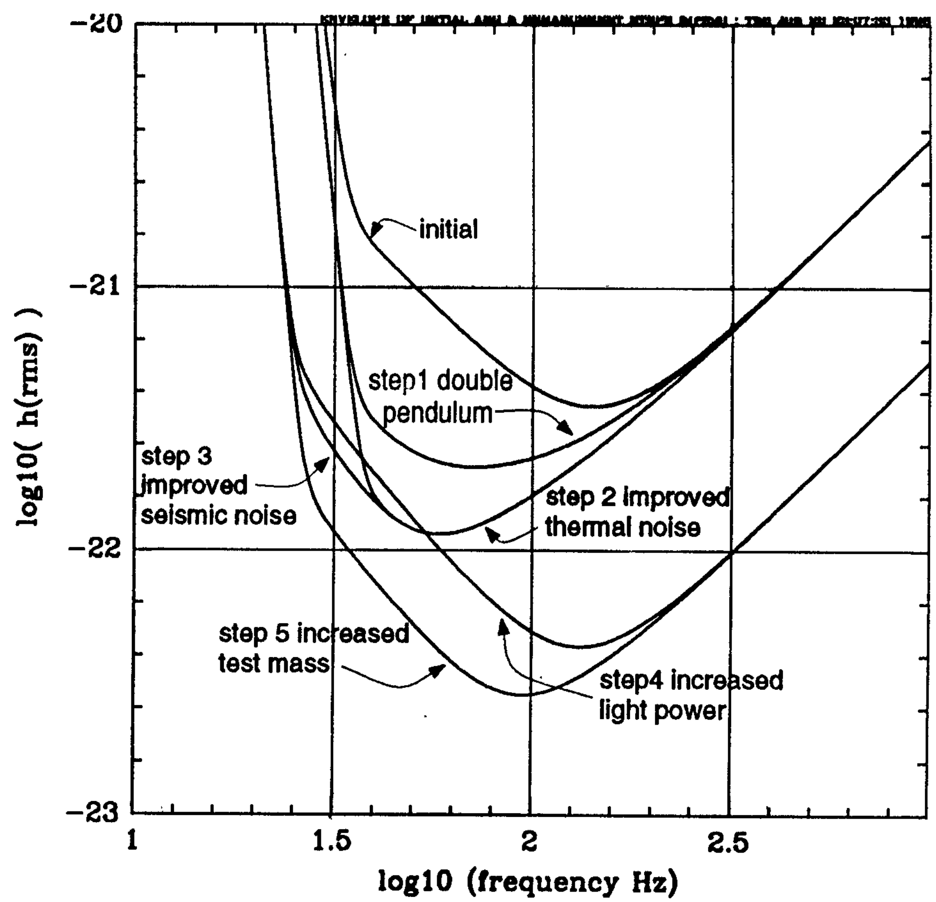
Baseline Isolation Performance



- Displacement noise 10^{-21} m/rHz @ 100 Hz

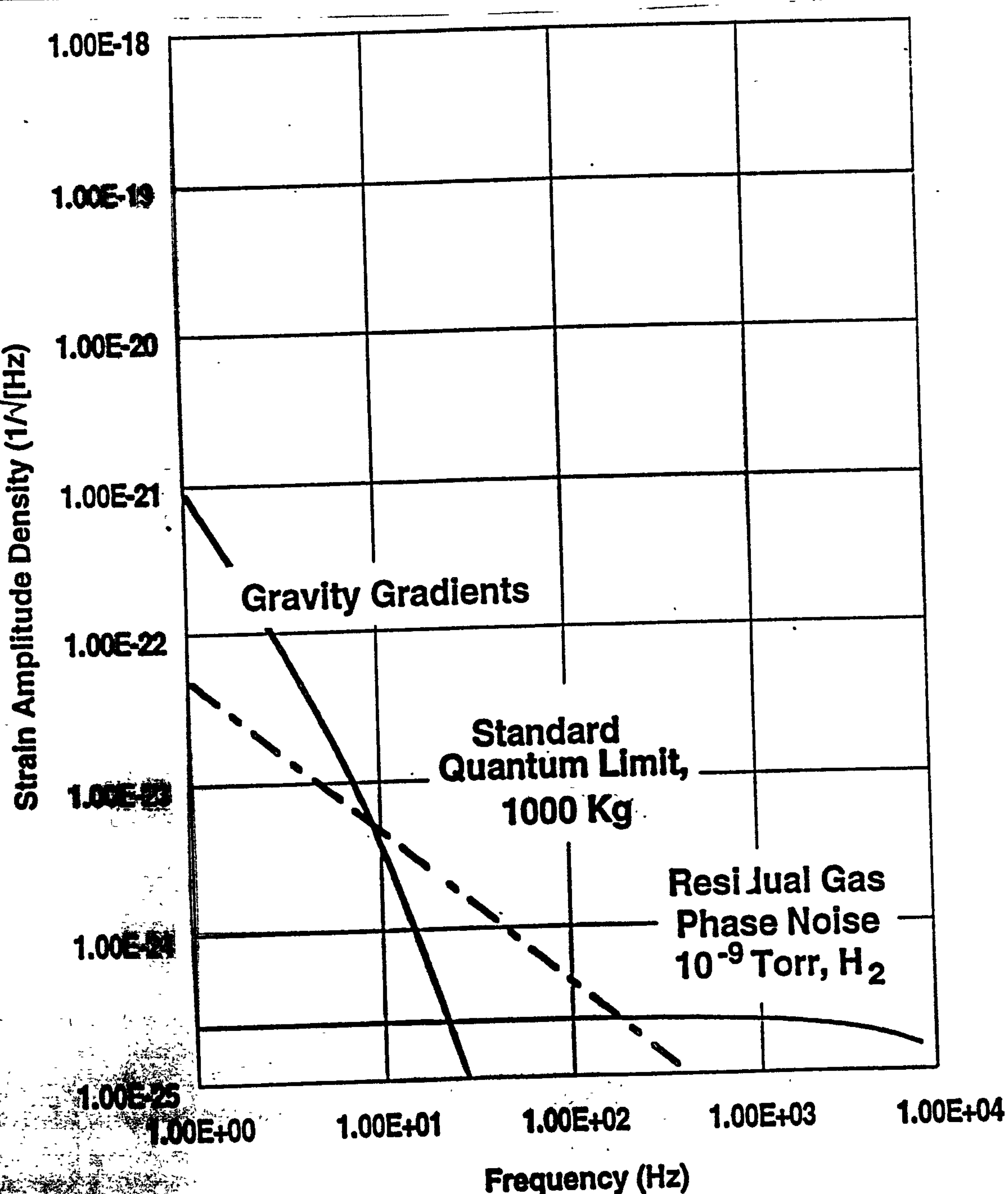
LIGO

Steps in the Advanced Subsystems Research



LIGO Facilities

Limiting Noise Floor



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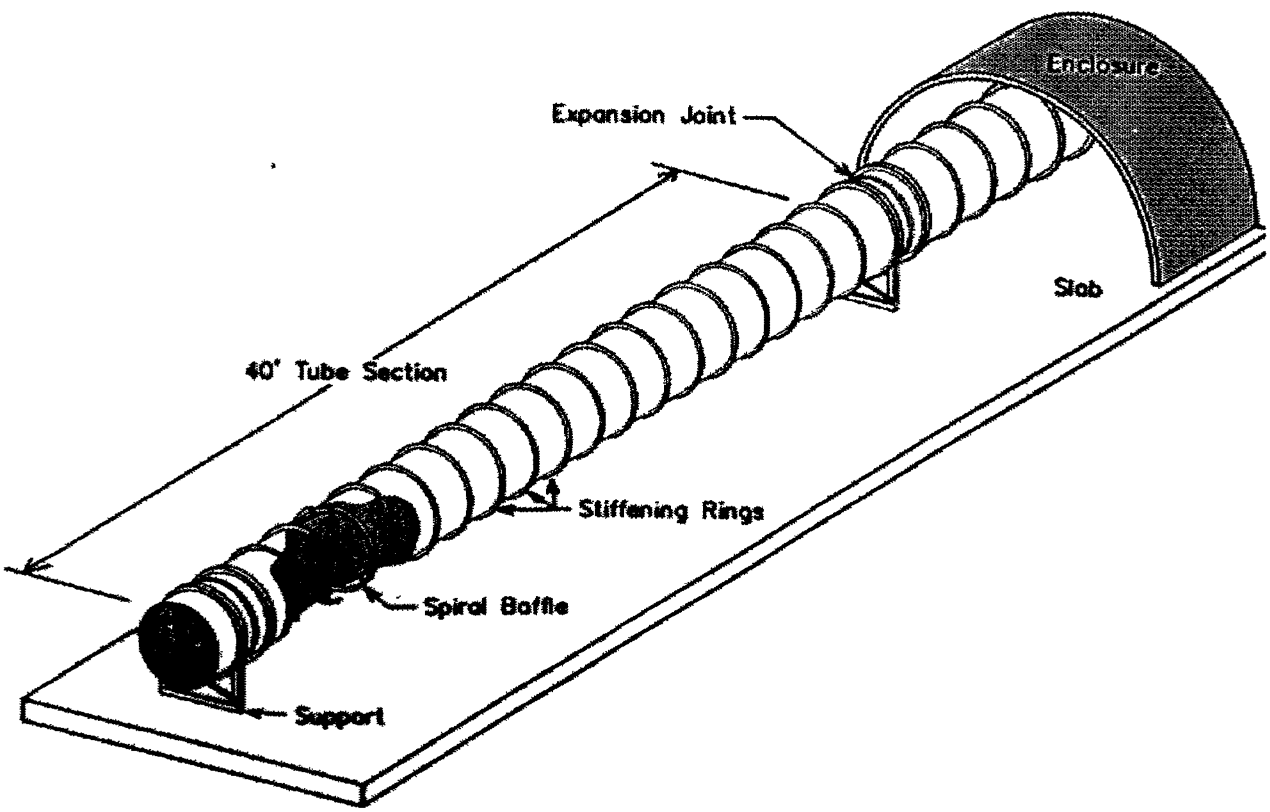
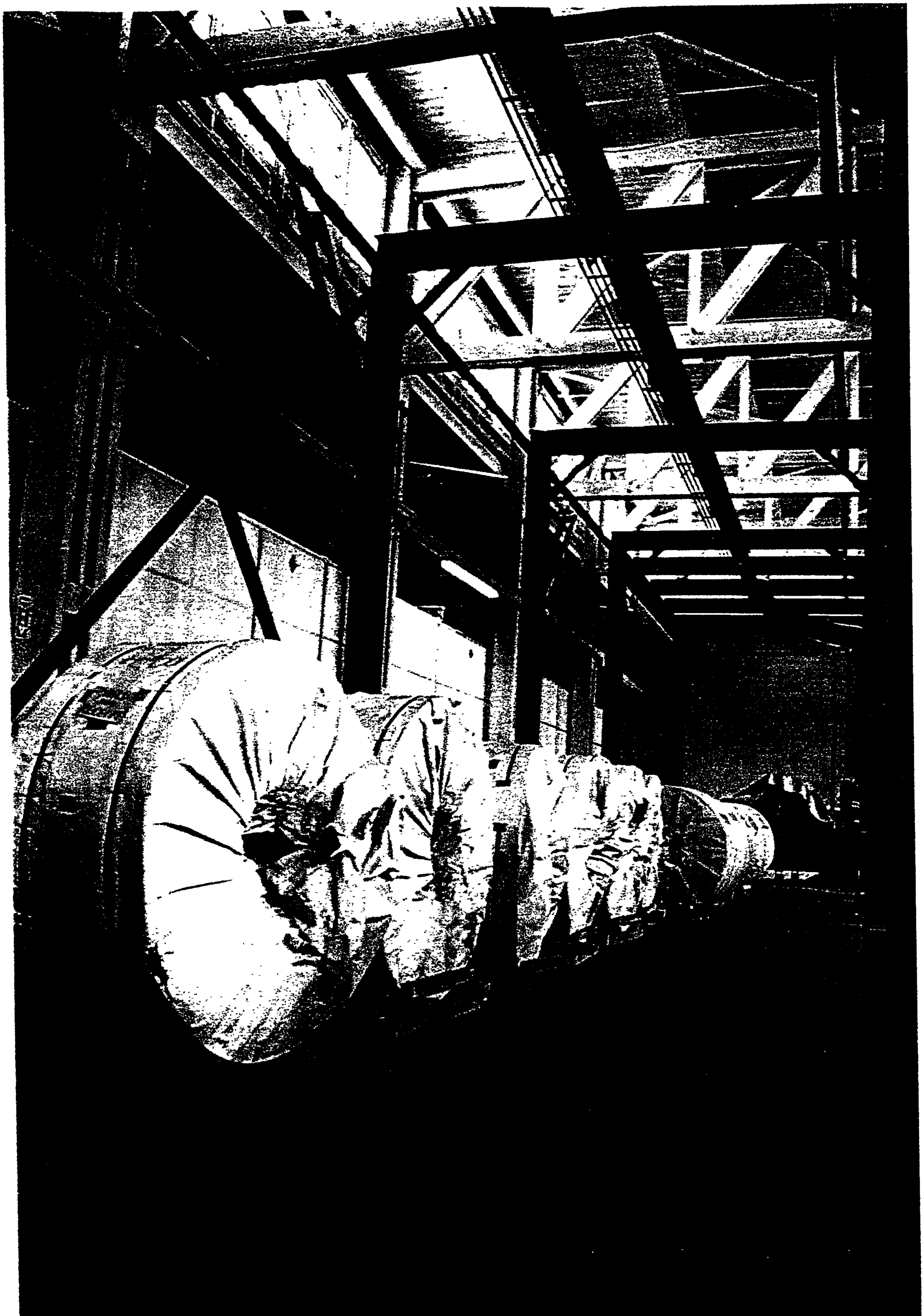
LIGO Plans

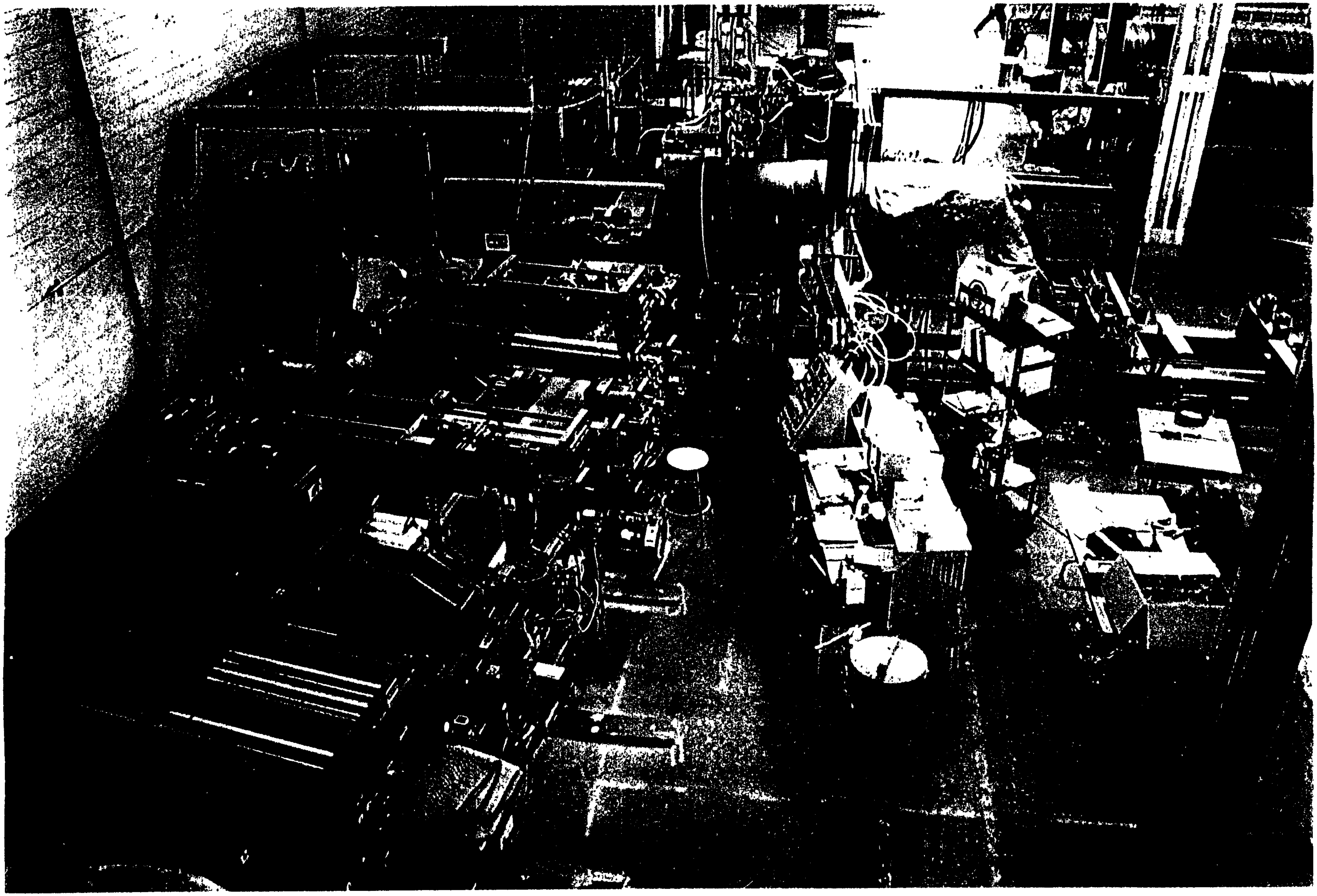
- Main Activity

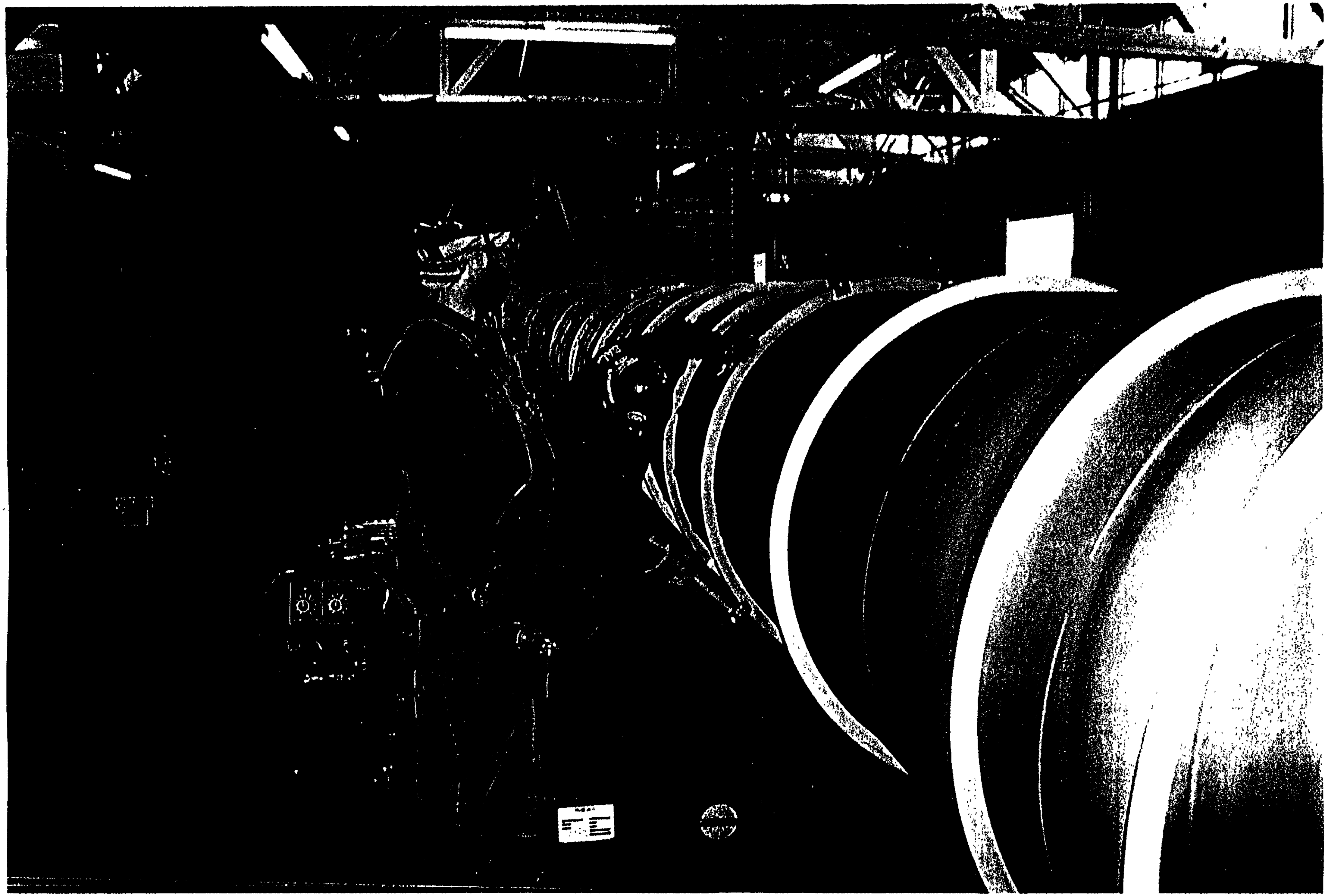
1996	Construction Underway	
	-mostly civil	
1997	Facility Construction	
	-vacuum system	
1998	Interferometer Construction	
	-complete facilities	
1999	Construction Complete	
	-interferometers in vacuum	
2000	Commission Detectors	
	-first light; testing	
2001	Engineering Tests	
	-sensitivity; engineering run	
2002	Initial LIGO Detector Run	
	- $h \sim 10^{-21}$	

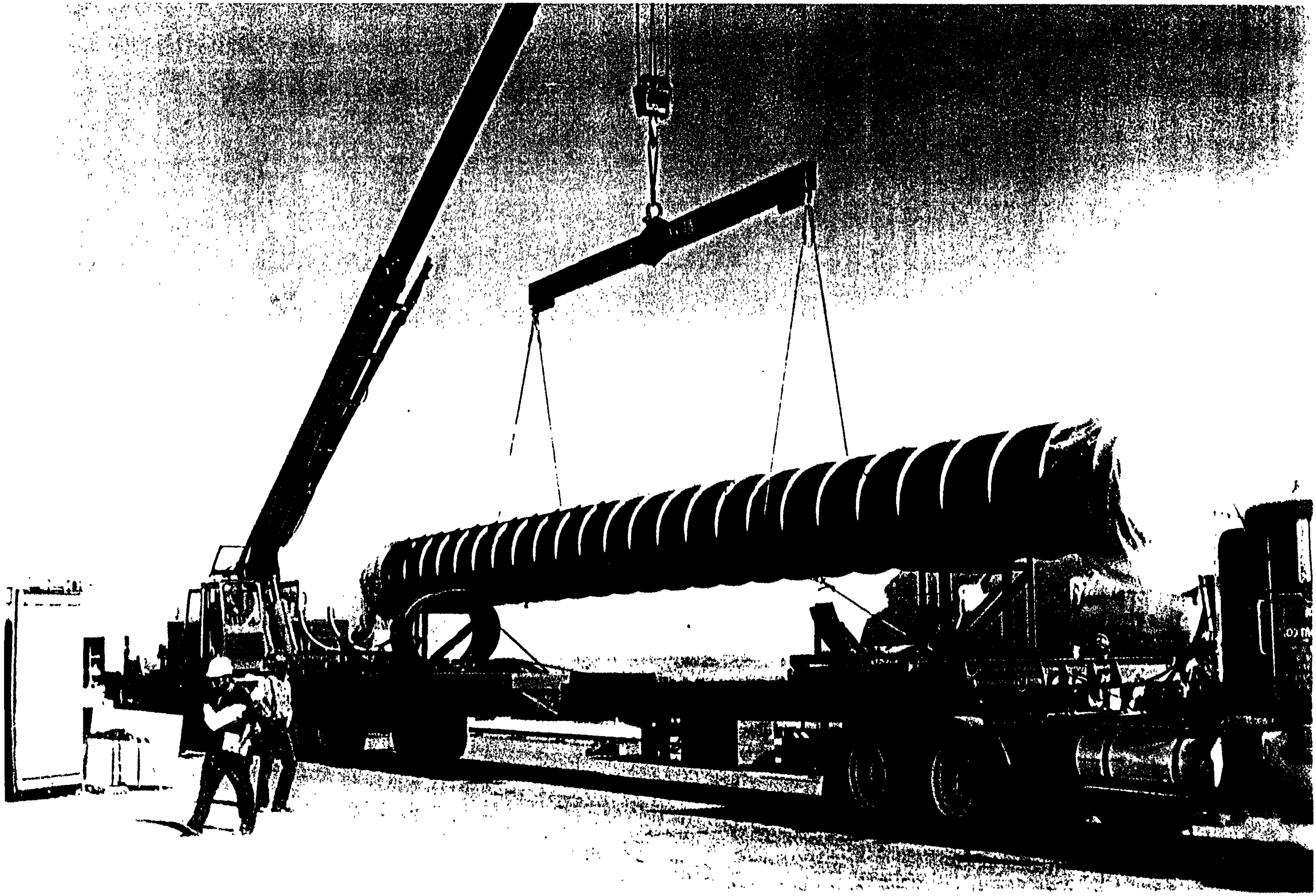
Beam Tube


Enclosure
Expansion Joint
Slab
40' Tube Section
Stiffening Rings
Spiral Baffle
Support









LIGO Facilities

Beam Tube Enclosure

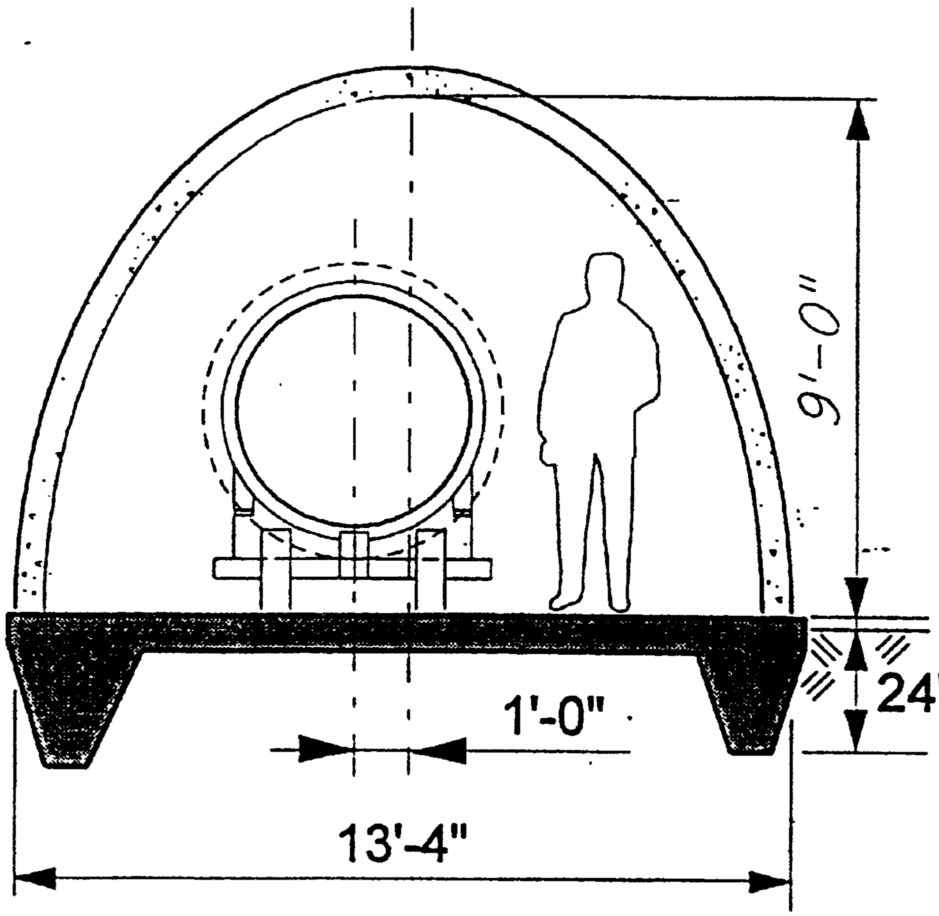
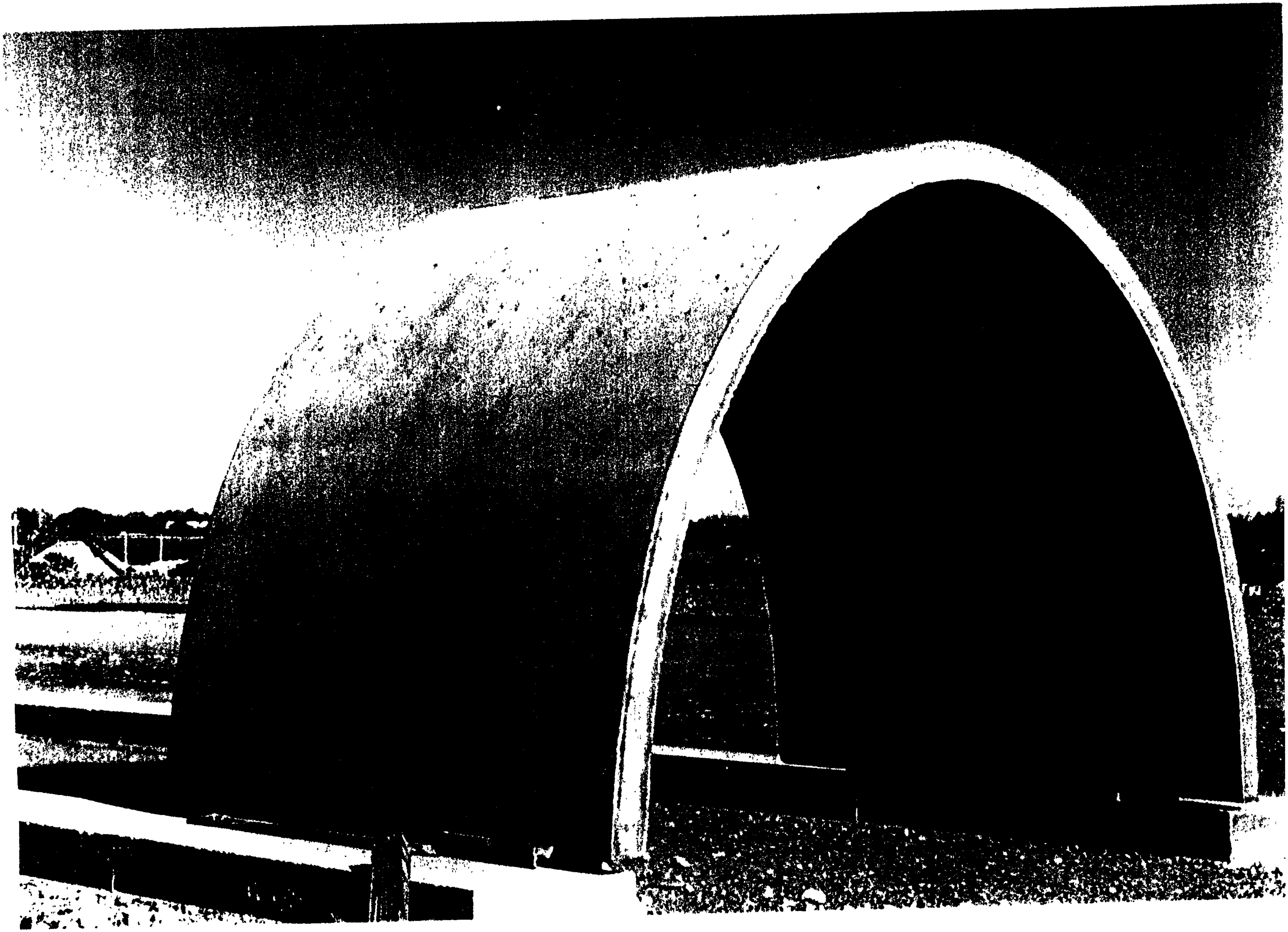
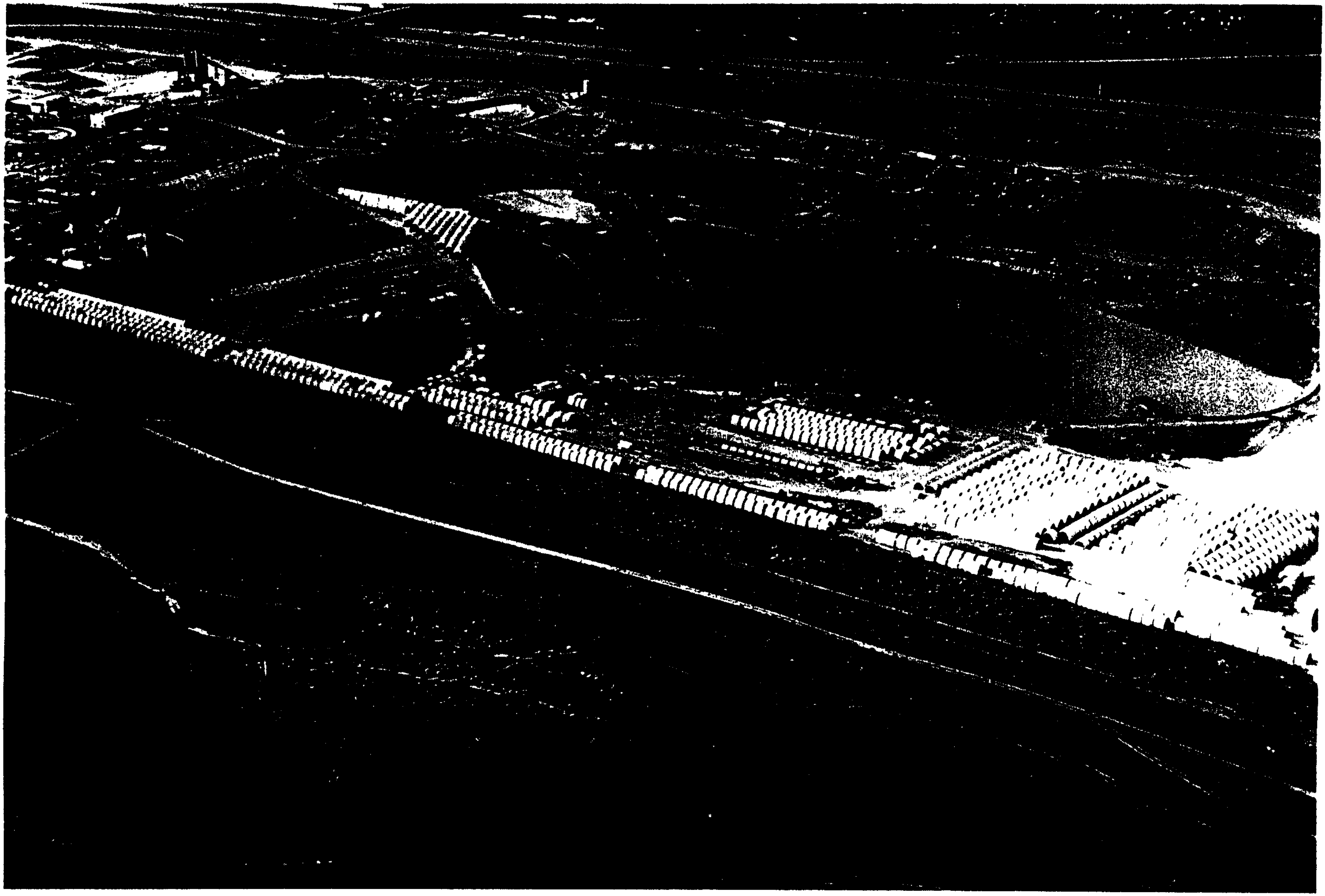
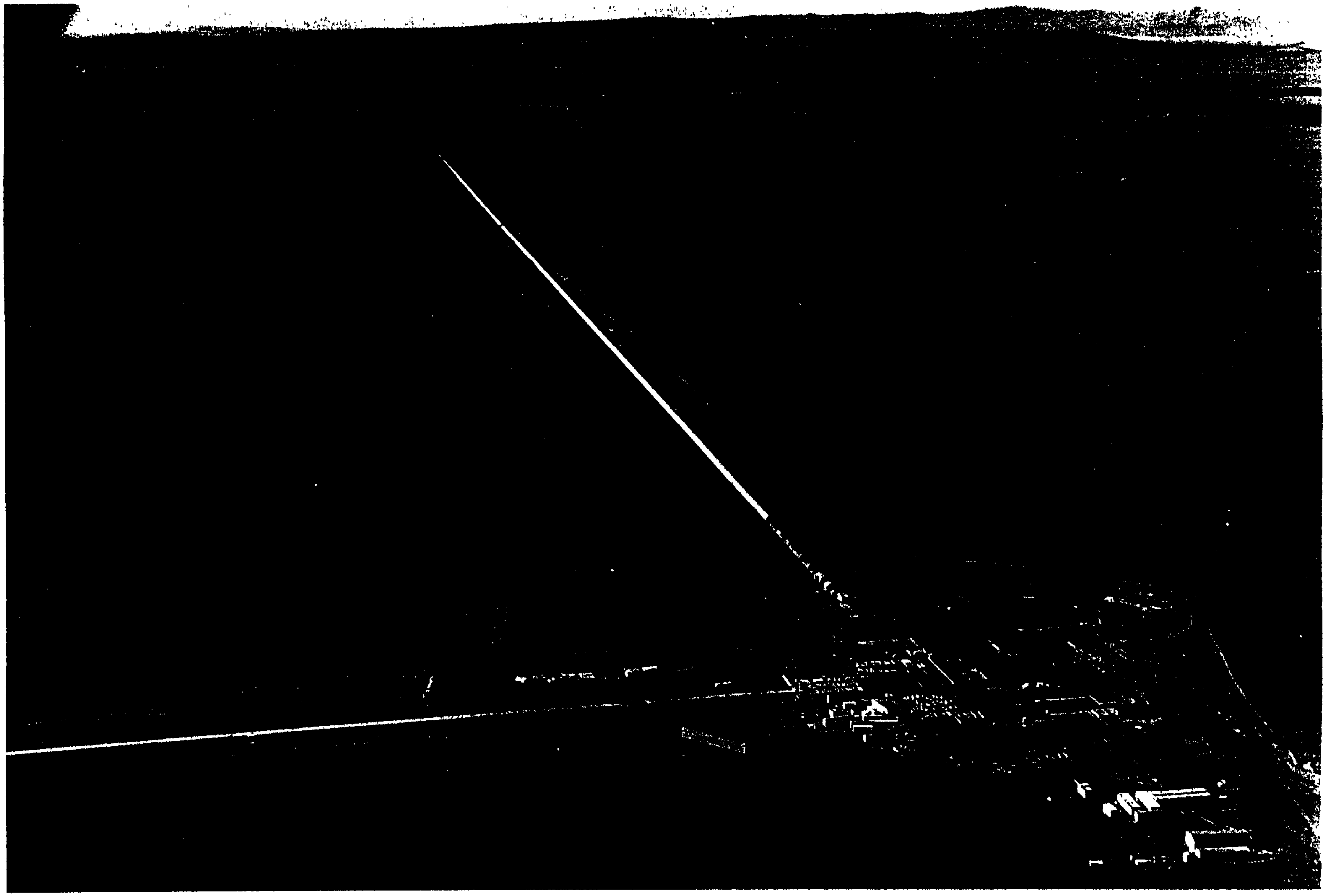


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

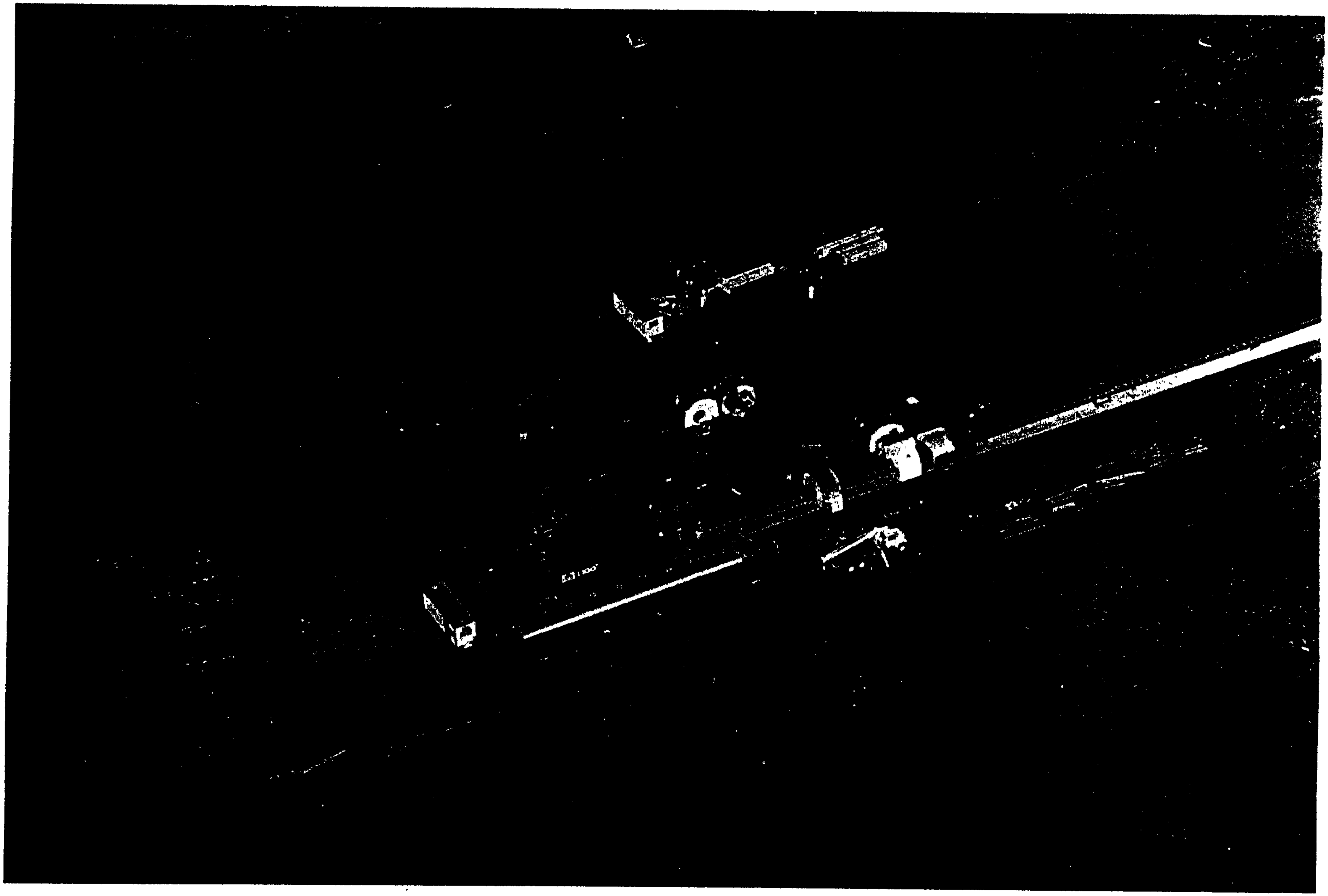




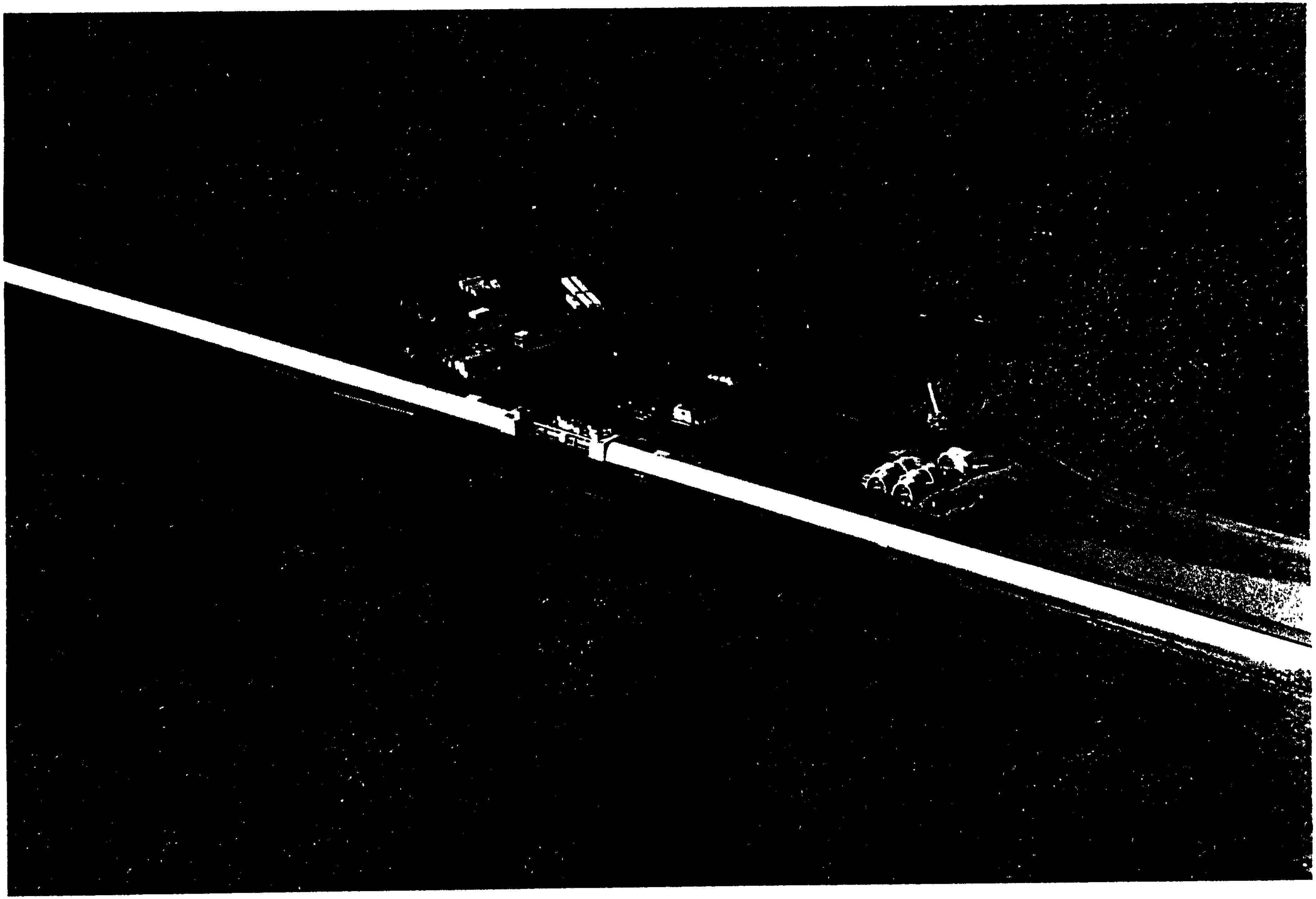
G970057- 01 -O-√



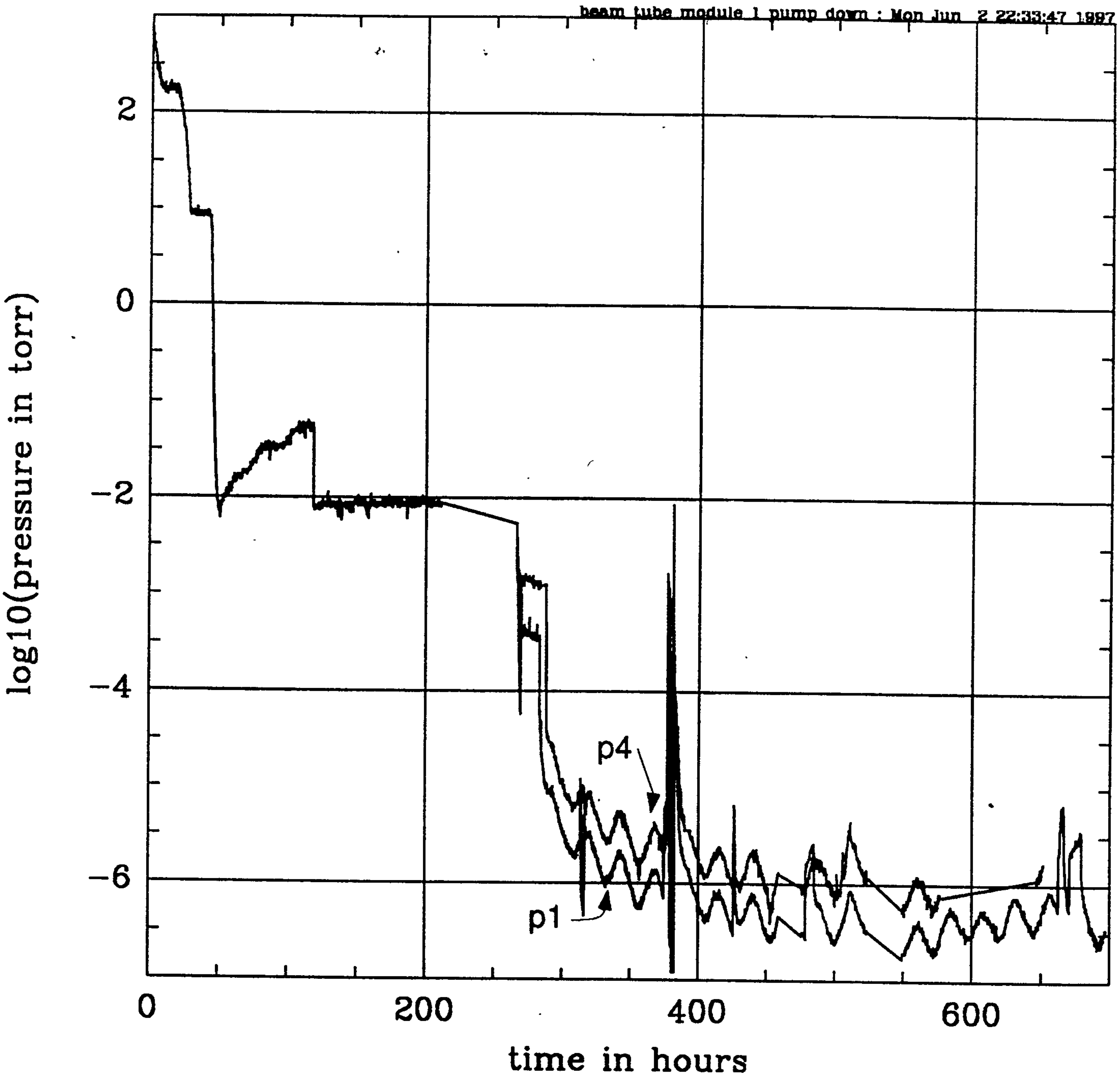
G970057- 05-O-V



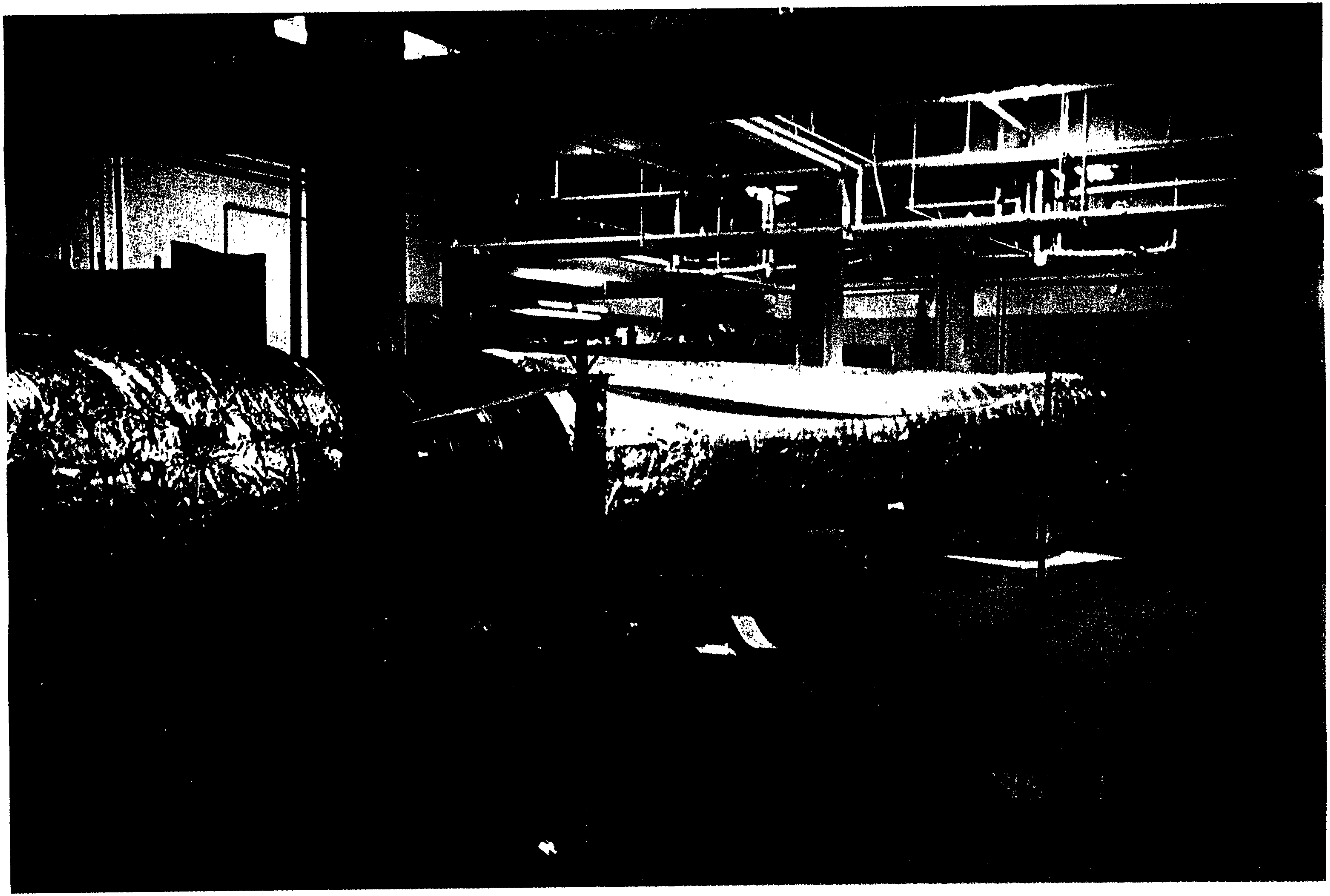
G970057- // -O-V



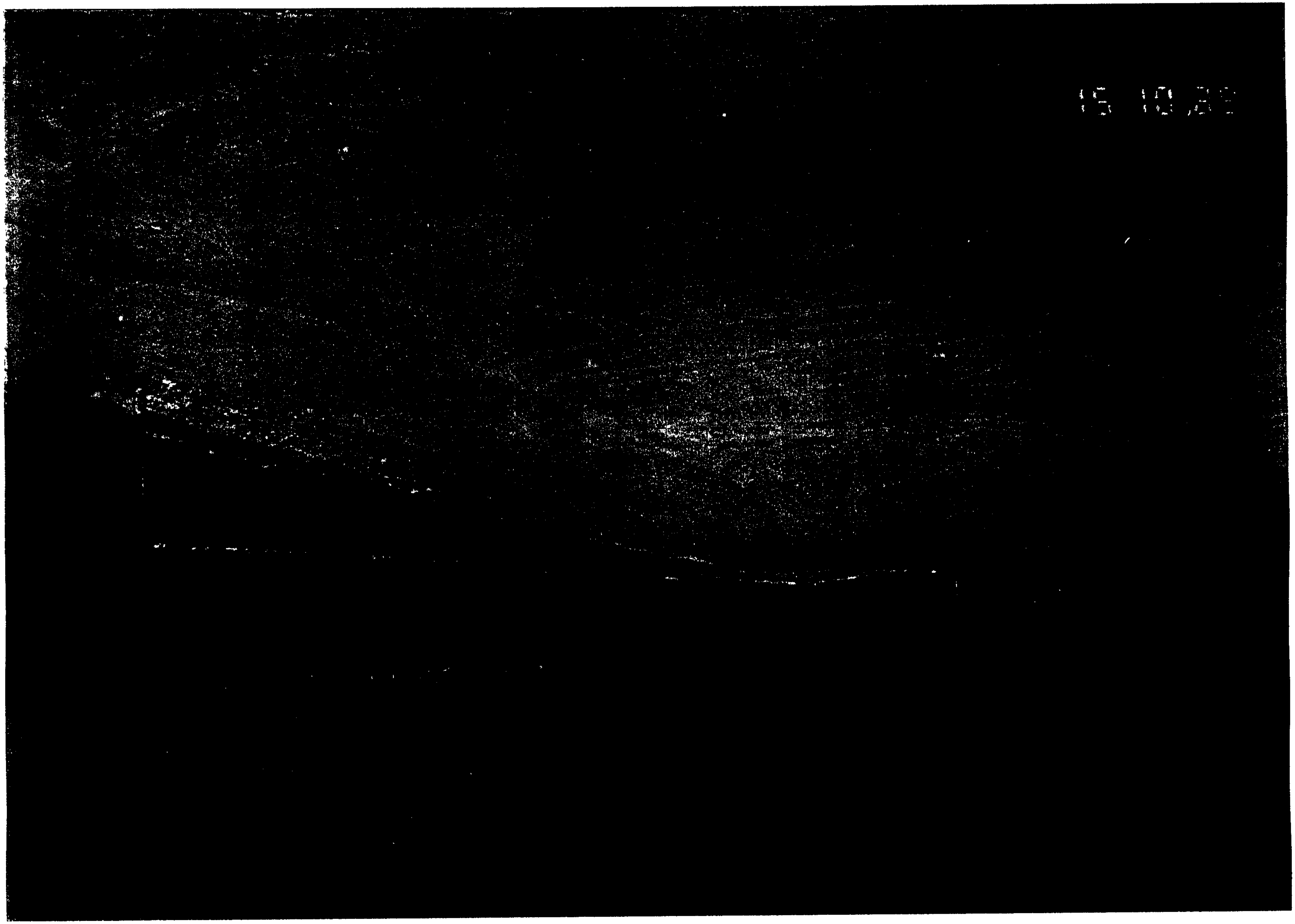
G970057- 07 -O-V

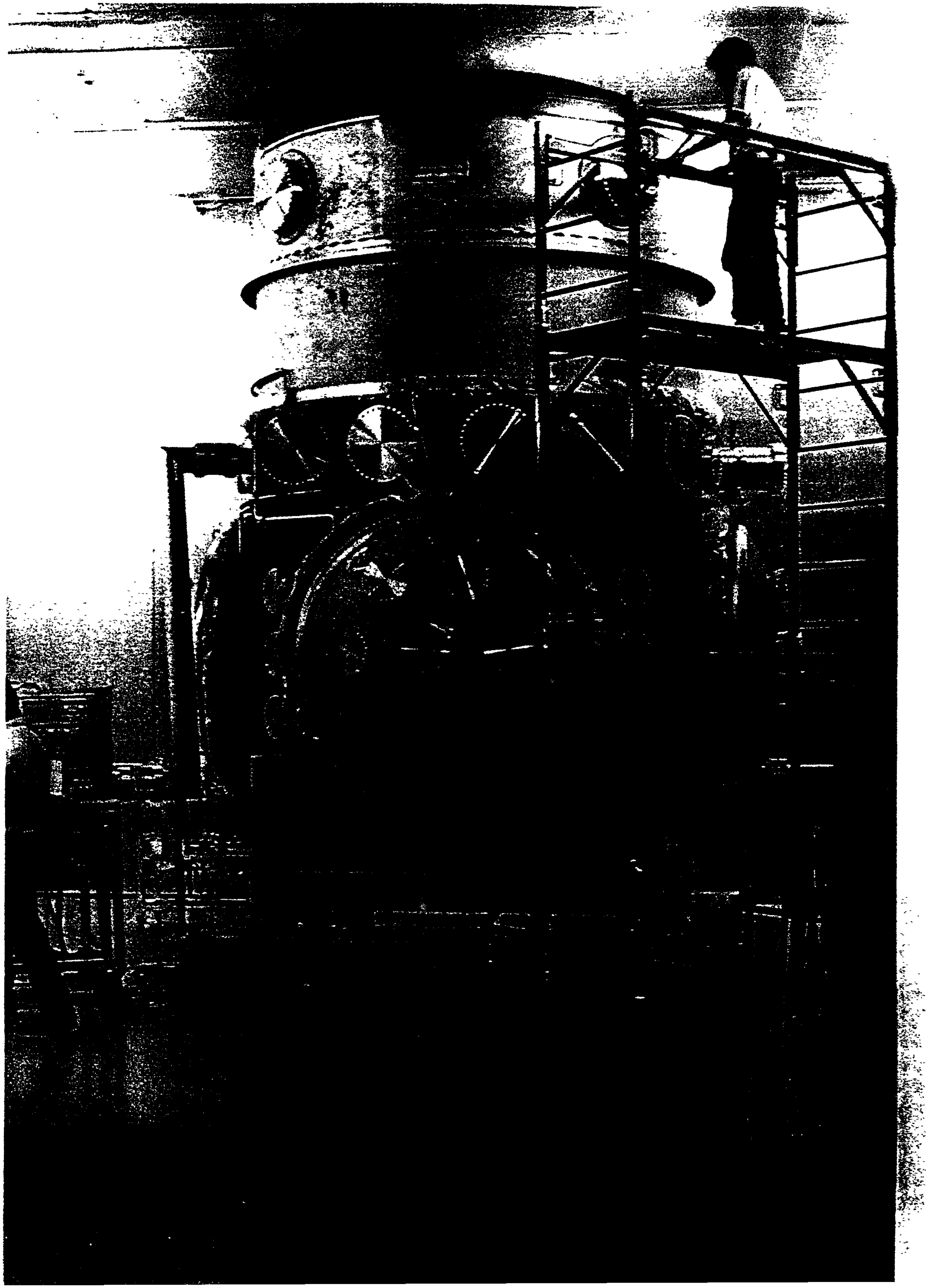


beam tube module 1 pump down : Mon Jun 2 22:33:47 1997
2
0
−2
−4
−6
log10(pressure in torr)
p4
p1
0
200
400
600
time in hours



G970056- 04 -O-V



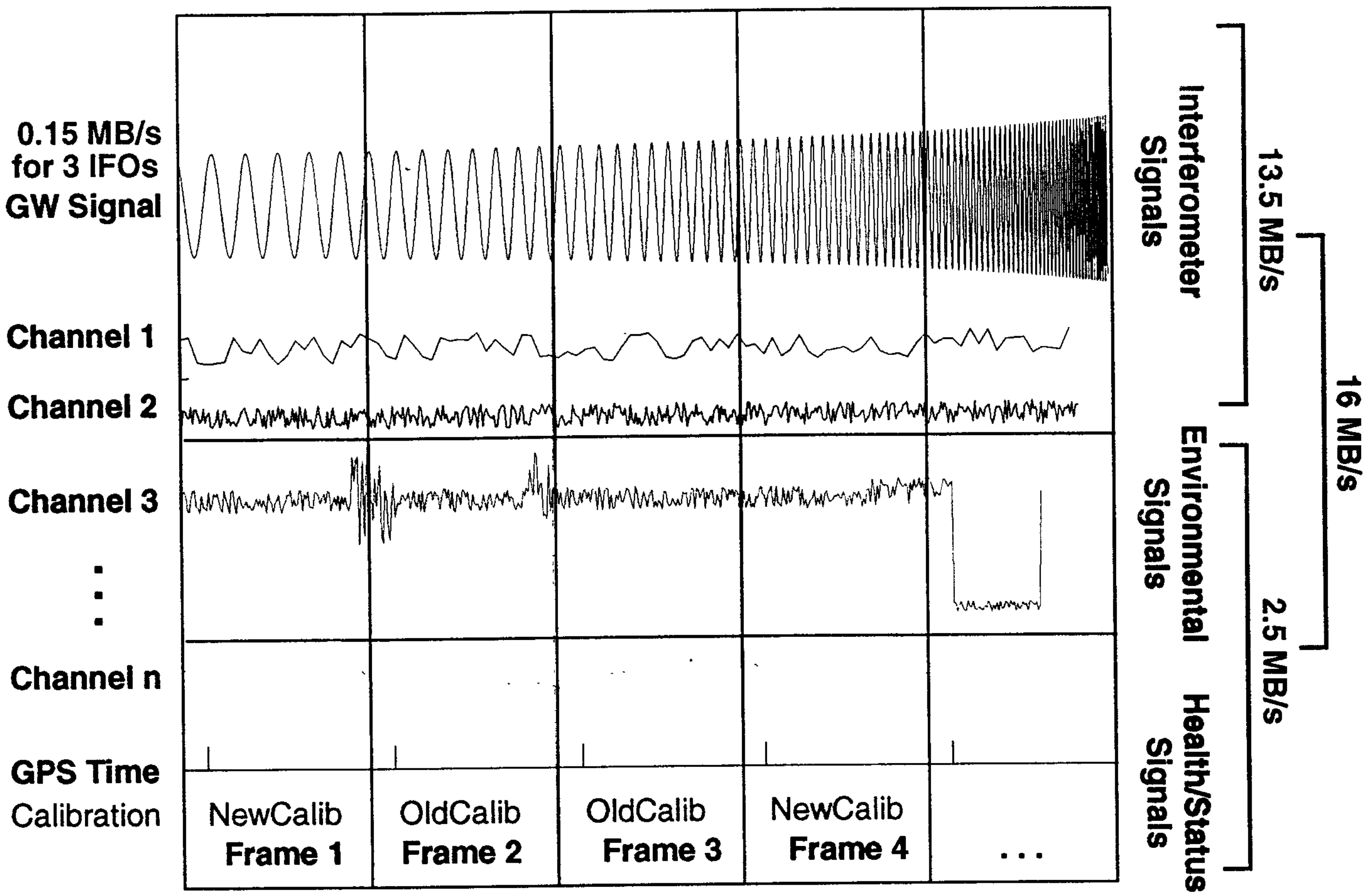


Detection Strategy

Coincidences

- Two Sites - Three Interferometers
  - » Single Interferometer ~50/hr
    - – non-gaussian level
  - » Hanford (Doubles) ~1/day
    - – correlated rate (x1000)
  - » Hanford + Livingston <0.1/yr
    - – uncorrelated (x5000)
- Signal Extraction
  - » signal from noise (vetoes, noise analysis)
  - » templates, wavelets, etc
- Data Recording (time series)
  - » graviational wave signal (0.2 MB/sec)
  - » total data (16 MB/s)
  - » on-line filters, diagnostics, data compression
  - » off line data analysis, archive etc

LIGO Data Stream and Data Frame Design

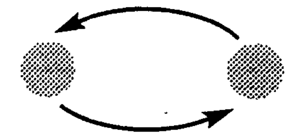


- Frame is (structured) self-contained snapshot of data for a period of time
  - GW channel & ancillary IFO channels
  - Environmental monitoring (veto) channels
  - Facilities/Vacuum health & status

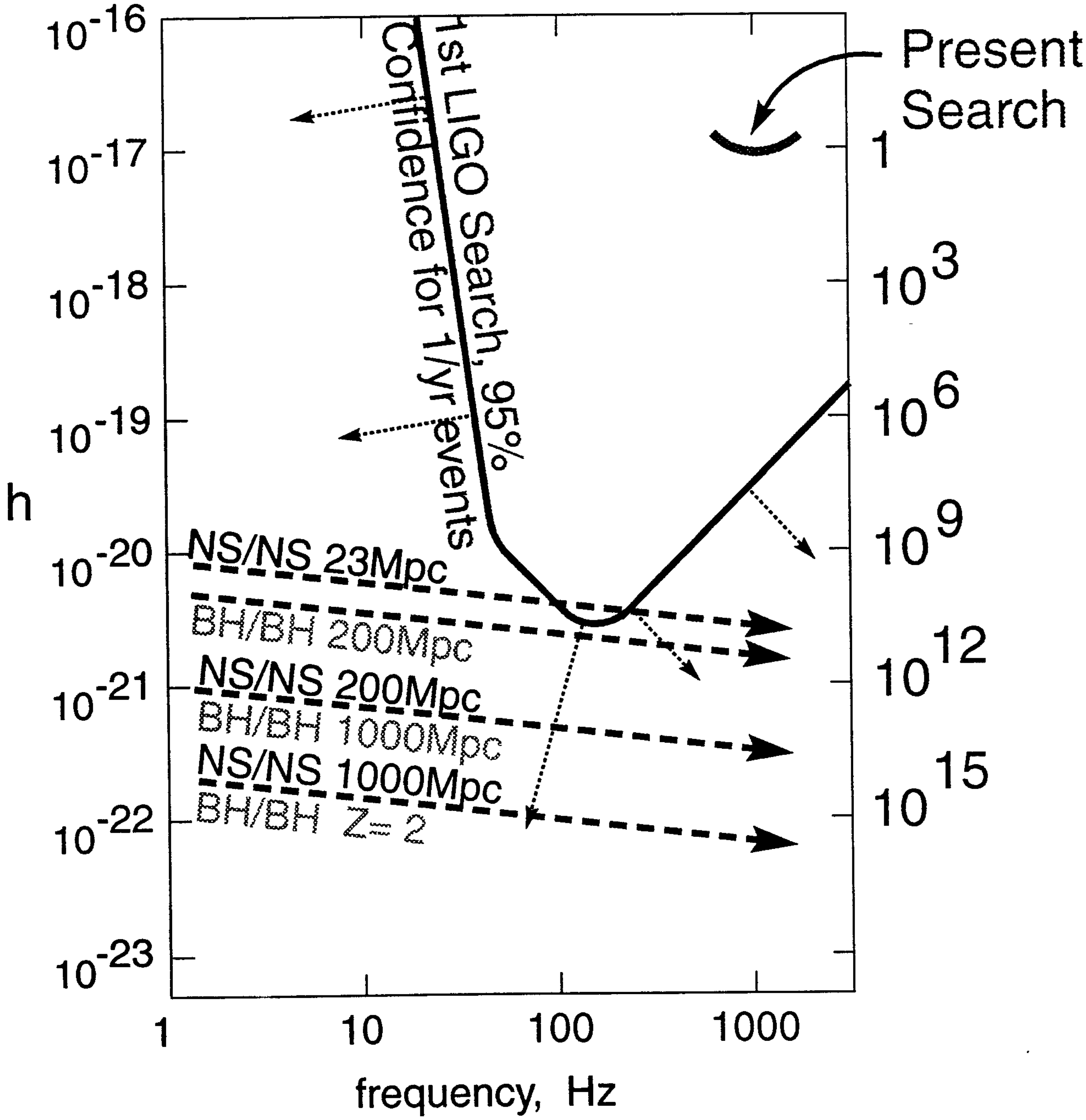
LIGO

- Construction Project
  - » Support NSF - Major Research (~$300M)
  - » Joint Caltech-MIT project
  - » Scheduled completion ~2000
- Scientific Collaboration
  - » Officially formation - August 1997
  - » Present collaboration
    - – Caltech, MIT, Hanford, Livingston, Stanford, Oregon, JILA, Michigan, Penn State, LSU, Florida (about 100 collaborators)
- Run Plan
  - » 2000-2001 commissioning
  - » 2002-2004 data run @ $h = 10^{-21}$
  - » 2004 + improvements and data running
- Detection of Gravitational Waves in 10 years or less

NEUTRON STAR BINARIES



["Near-Guaranteed" source]



- *15 minutes &10,000 orbits in LIGO band*
- *Rich information in waveforms: masses, spins, distance, direction, nuclear equation of state*

Gravitational Wave Experiments

- Physics -Gravitational Field
  - » fundamental properties; spin 2; velocity = c; etc.
  - » tests of general relativity; strong field limit
- Astrophysics
  - » new probe of astrophysical sources (e.g.. binary systems, supernovae, neutron stars)
  - » cosmology: (stochastic background sources)
- Support
  - » LIGO - NSF Gravity (U.S. Project)
  - » VIRGO - INFN/CRN (Italian-French Project)
- Conferences
  - » U.S. - grew out of general relativity community
  - » Europe - non-accelerator physics
    - – 'Beyond the Desert' (June 97) see program
    - – 'Amaldi Meeting' at CERN (July 97) Veneziano
- Physicists Involved
  - » HEP for electronics, computing, project mgt.
  - » lasers, controls, precision engineering, low noise systems, etc.

From: Heinrich Paes <beyond97@trick.mpi-hd.mpg.de>

-LAST CIRCULAR-

---BEYOND-the-DESERT---

Accelerator- and Non-Accelerator approaches

(Castle Ringberg, Tegernsee, Germany, June 8-14)

Non Accelerator **experiments**

15:10 F. Mauri **(Pavia): Present status and future perpectives in the proton decay searches**

15:35 H.V. **Klapdor-Kleingrothaus (MPI Heidelberg):** Double Beta Decay and **Beyond Standard Model Physics**

16:05 Y. Kamyshkov **(Oak Ridge): Search for** (B-L) **nonconservation** in **neutron-antineutron transitions**

16:35 COFFEE

17:00 B. **Barish (Caltech): Magnetic Monopole Searches**

17:30 B. **Schutz (Potsdam): Gravitational wave searches during the next two decades**

18:00 F. **Fidecaro (Pisa): Interferometers for Gravitational Wave** detection: **Virgo**

18:20 C. **Weinheimer (Mainz): Status of the Mainz Tritium Experiment**

18:40 DINNER

20:00 K. **Jungmann (Heidelberg): Searching New Physics in the Muonium Atom**

20:20 A. **Bettini (Padova): The Future of the Gran Sasso Underground Laboratory**