LIGO

Status and Plans

Barry C. Barish

Caltech

OMNI-I Workshop

Sao Jose dos Campos, Brazil

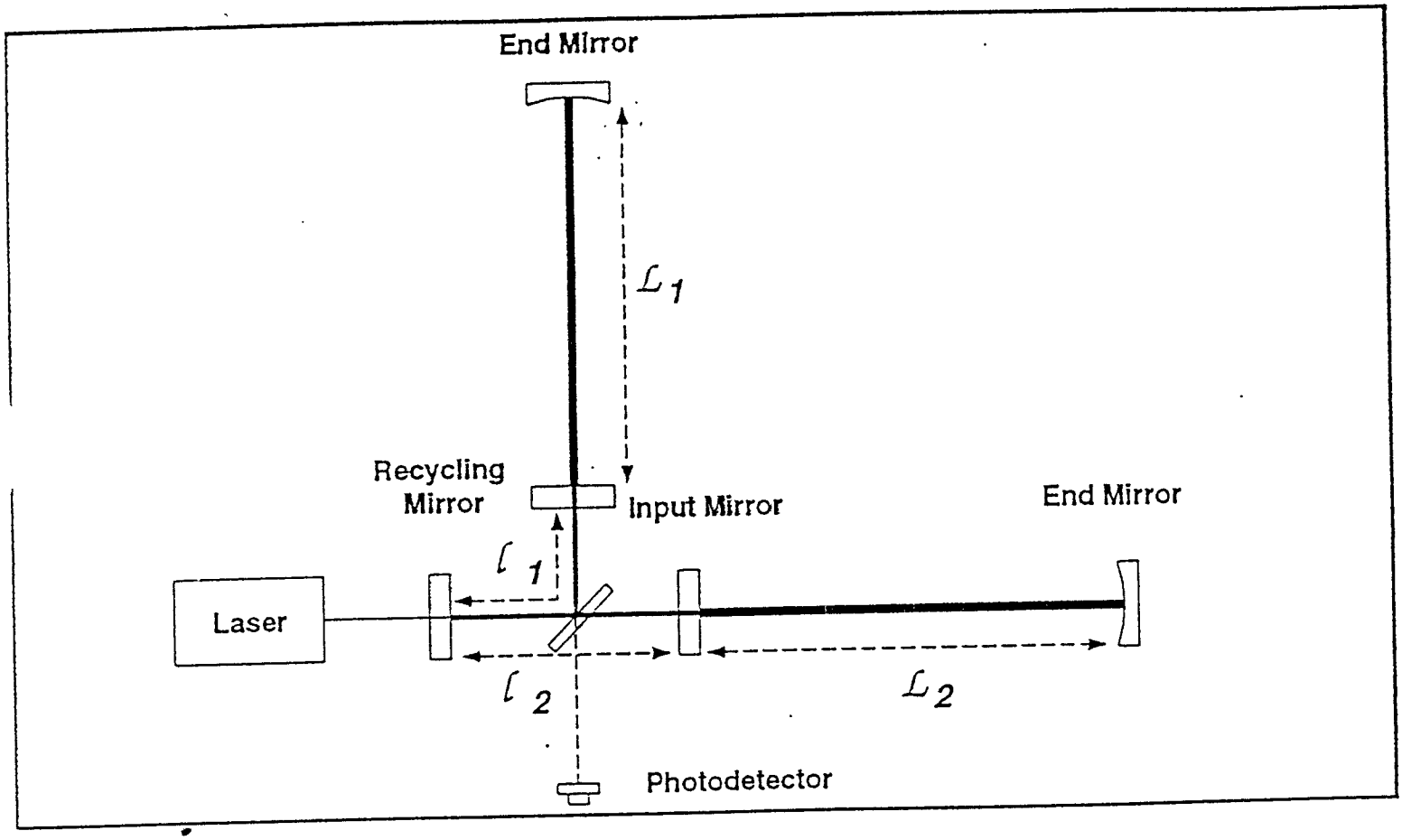
27-30 May 1996

LIGO-G960205-00-M

LIGO

Basic Configuration

- Michelson with Fabry-Perot cavities

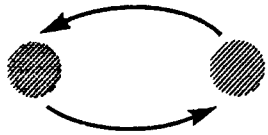


Initial Interferometer

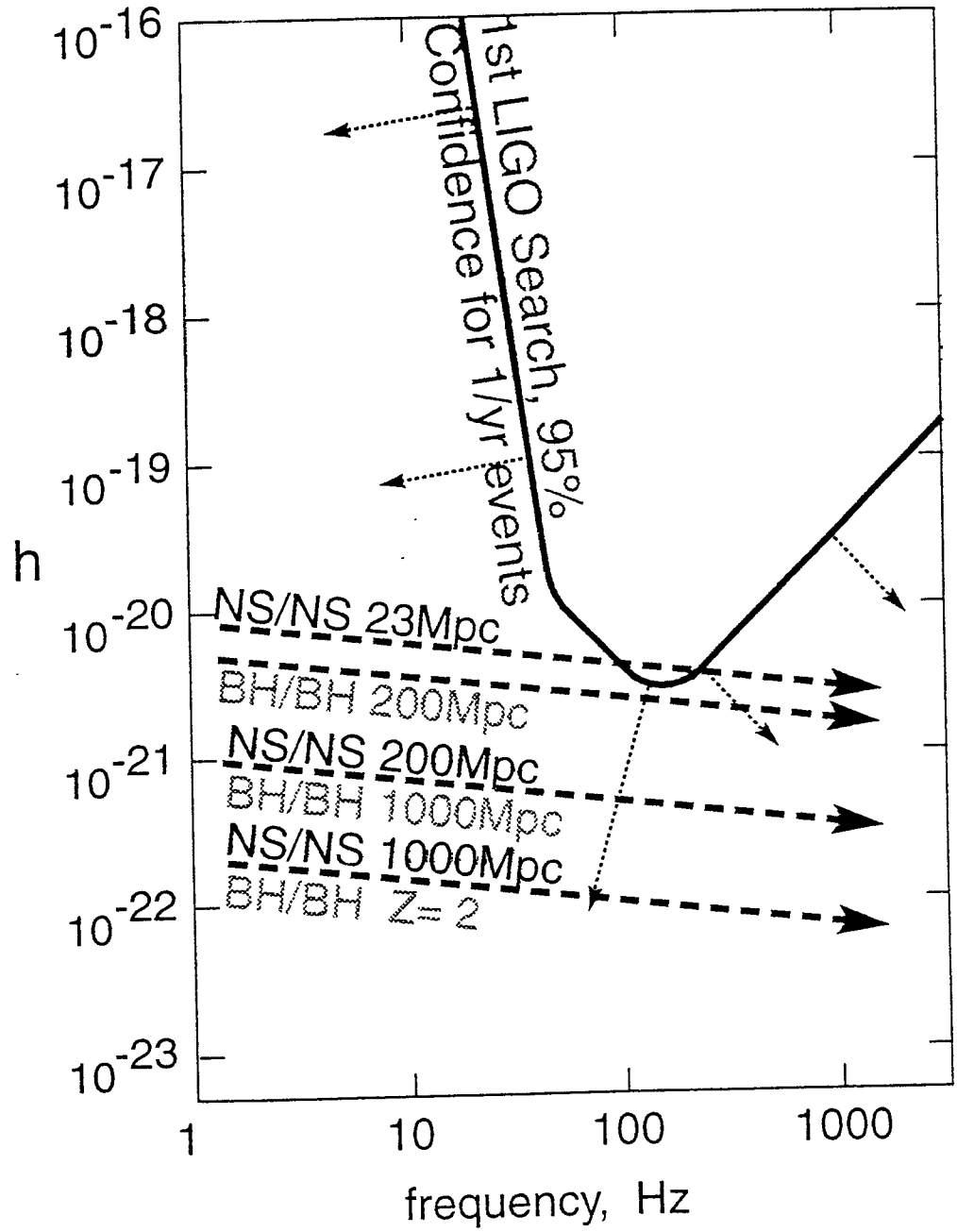
Specifications

Strain Sensitivity [rms, 100 Hz band]	10^{-21}
Displacement Sensitivity [rms, 100 Hz band]	4×10^{-18} *m*
Fabry-Perot Arm Length	4000 *m*
Vacuum Level	$< 10^{-6}$ *torr*
Laser Wavelength	1064 *nm*
Optical Power at Laser Output	10 *W*
Optical Power at Interferometer Input	5 *W*
Power Recycling Factor	30
Input Mirror Properties	Reflectivity = 0.97
End Mirror Properties	Reflectivity > 0.9998
Arm Cavity Optical Loss	≤ 3%
Light Storage Time in Arms	1 *ms*
Test Masses	Fused Silica, 11 *kg*
Mirror Diameter	25 *cm*
Test Mass Period Pendulum	1 *sec*
Seismic Isolation System	Passive, 4 stage
Seismic Isolation System Horizontal Attenuation	$\geq 10^{-7}$ (100 *Hz*)
Maximum Background Pulse Rate	1 *per minute*

NEUTRON STAR BINARIES



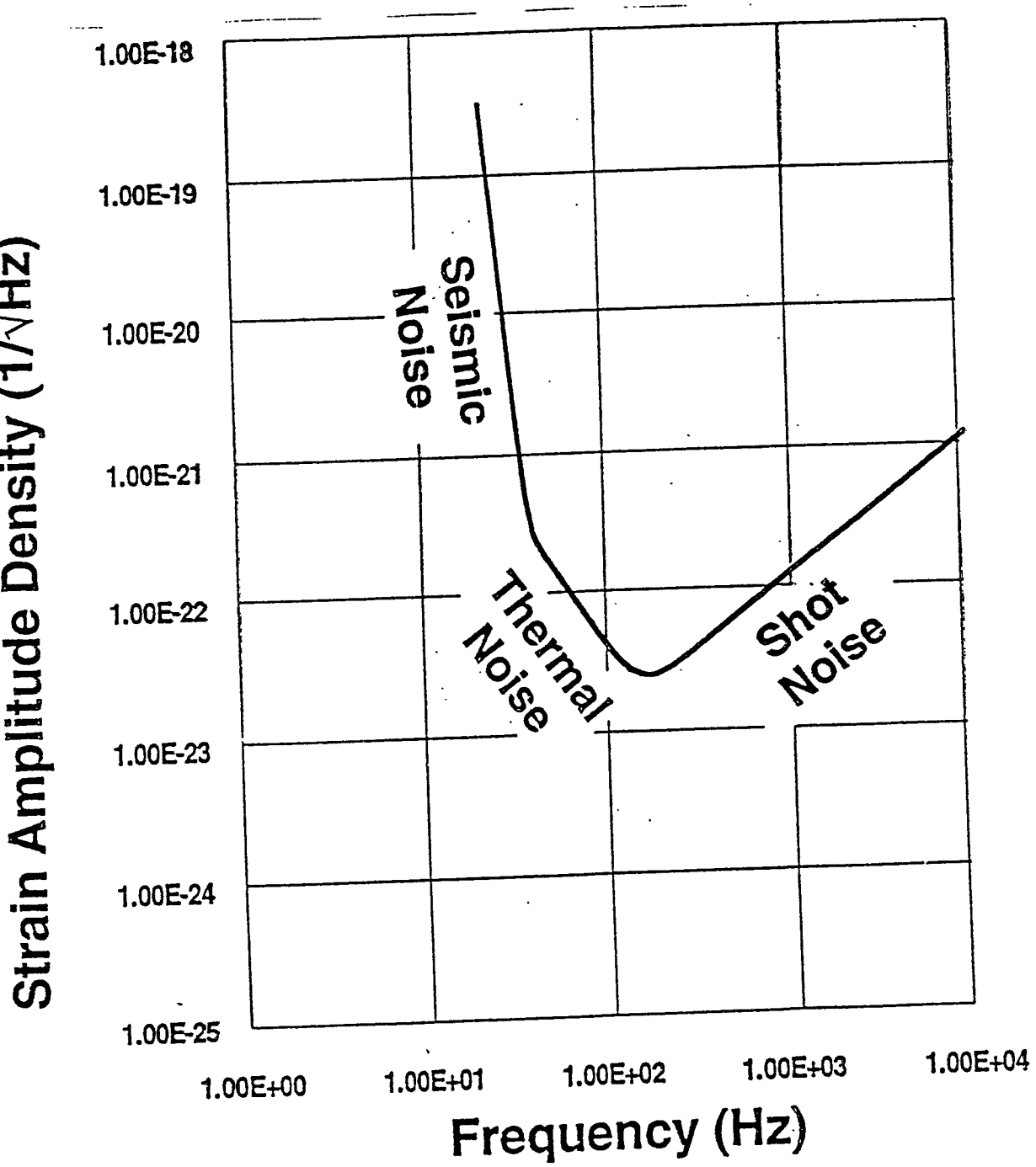
["Near-Guaranteed" source]



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

Initial Interferometers

Noise Floor



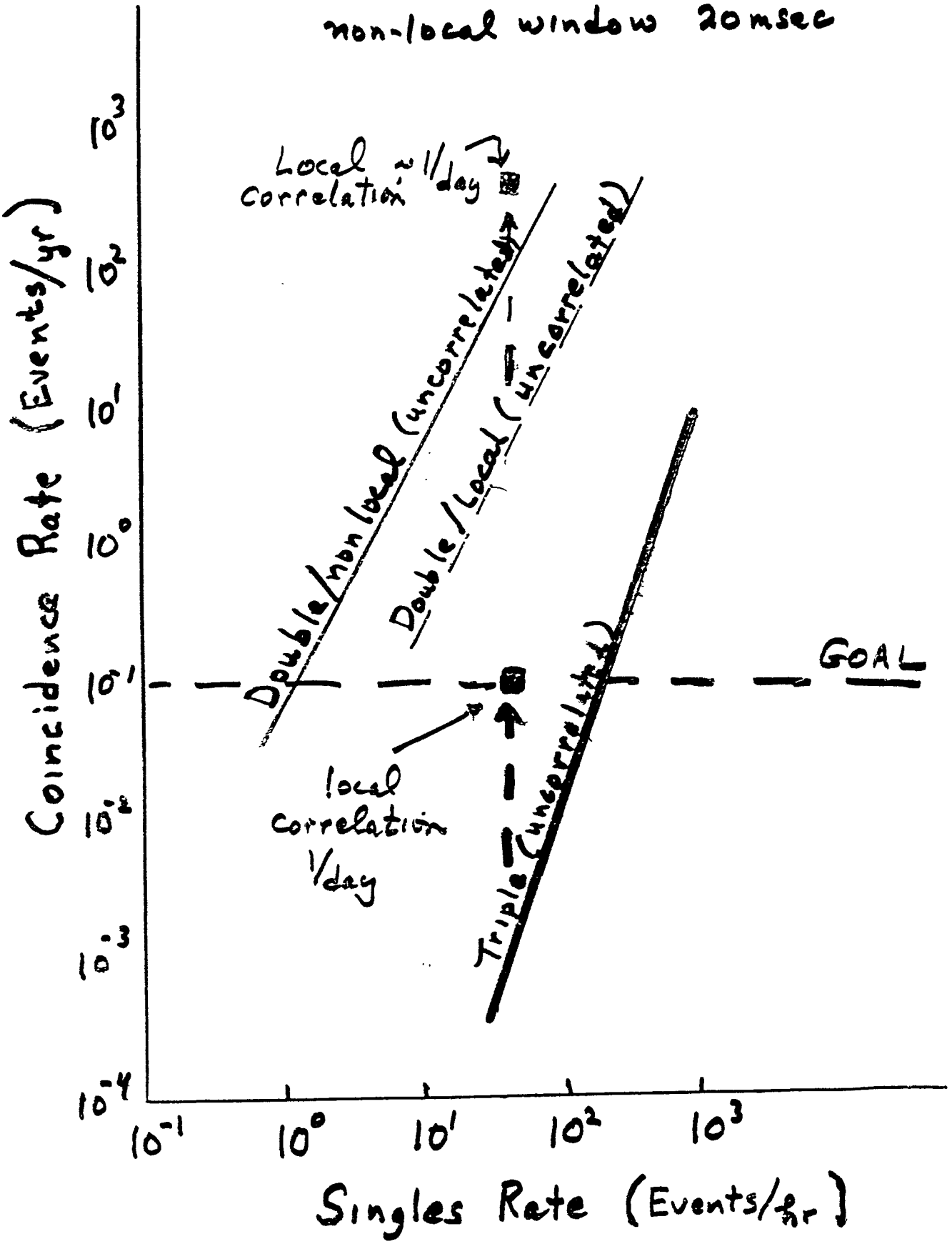
LIGO

Gravitational Wave Detection Strategy

- Interferometer Sensitivity
  - ⇒ R&D Program
    - Technology Development
    - Demonstration Experiments
  - ⇒ Engineering Implementation
    - Precision Engineering Design
    - Quality Control
- 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)

MULTIPLE COINCIDENCES

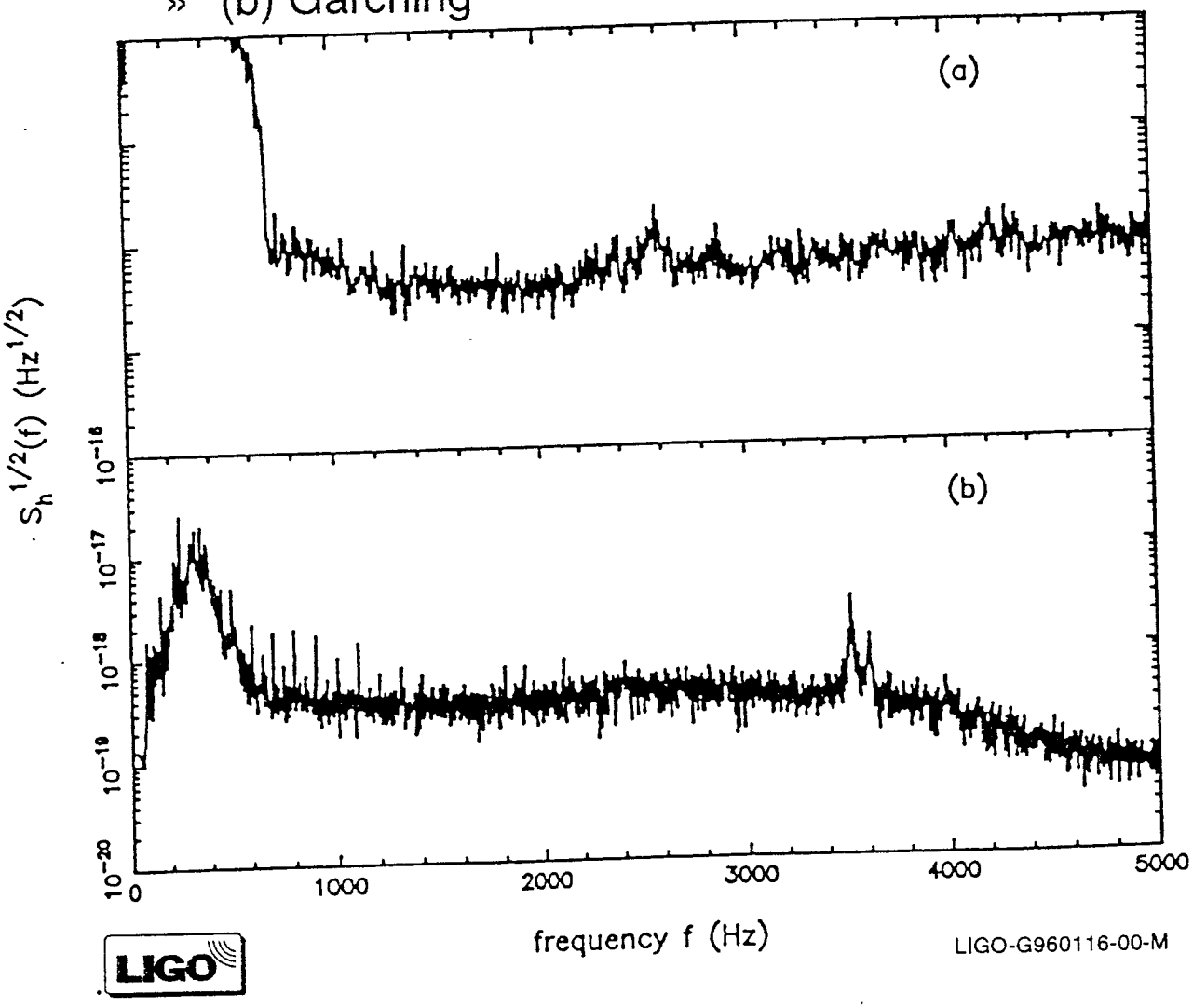
local window 1msec
non-local window 20msec



Interferometers

Coincidence Experiment

- Interferometers
  - » Glasgow (Fabry-Perot interferometer)
  - » Garching (Michelson delay-line interferometer)
- Strain Sensitivities (~10^{-17} rms noise)
  - » (a) Glasgow
  - » (b) Garching

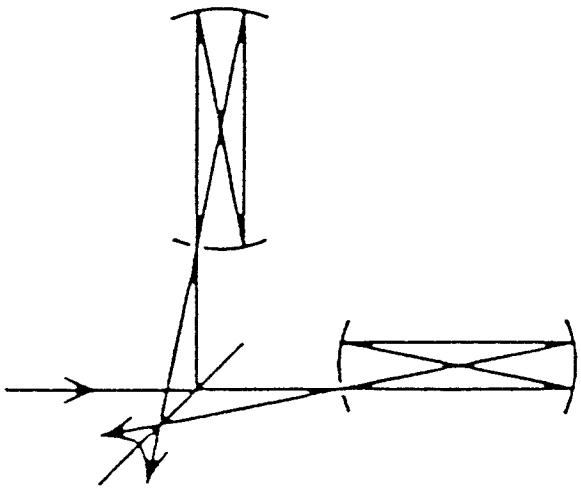


LIGO

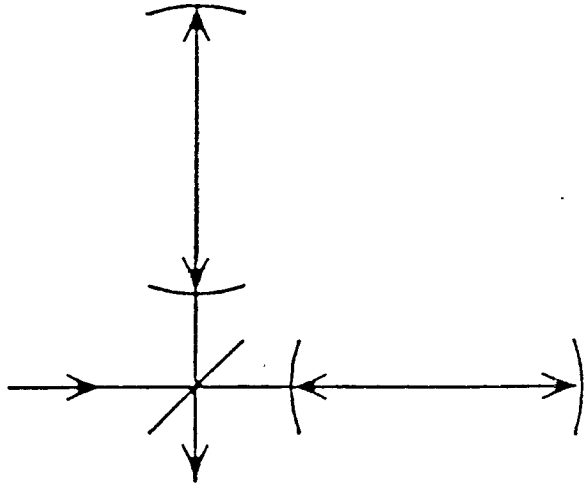
Interferometer

types

- Folded interferometers
  - » Delay-Line (N=4)
  - » Fabry-Perot



Delay-Line (*N*=4)

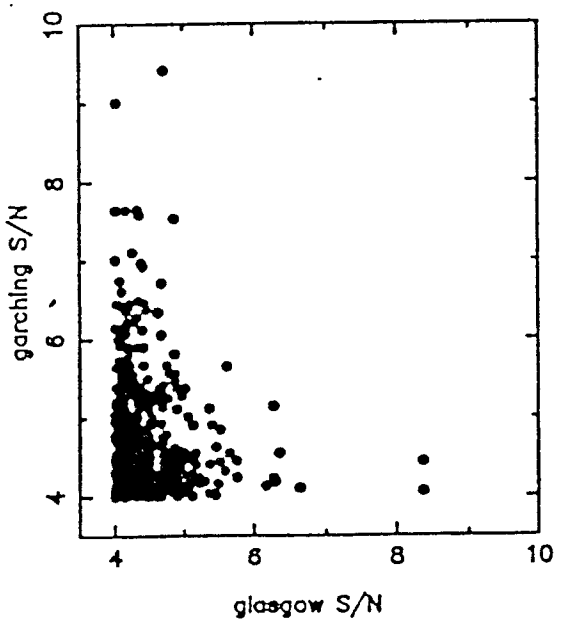


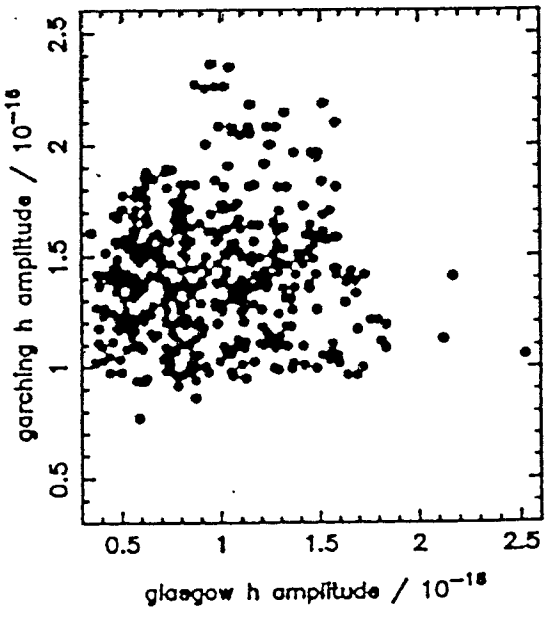
Fabry-Perot

Interferometers

Coincidence Experiment

- Glasgow - Garching
- 100 hour coincidence experiment
  - » Analysis
    - level 1 - housekeeping vetoes
    - level 2 - 62 hrs good data (<4 10-17 for 1.6 sec)
    - level 3 - require same strain in both detectors
  - » Result
    - $h < 1.6\ 10^{-16}$ from zenith and optimumpolarization
    - $h < 3.6\ 10^{-16}$ any direction and any polarization

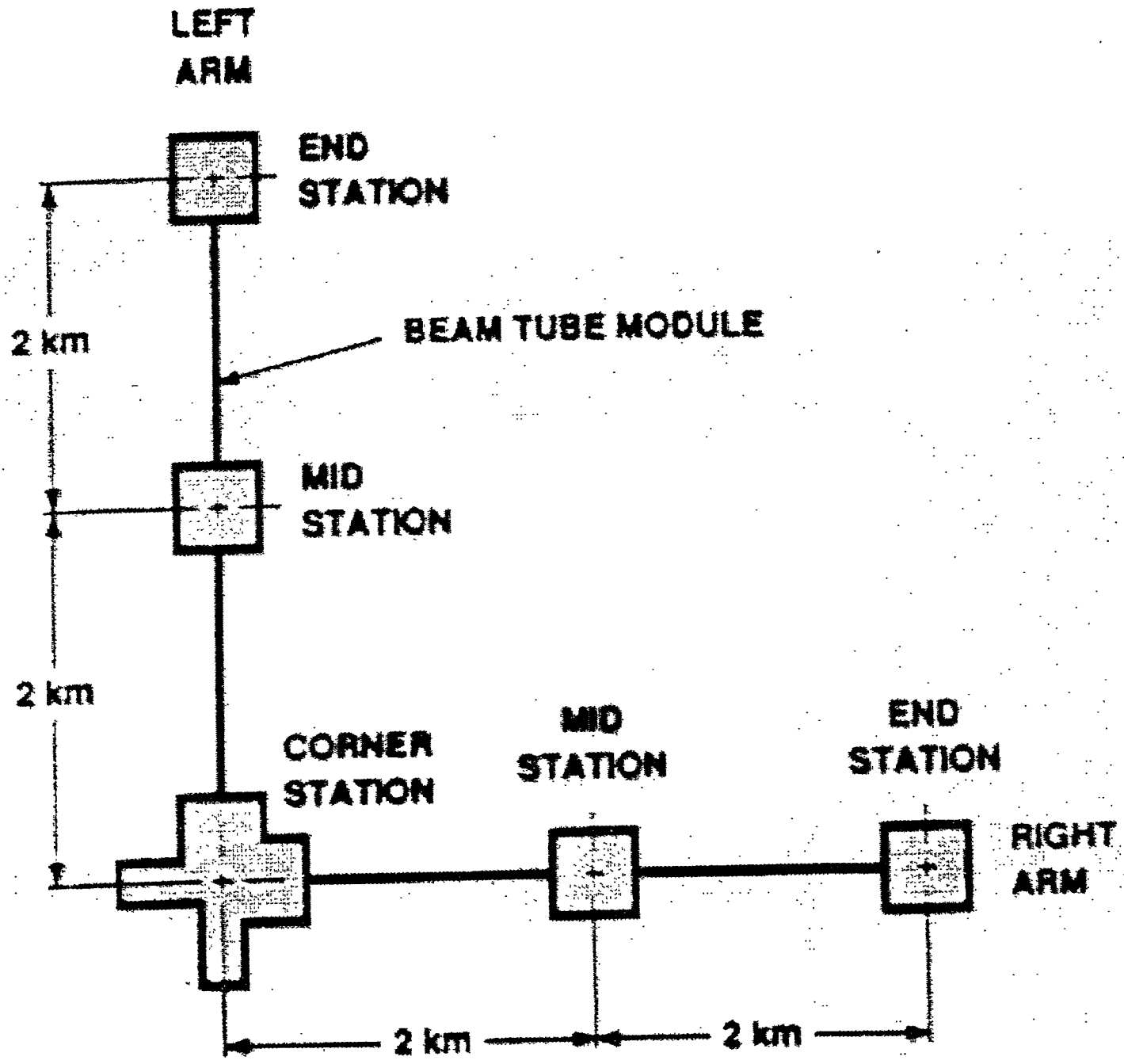




LIGO

LIGO Project
Technical

- Major Facilities
  - » Beam Tube
  - » Vacuum Systems
  - » Civil Construction
- Detector
  - » Detection Strategy
  - » Interferometers
- R&D
  - » Noise Sources and Sensitivity
  - » Demonstration Experiments
- Status and Plans


LEFT
ARM
END
STATION
2 km
BEAM TUBE MODULE
MID
STATION
2 km
CORNER
STATION
MID
STATION
END
STATION
RIGHT
ARM
2 km
2 km

Gravitational Wave Strength

Strain Sensitivity

$$h \approx \frac{G(E_{kin}^{ns}/c^2)}{r}\frac{1}{c^2}$$

for $E_{kin}^{ns}/c^2 \sim M_\Theta$

$h \sim 10^{-20}$ for Virgo Cluster of Galaxies

$h \sim 10^{-23}$ at Hubble Distance

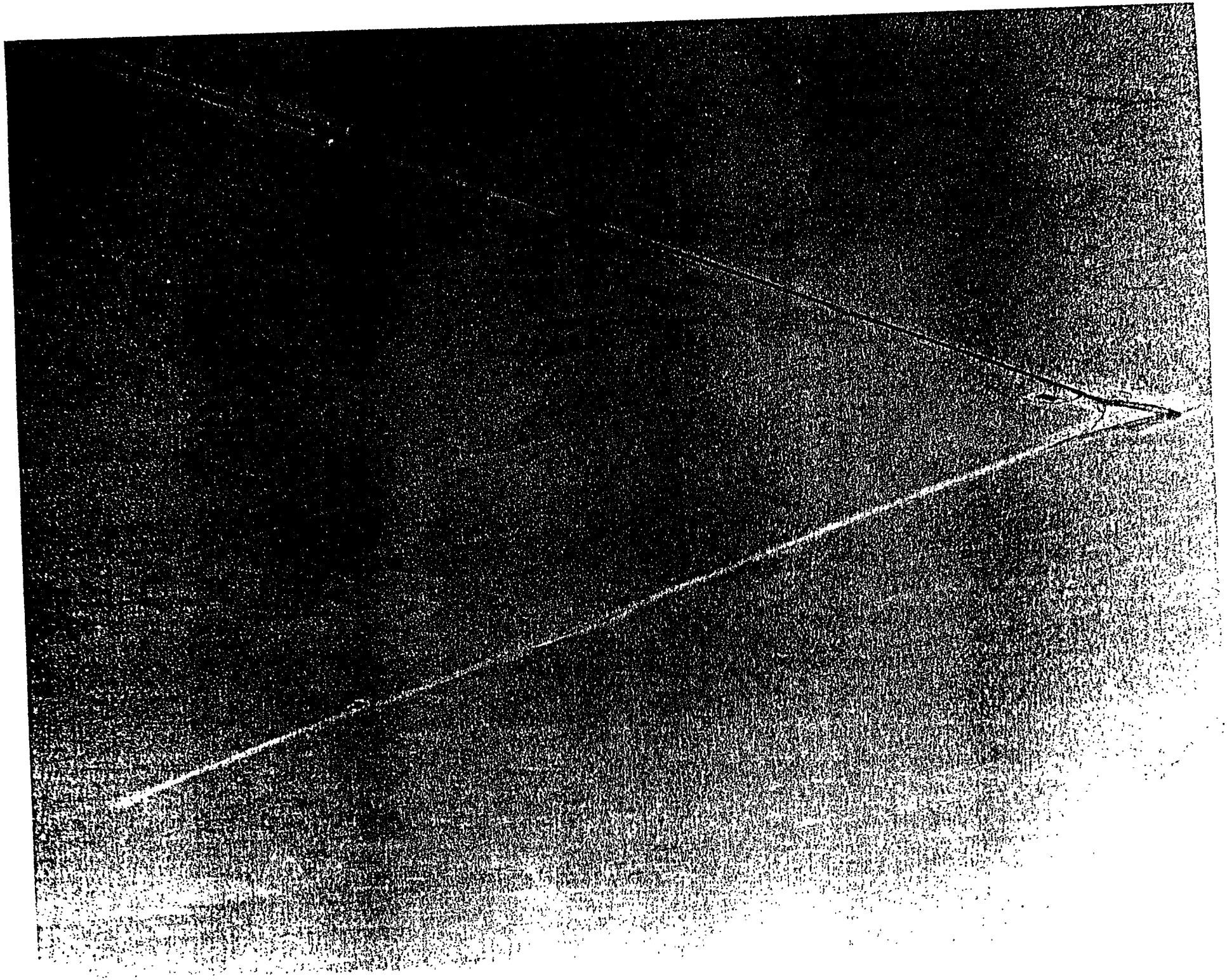
LIGO Goal: $h \sim 10^{-22}$

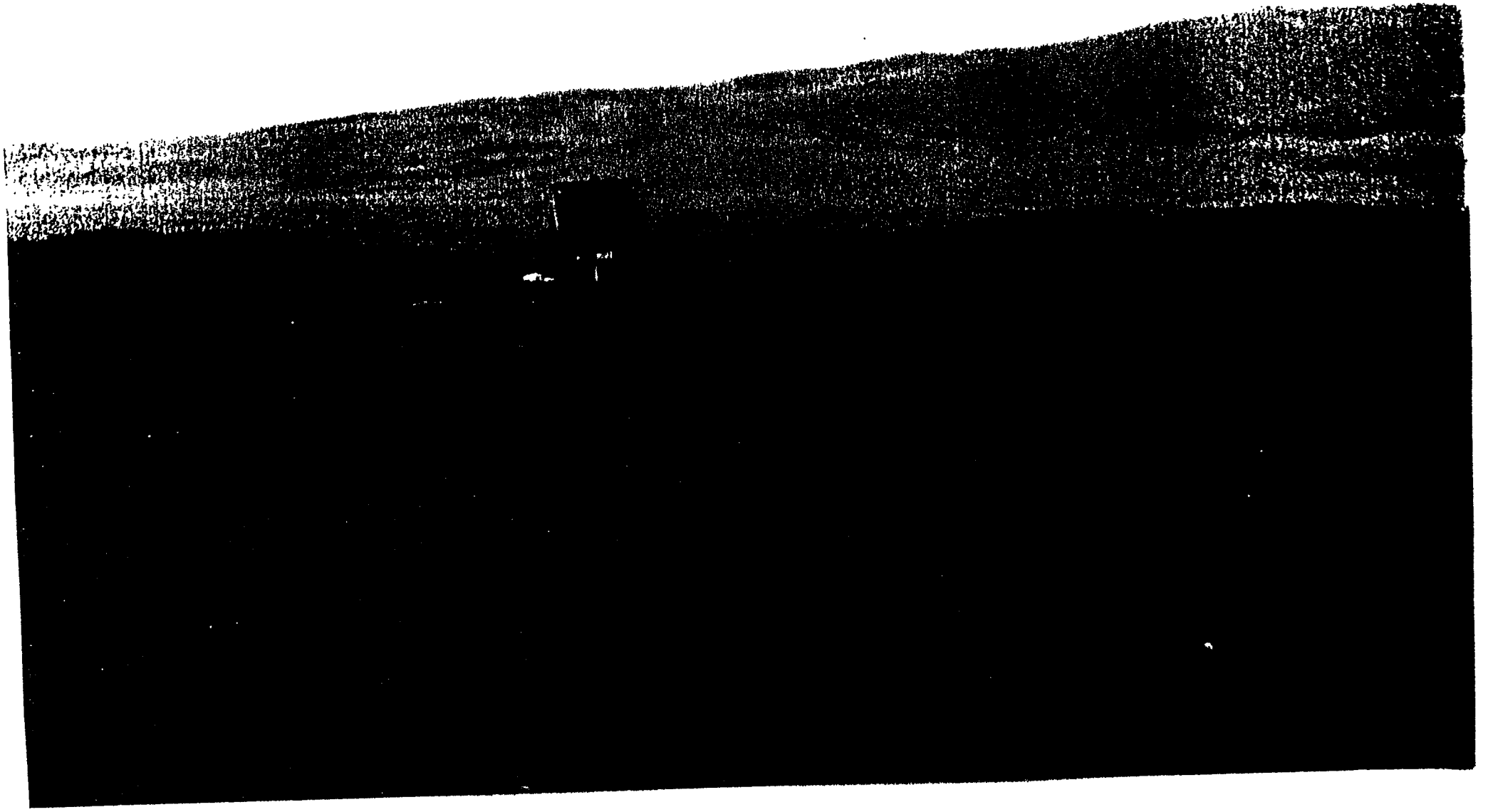
Detector $\Delta L = hL$

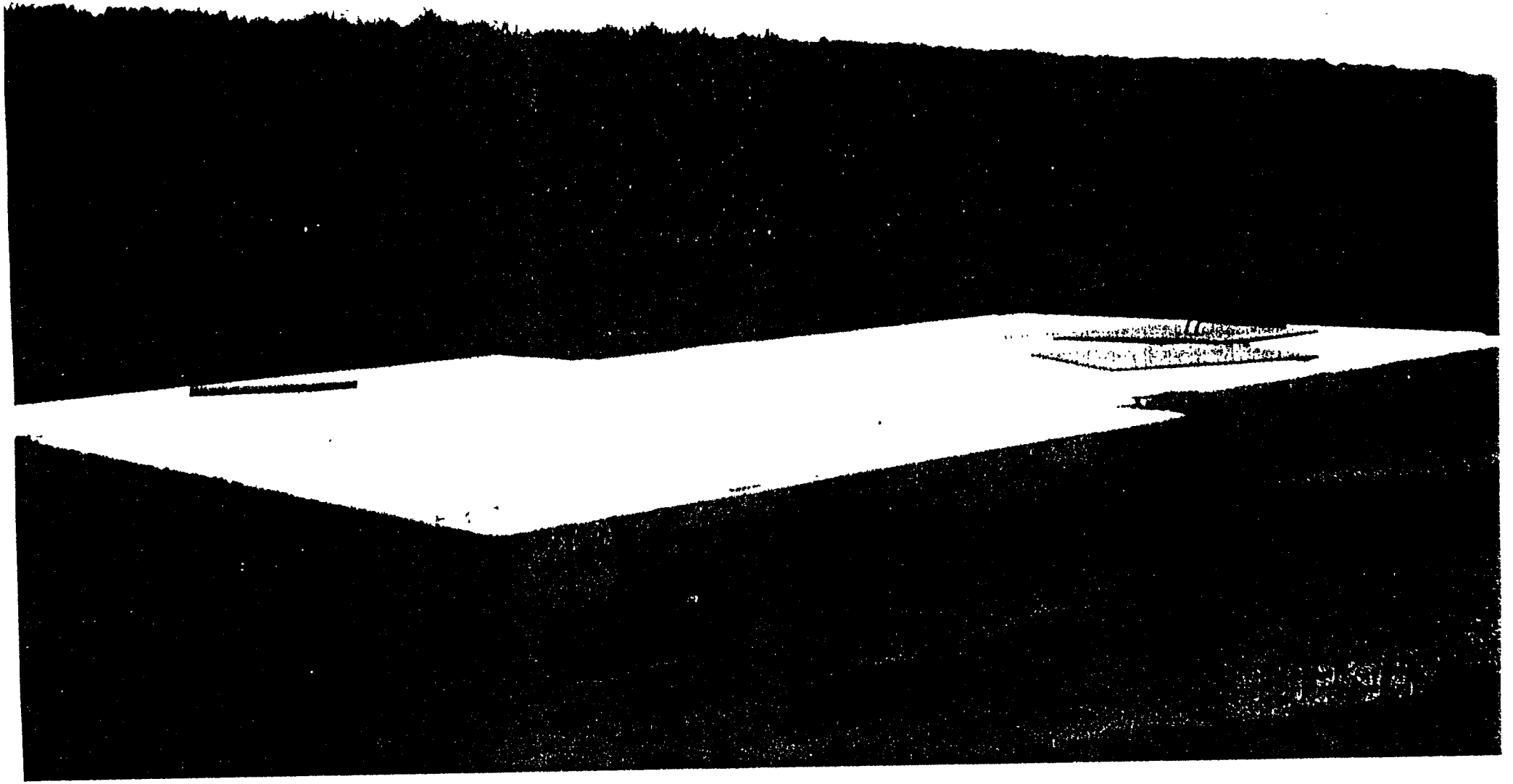
$L = 4km \Rightarrow \Delta L = 10^{-16} cm$

This leads to Stringent Specifications:

- Vacuum
- Seismic and Acoustic Isolation
- Test Mass Suspensions
- Optics
- etc.



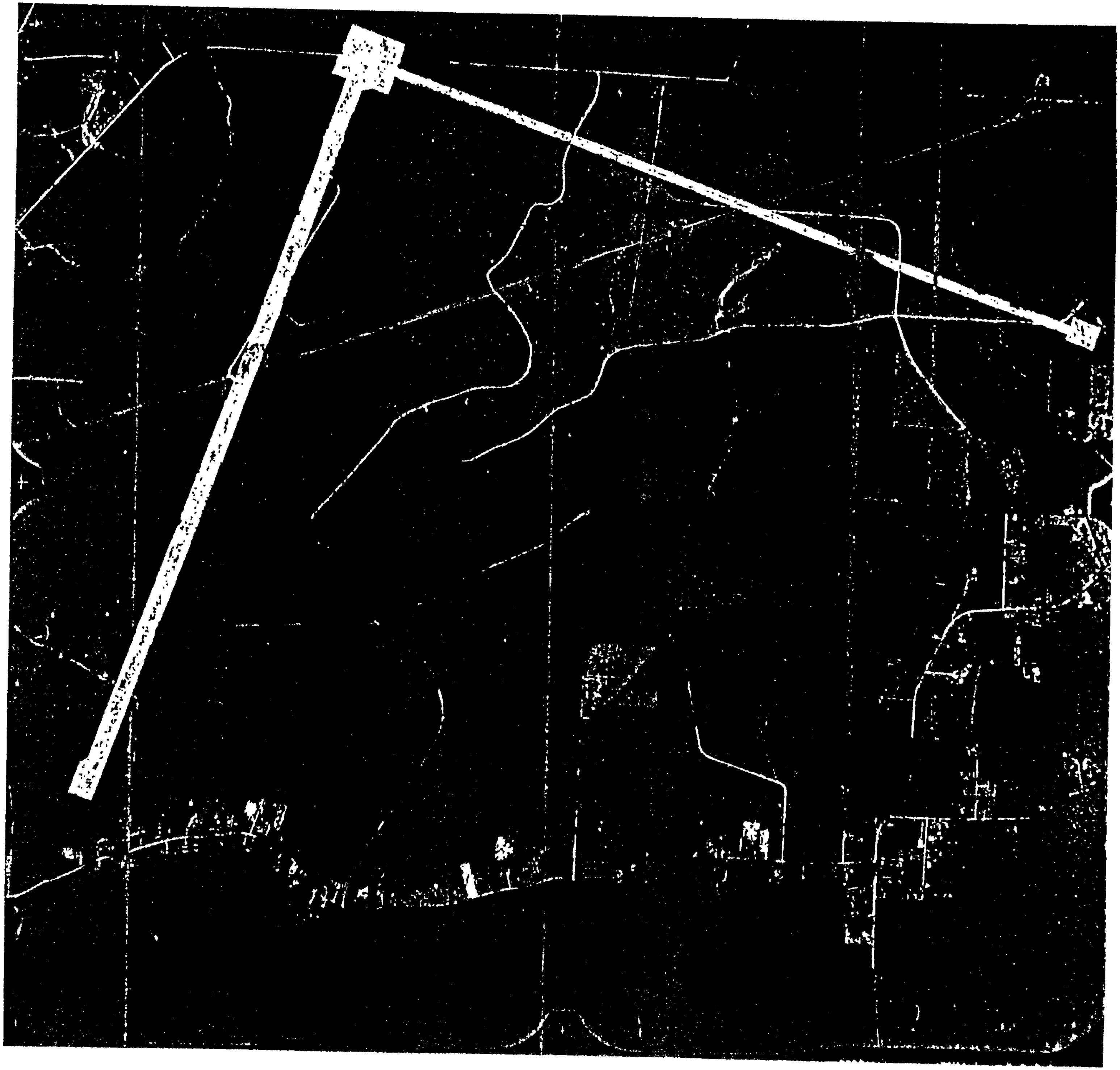




LIGO

LIVINGSTON PARISH

LOUISIANA

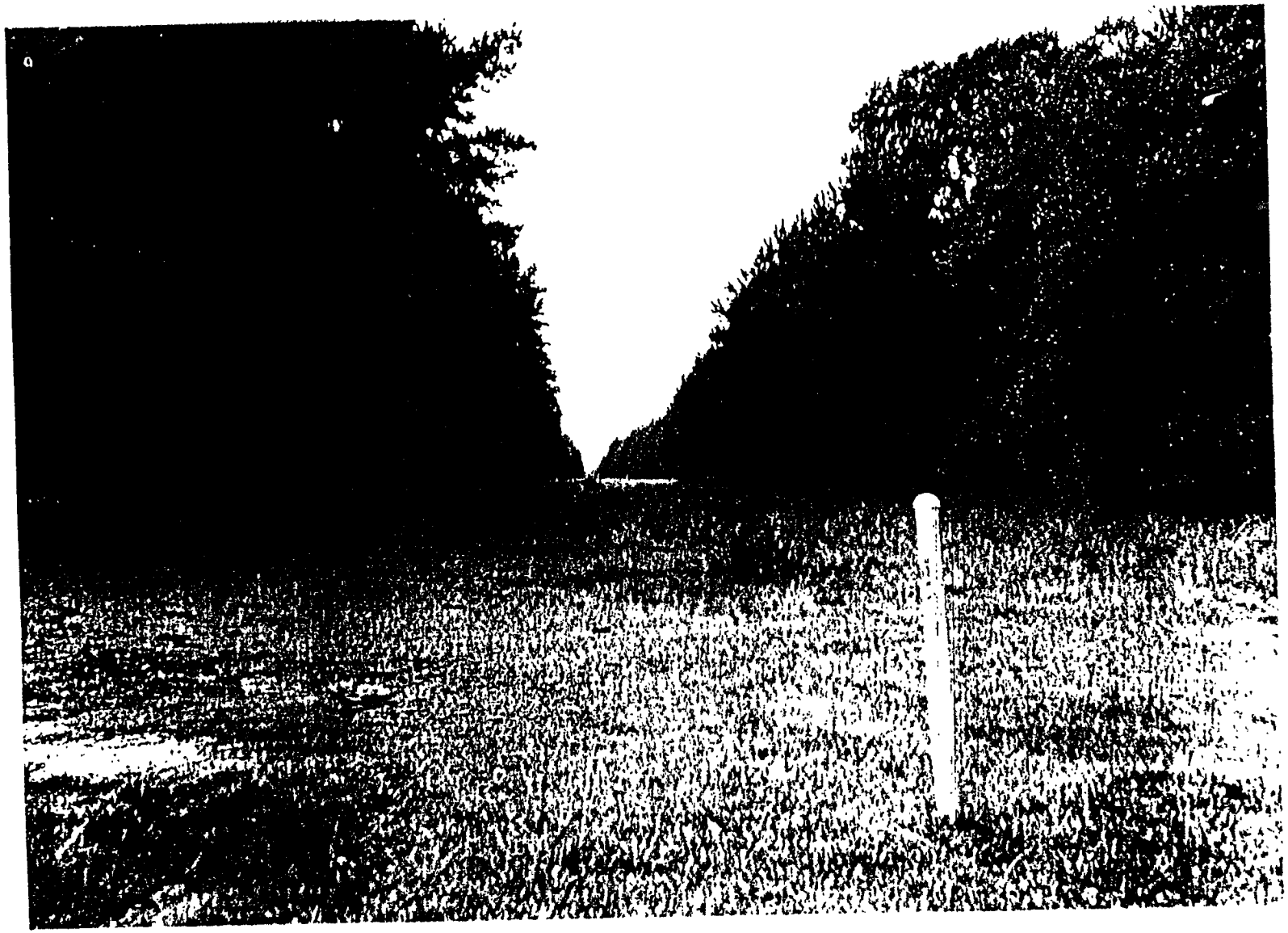


AERIAL PHOTO BY:

GULF COAST AERIAL MAPPING

FLOWN:AUGUST 25, 1995

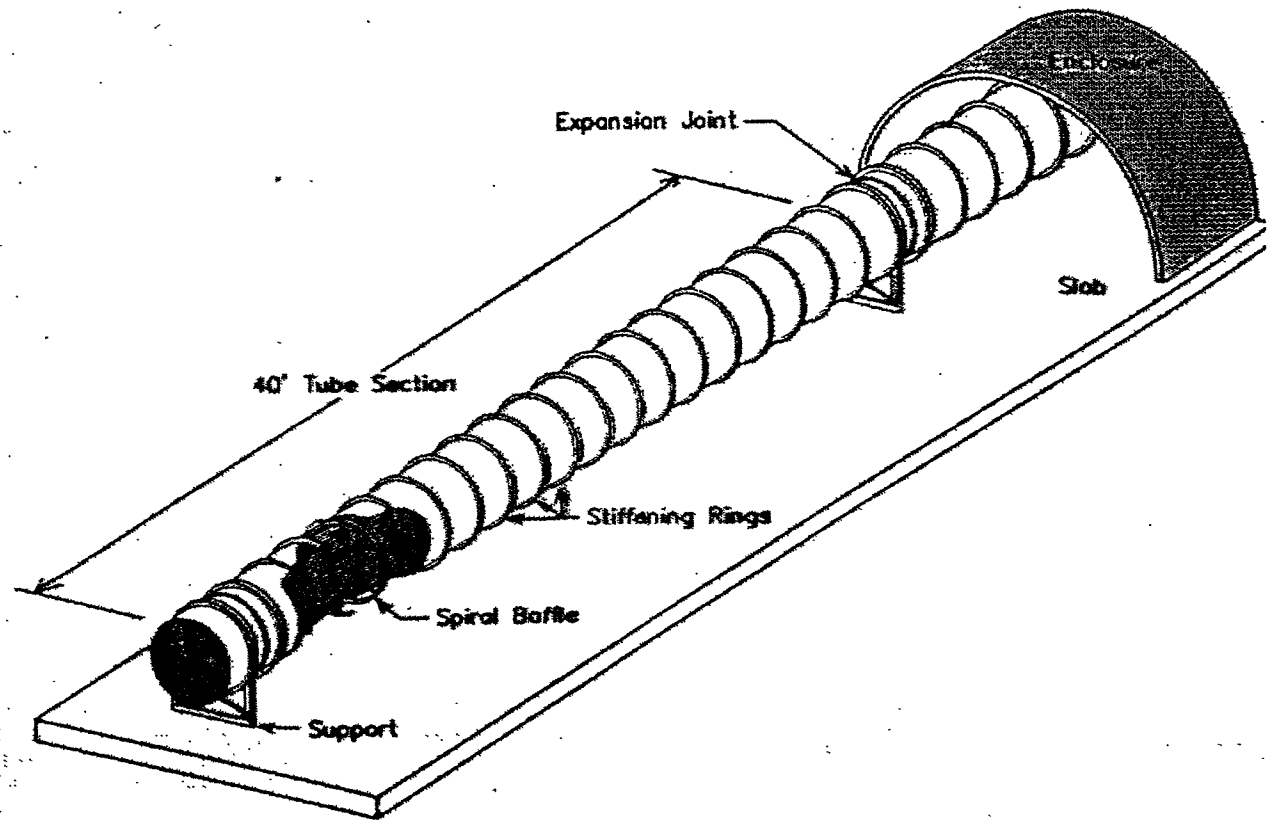
ALTITUDE: 12,000 FEET



G960025-02-O-V

G960028-17-O-V

Beam Tube


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

Beam Tube

- Characteristics
  - ⇒ Arm Lengths - 4km
  - ⇒ Tube Diameter - 4 ft
  - ⇒ Initial Detector
    - 10^{-6} torr Hydrogen; 10^{-7} torr Water
  - ⇒ Advanced Detectors
    - 10^{-9} torr Hydrogen; 10^{-10} torr Water
  - ⇒ Quality Control
    - (materials, welding, cleaning, etc)

- Status and Plans
  - ⇒ Design Contract was with CBI
    - Final Design Report Accepted (6/94)
  - ⇒ Qualification Test
    - 130 ft Section - success (4/95)
  - ⇒ Contract Options

LIGO Facilities

Beam Tube Enclosure

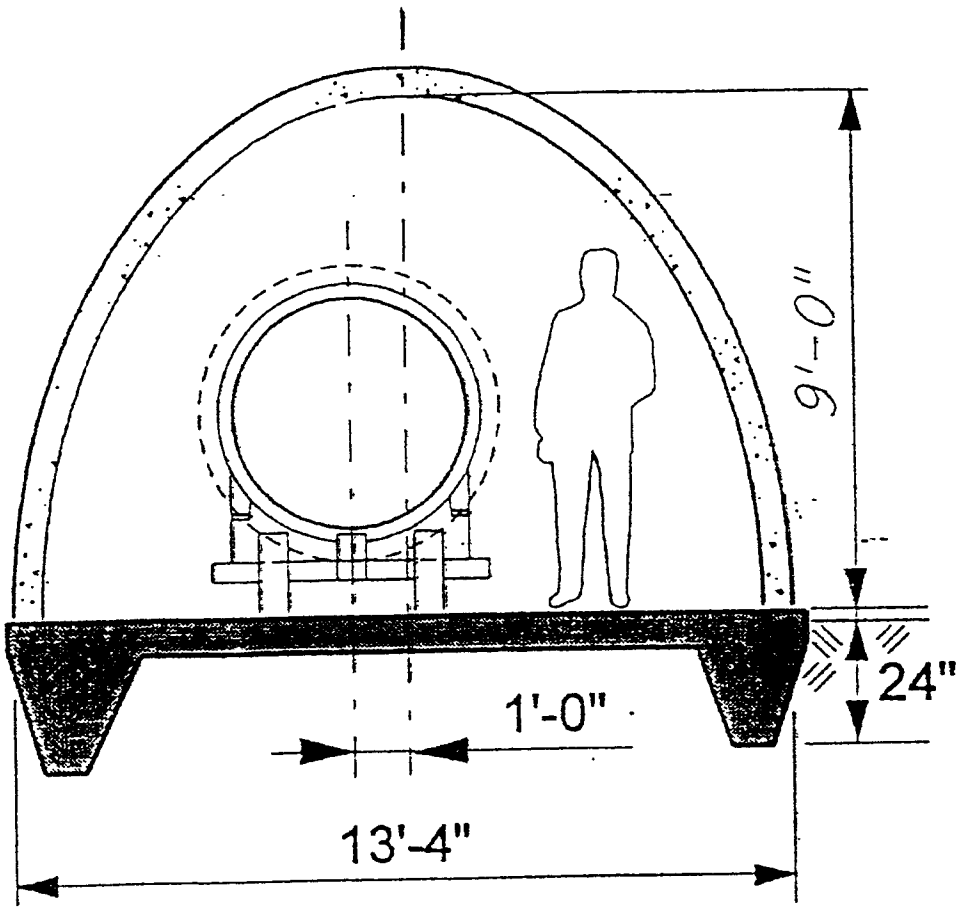
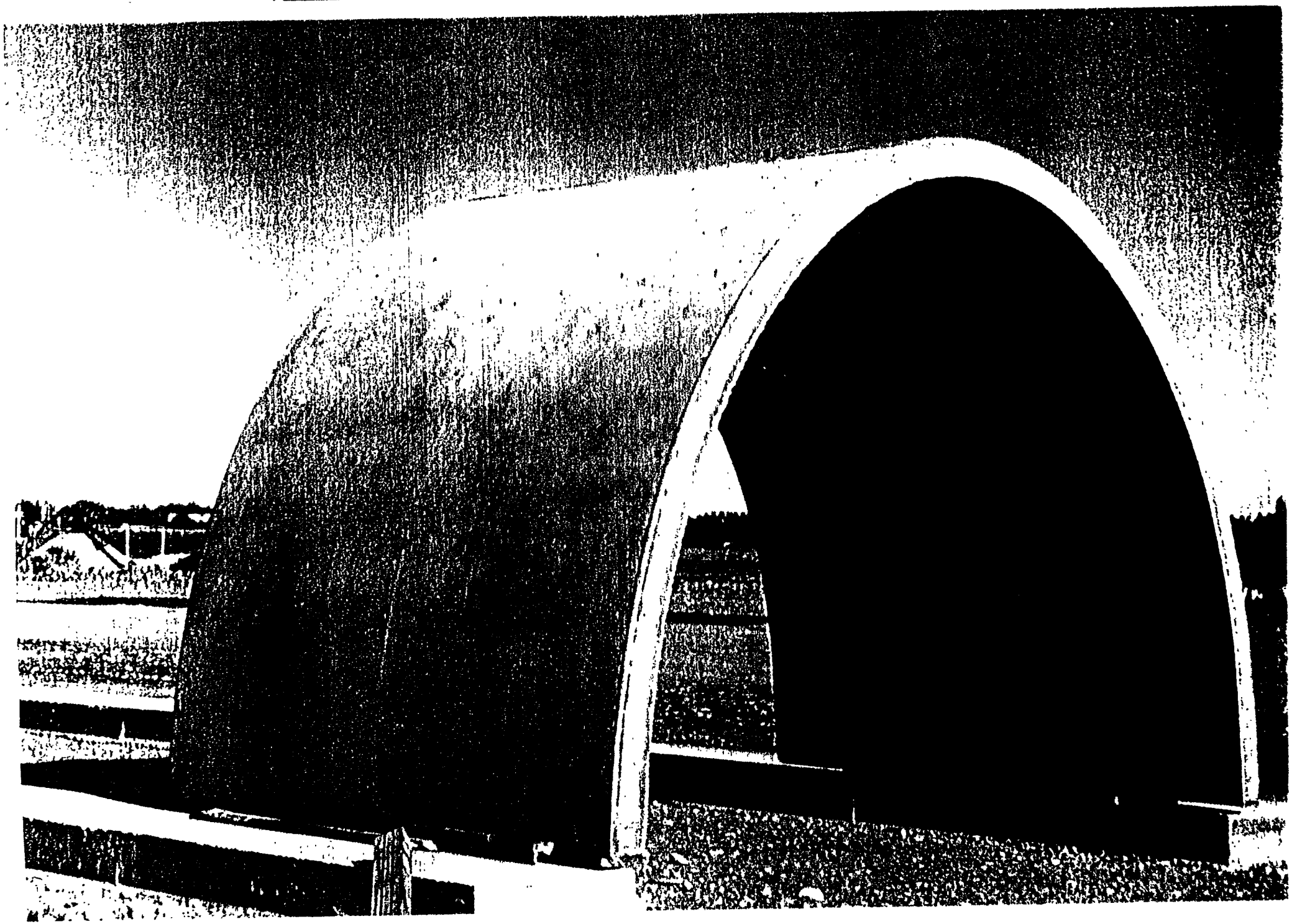
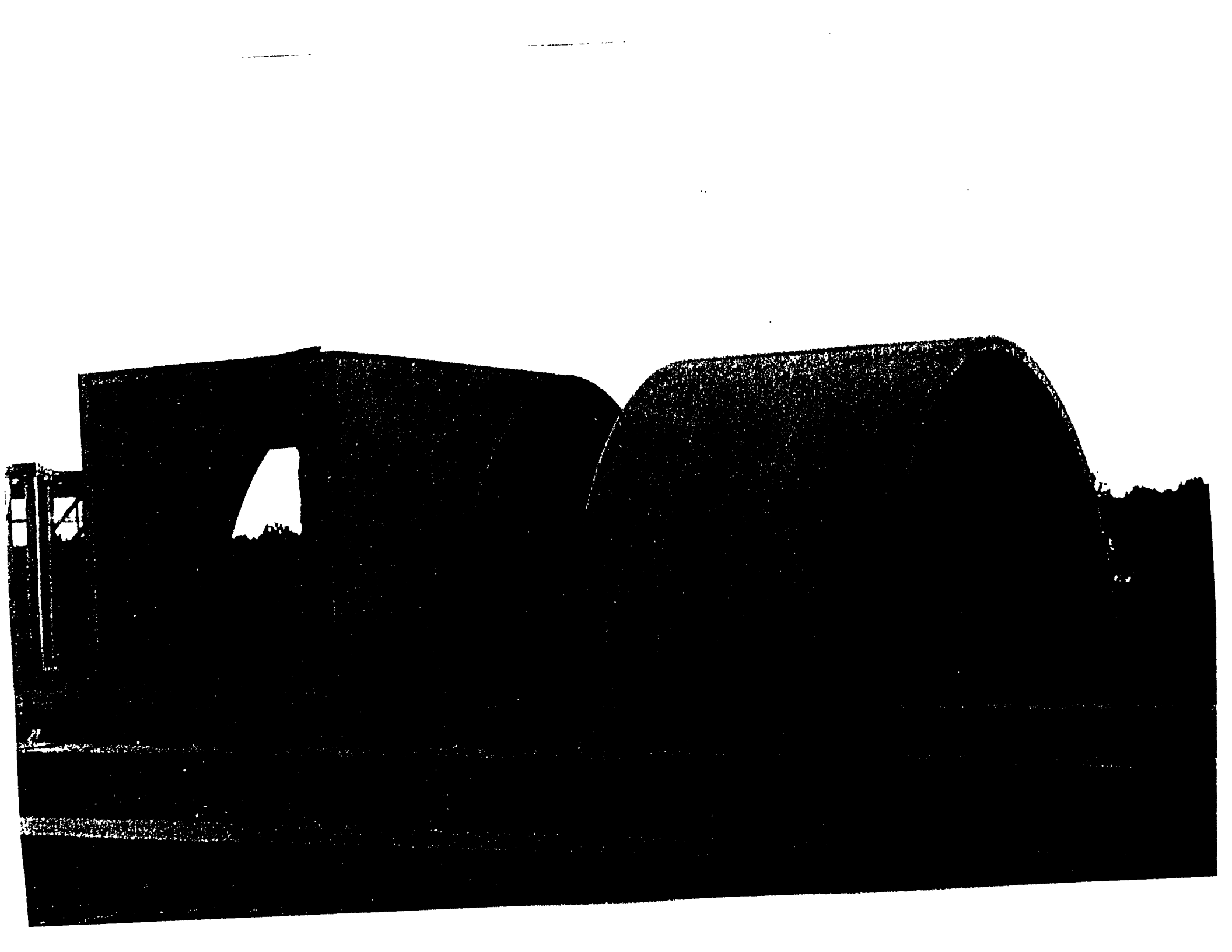
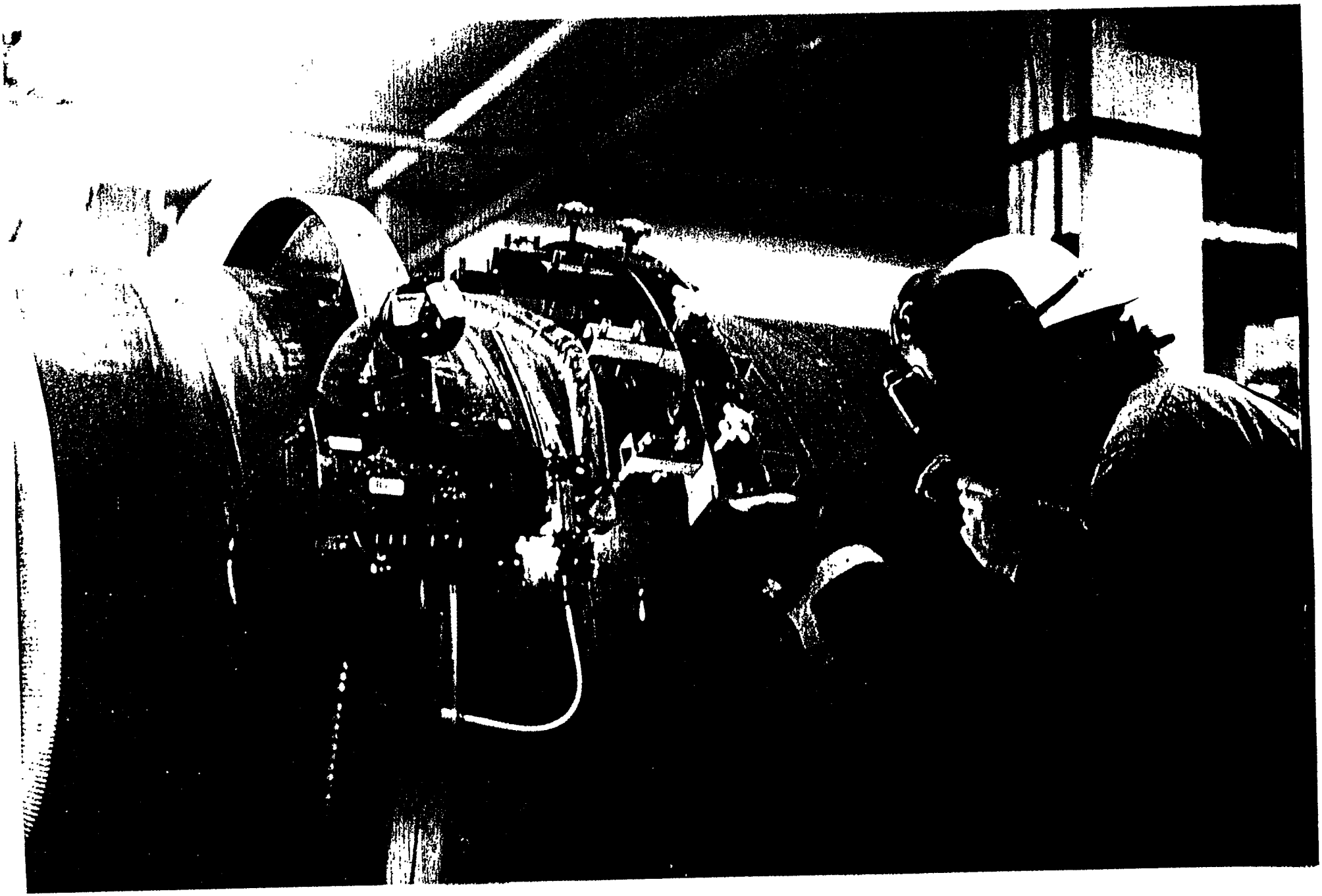


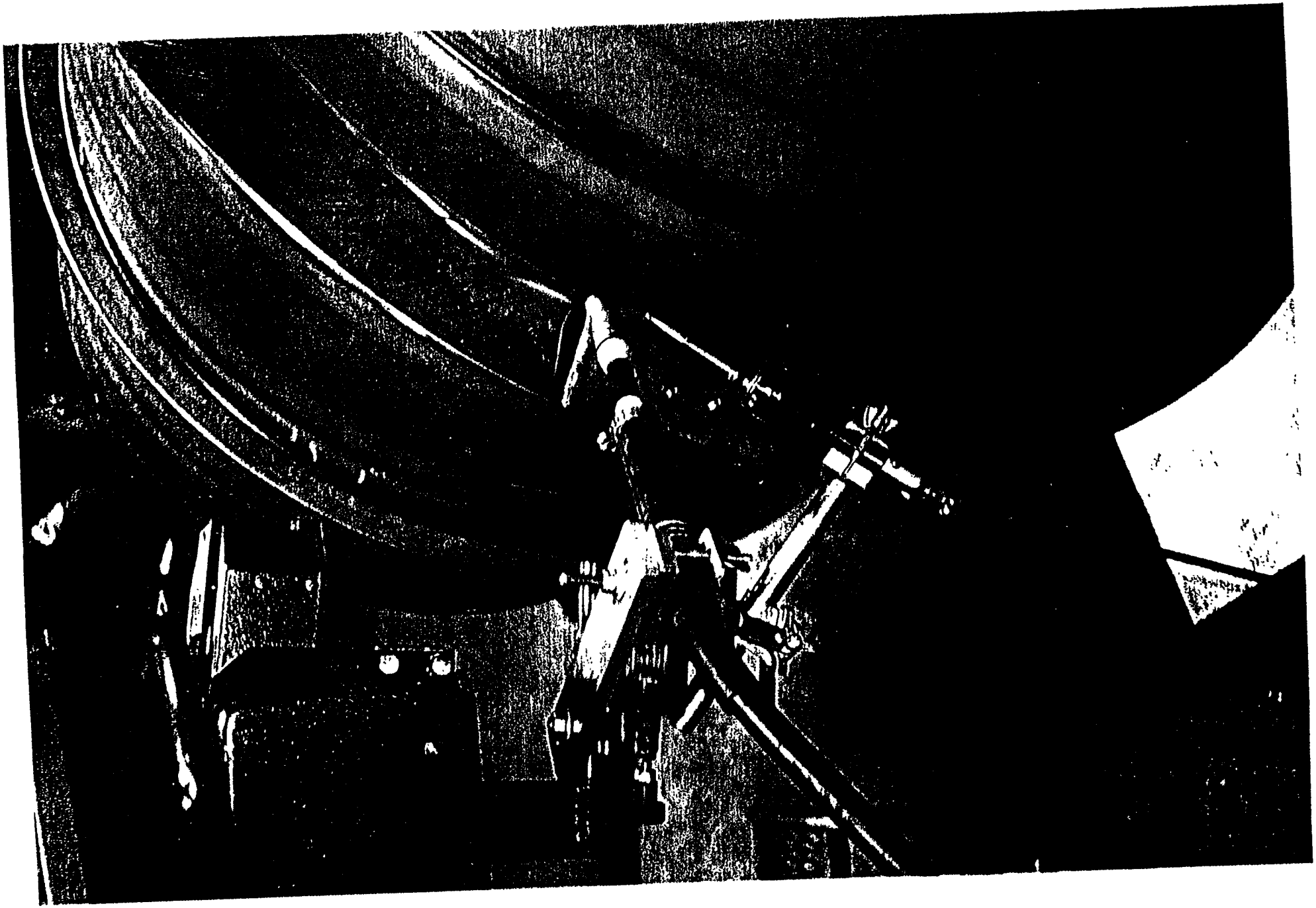
Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

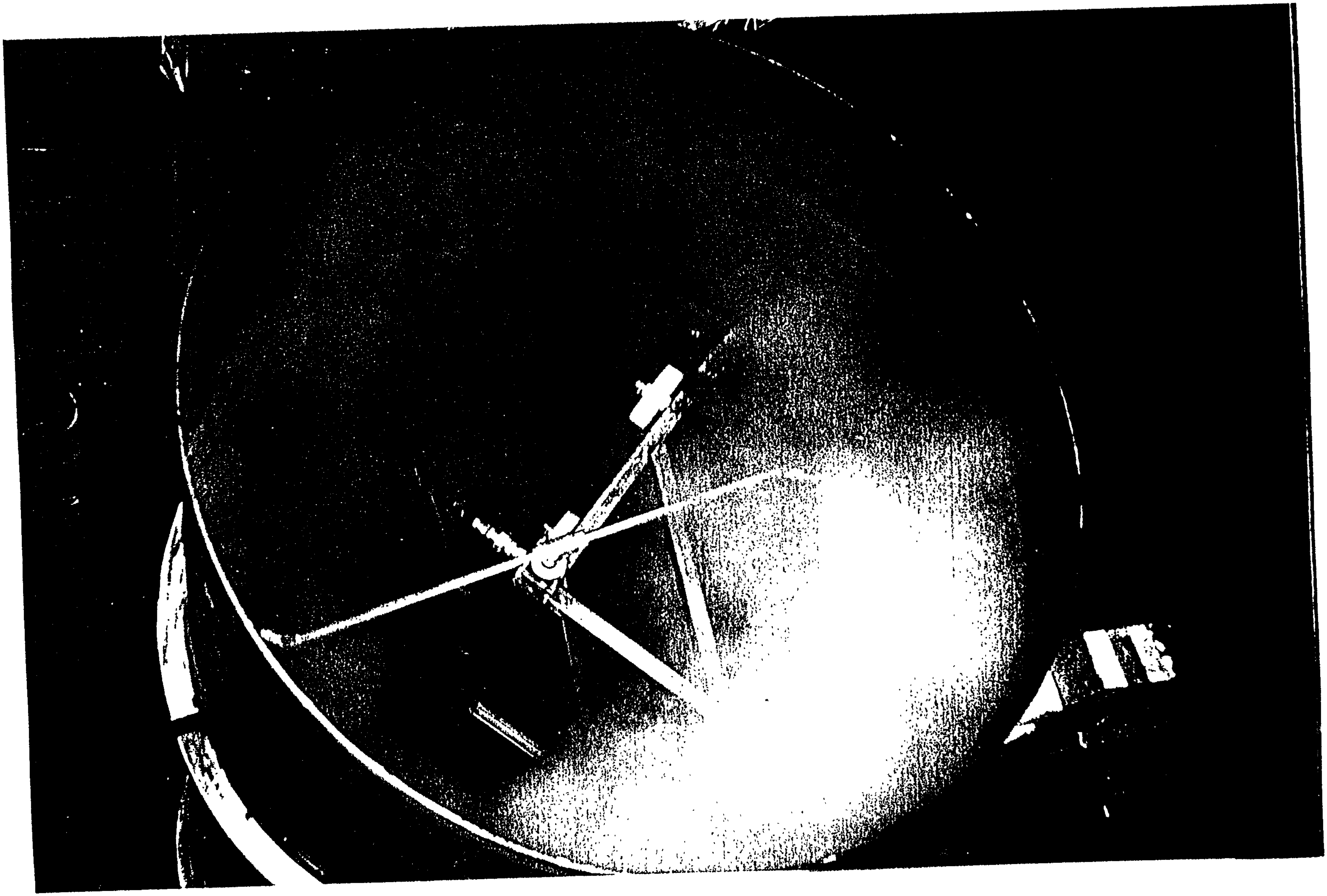




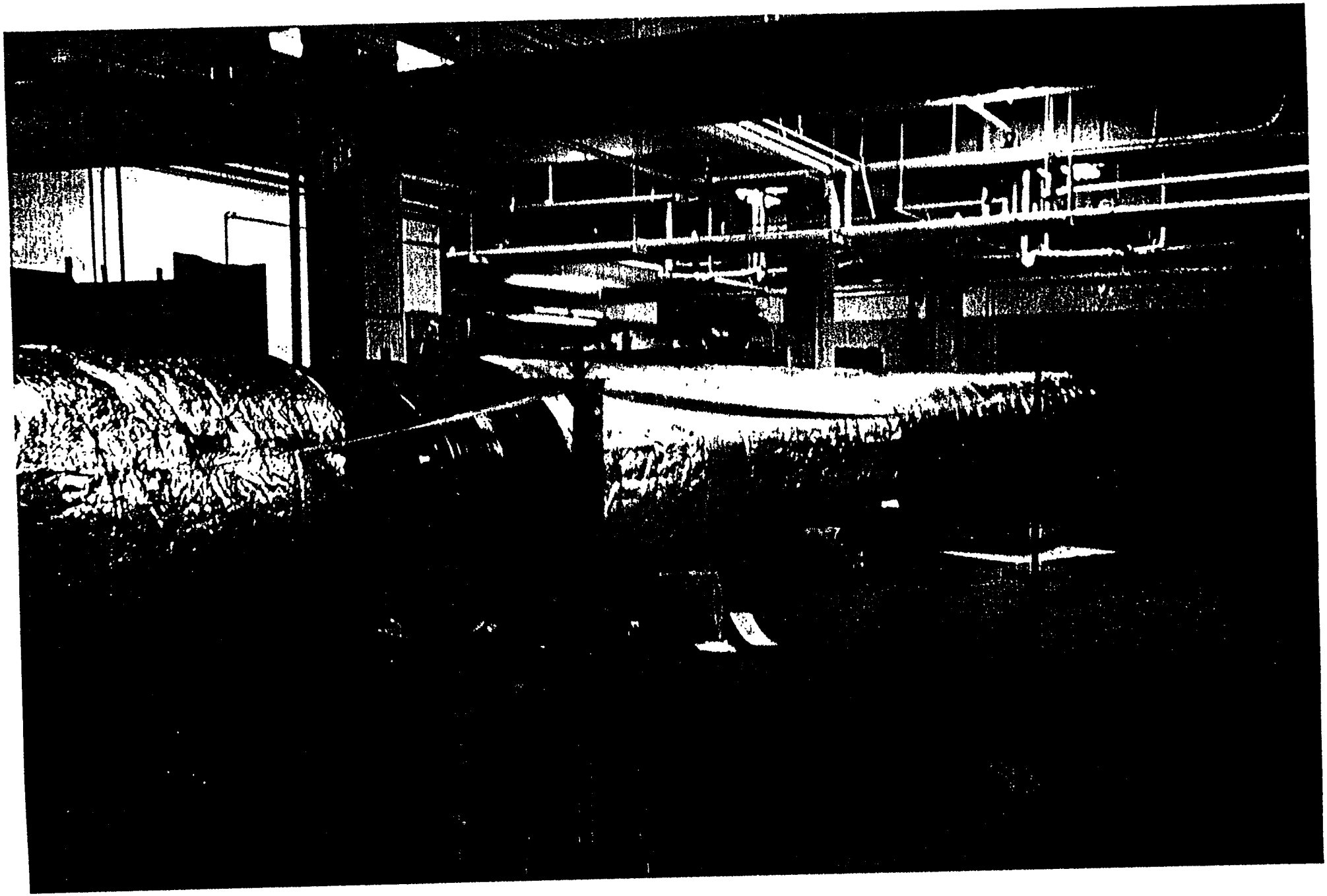


BT QT RING WELDING UNIT





STEAM CLEANING SPRAY UNIT



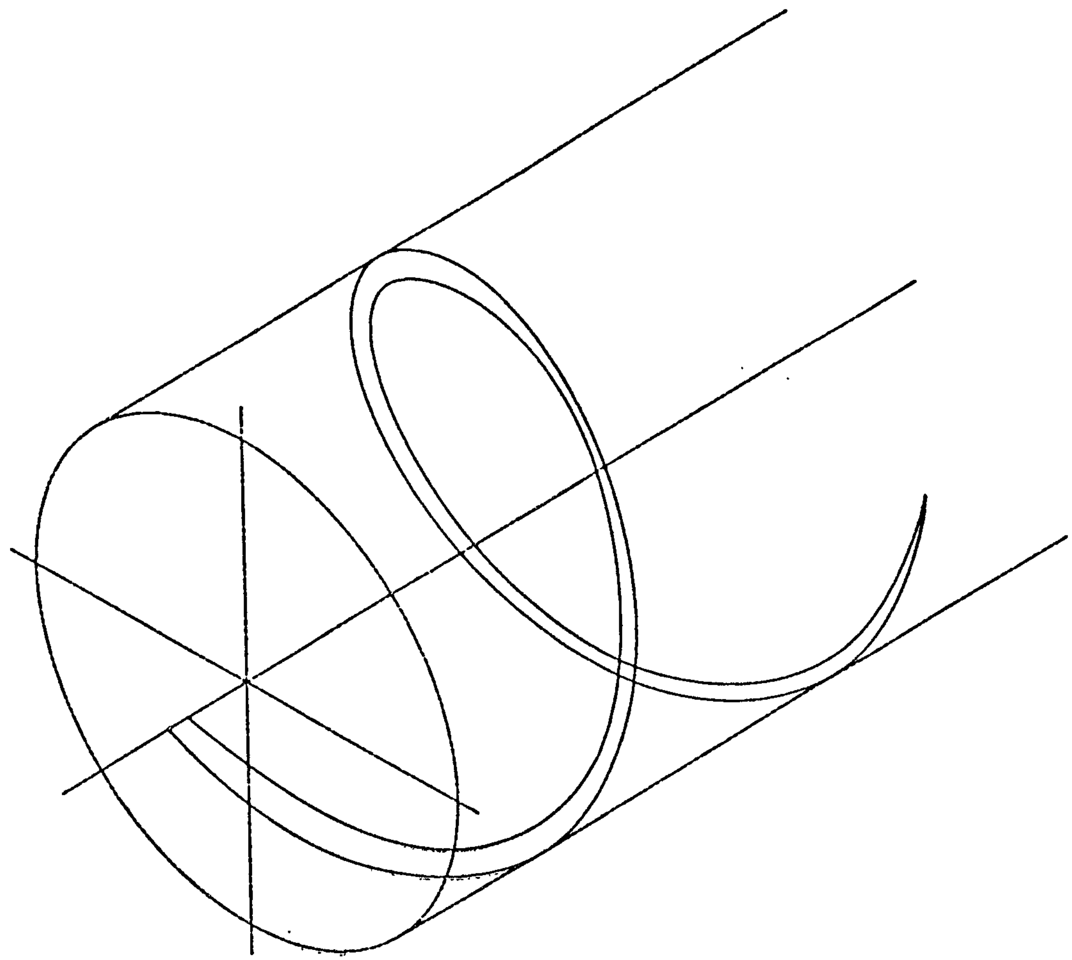
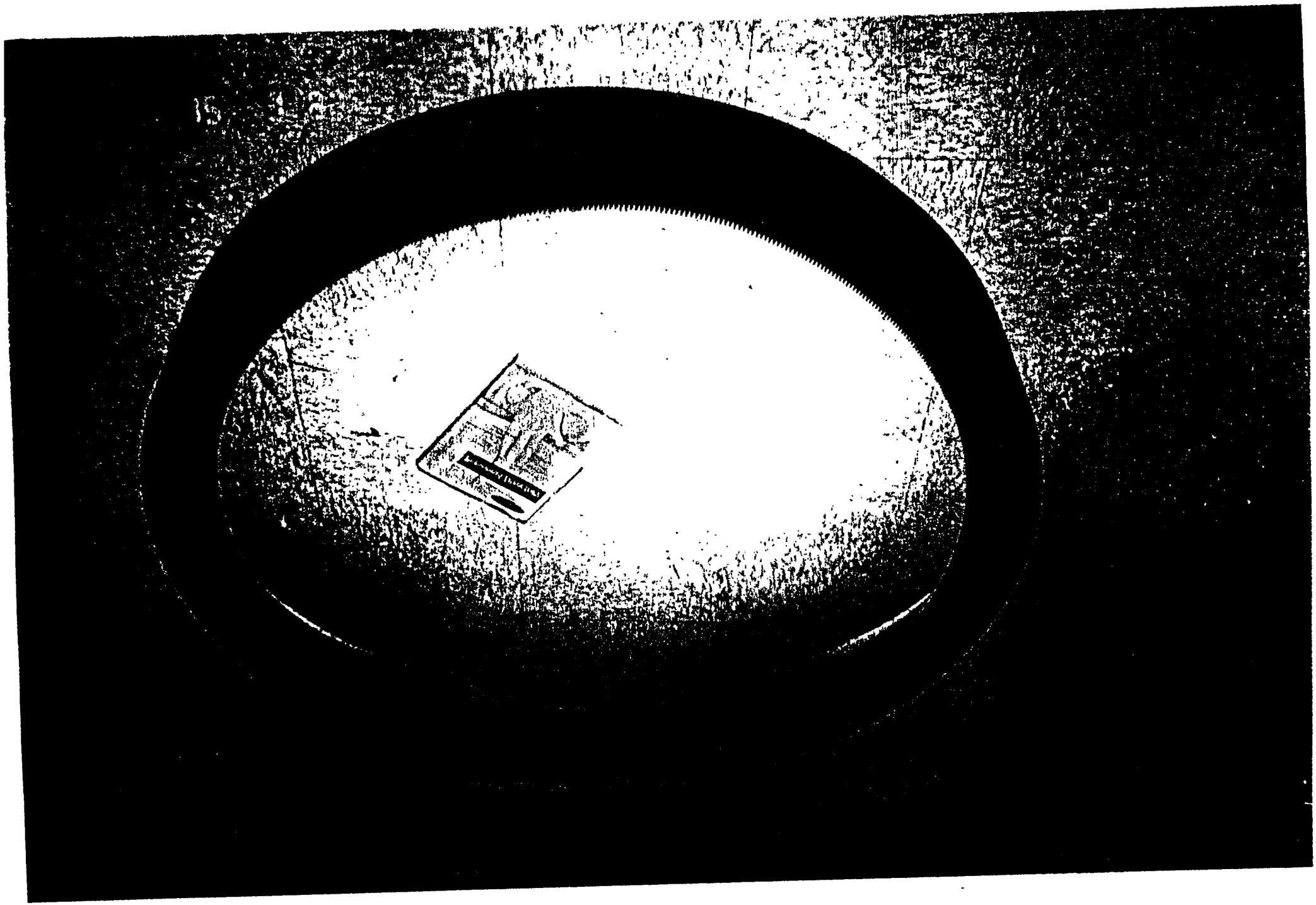
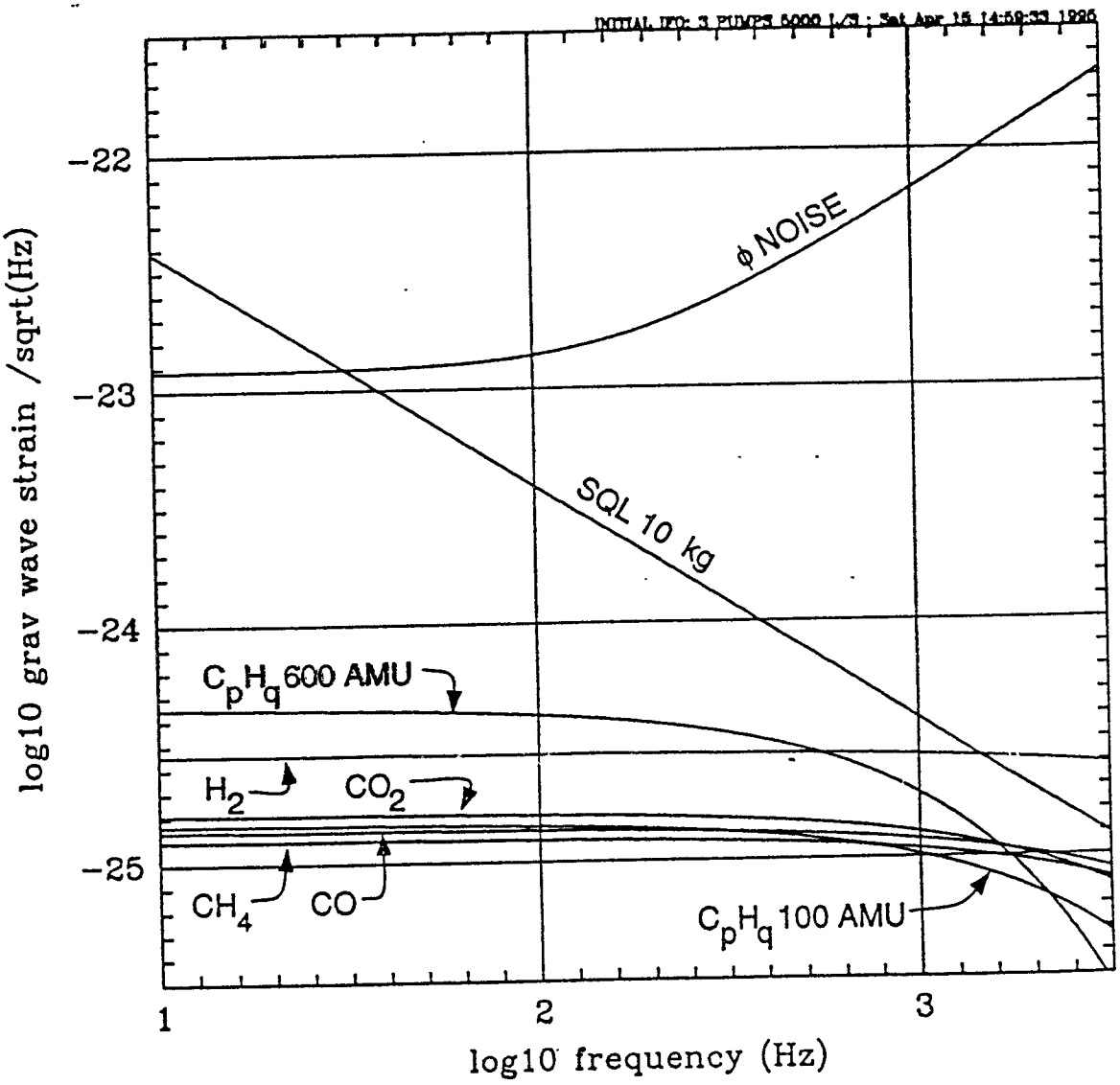


FIGURE1.1.2 #4 BAFFLE SCHEMATIC

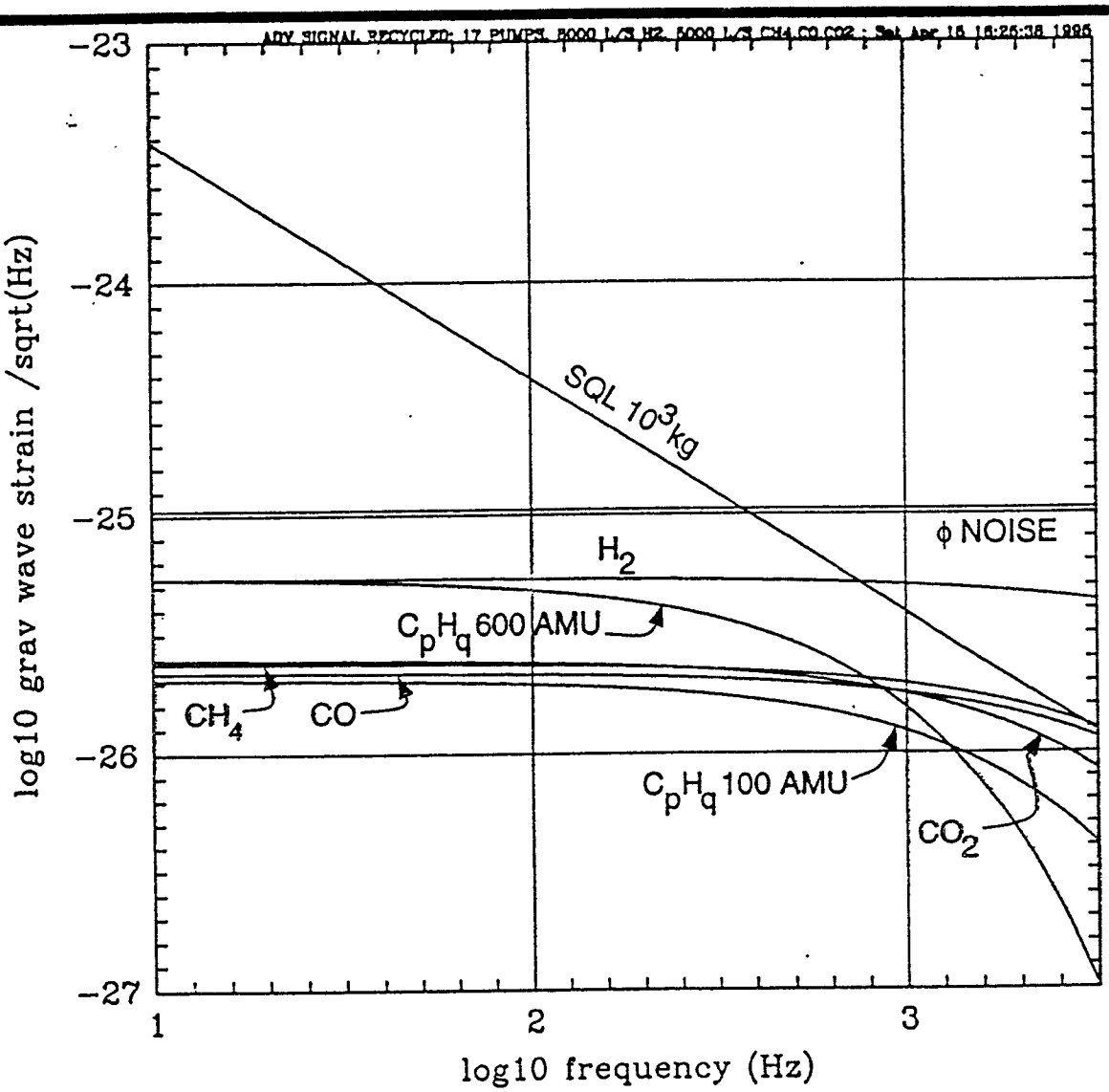


Initial Interferometer Noise Budget



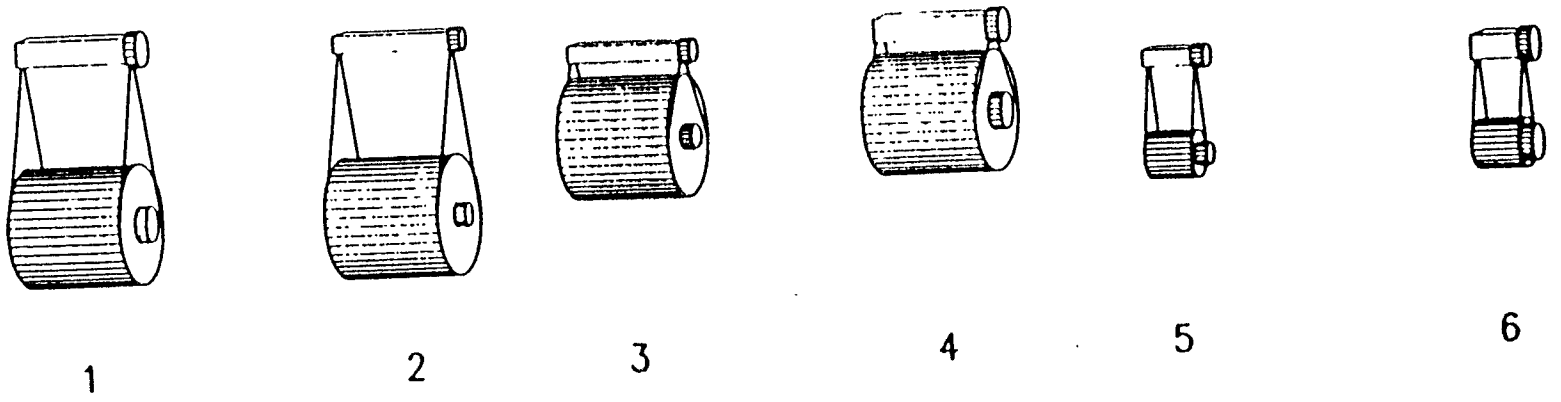
LIGO-G952001-00-B

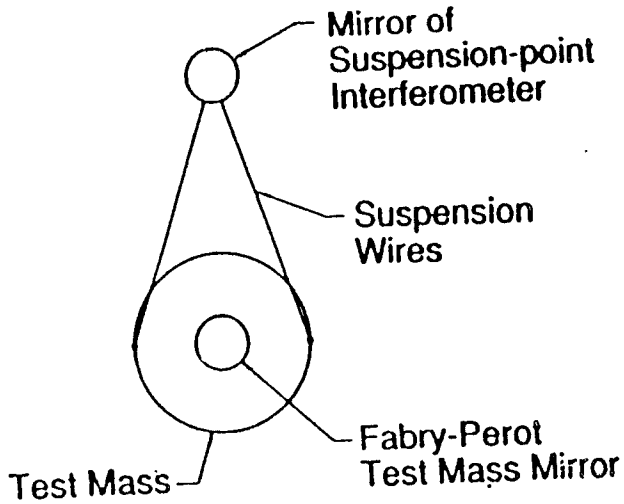
Advanced Interferometer Noise Budget

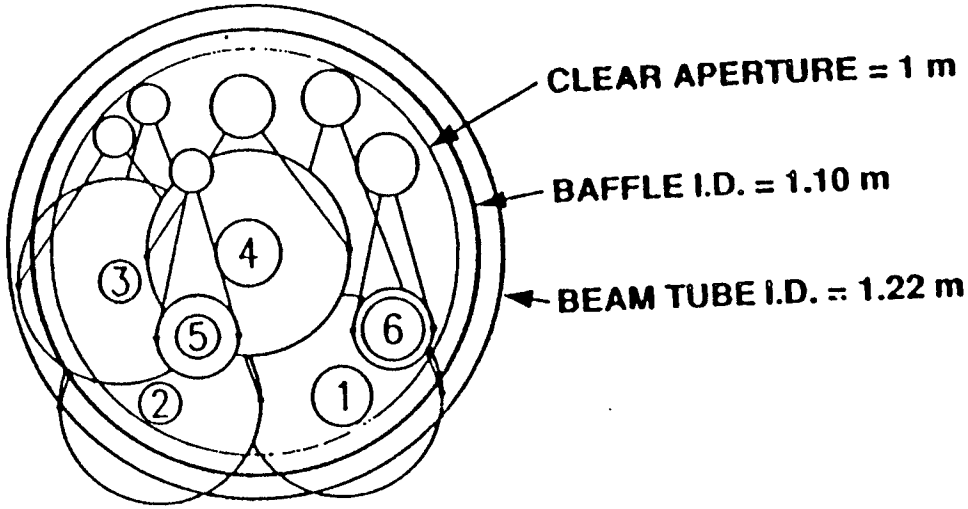


Advanced amplitude recycled interferometer parameters:
$A_m = 10^{-5}$
P_{in} = 100 W P_{circ}~ 1 MW
$\varepsilon_{opt} = 0.3$
λ = 1.06 μ

LIGO-G952001-00-B

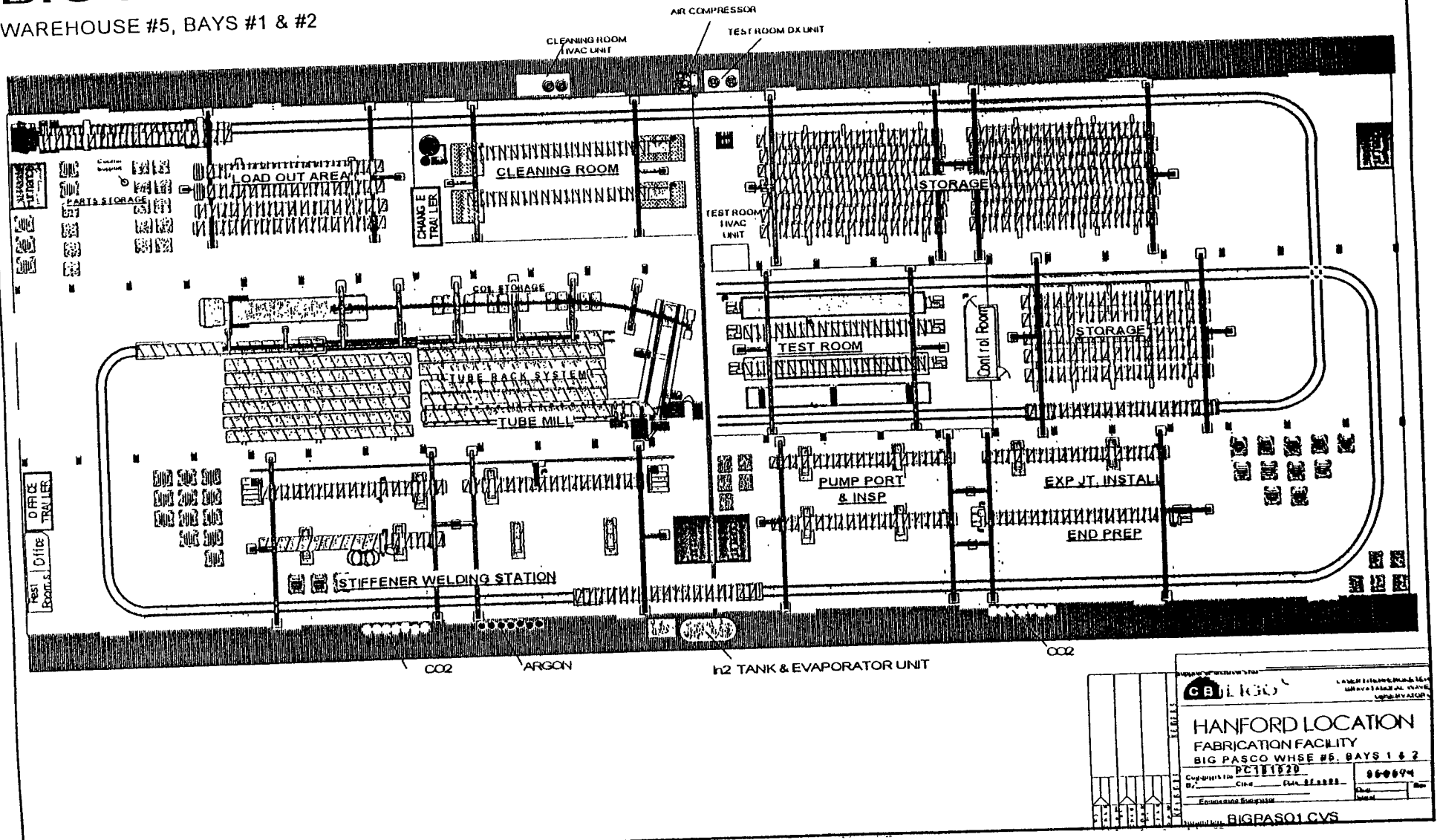

1
2
3
4
5
6


Mirror of
Suspension-point
Interferometer
Suspension
Wires
Fabry-Perot
Test Mass Mirror
Test Mass


CLEAR APERTURE = 1 m
BAFFLE I.D. = 1.10 m
BEAM TUBE I.D. = 1.22 m
1
2
3
4
5
6

BIG PASCO

WAREHOUSE #5, BAYS #1 & #2



CBI

HANFORD LOCATION

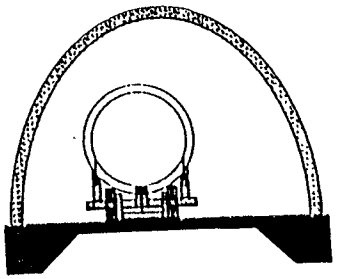
FABRICATION FACILITY

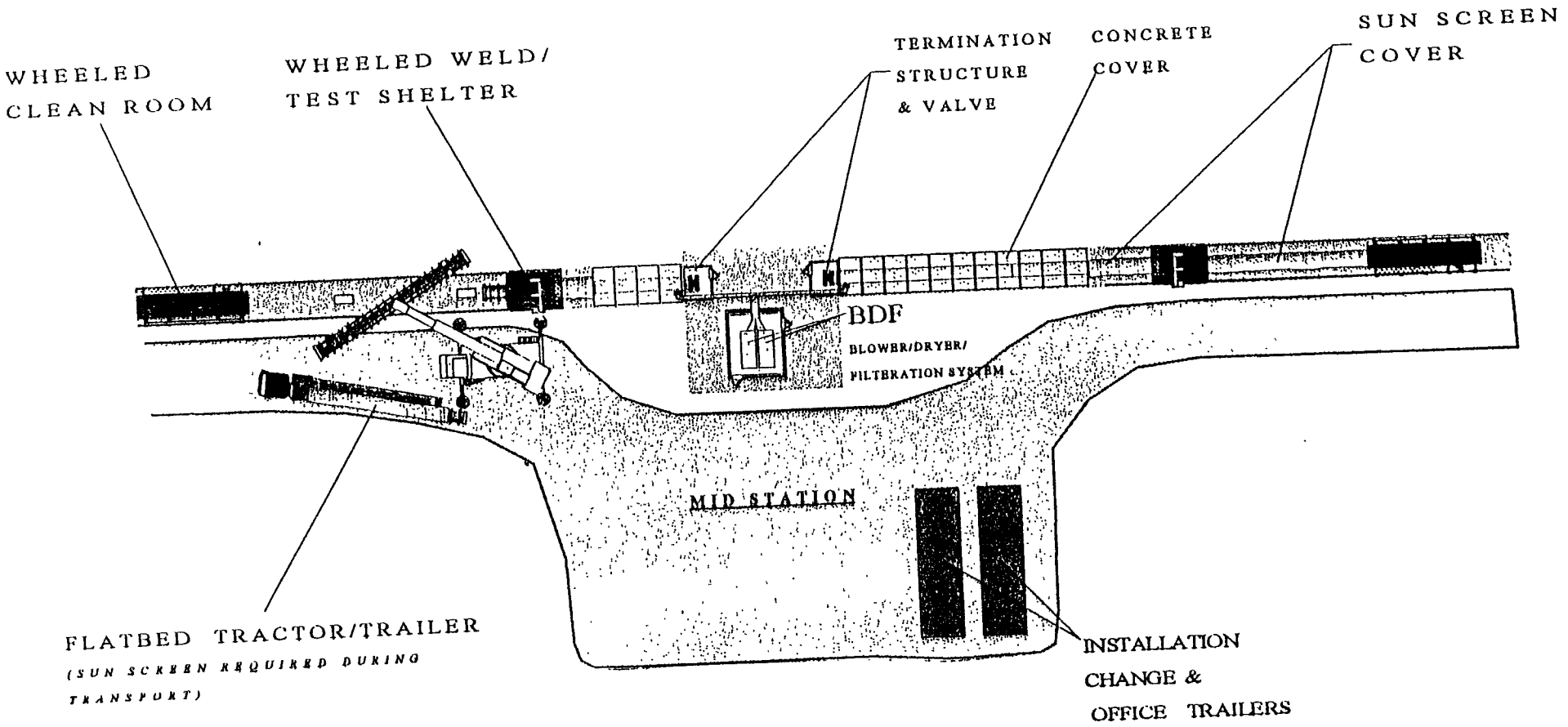
BIG PASCO WHSE #5, BAYS 1 & 2

PC181520

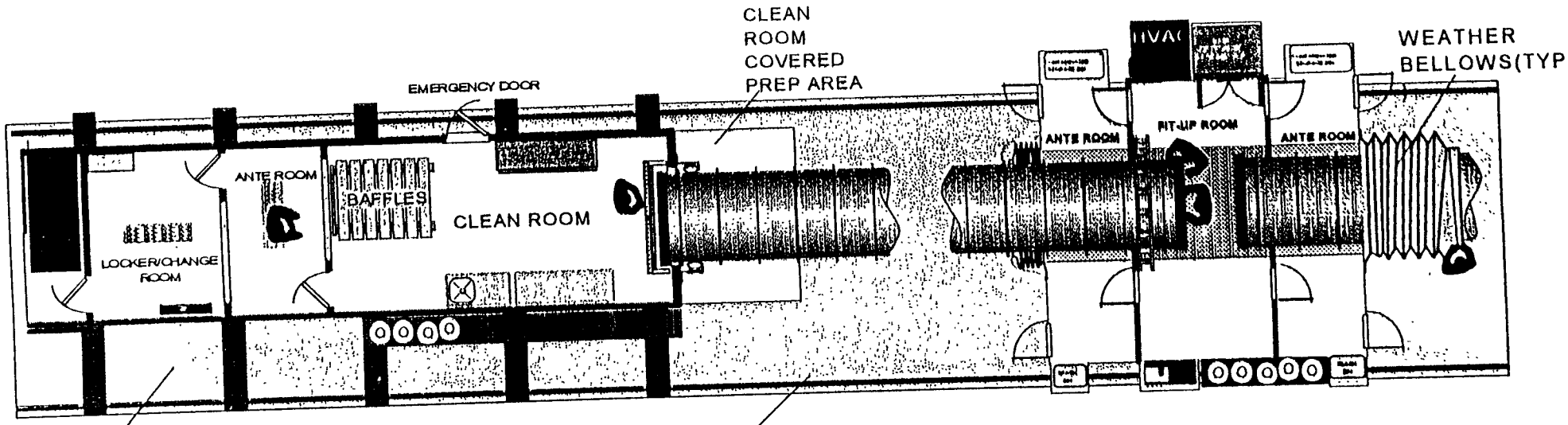
BIGPASO1.CVS

LIGO INSTALLATION PLAN





INSTALLATION PLAN

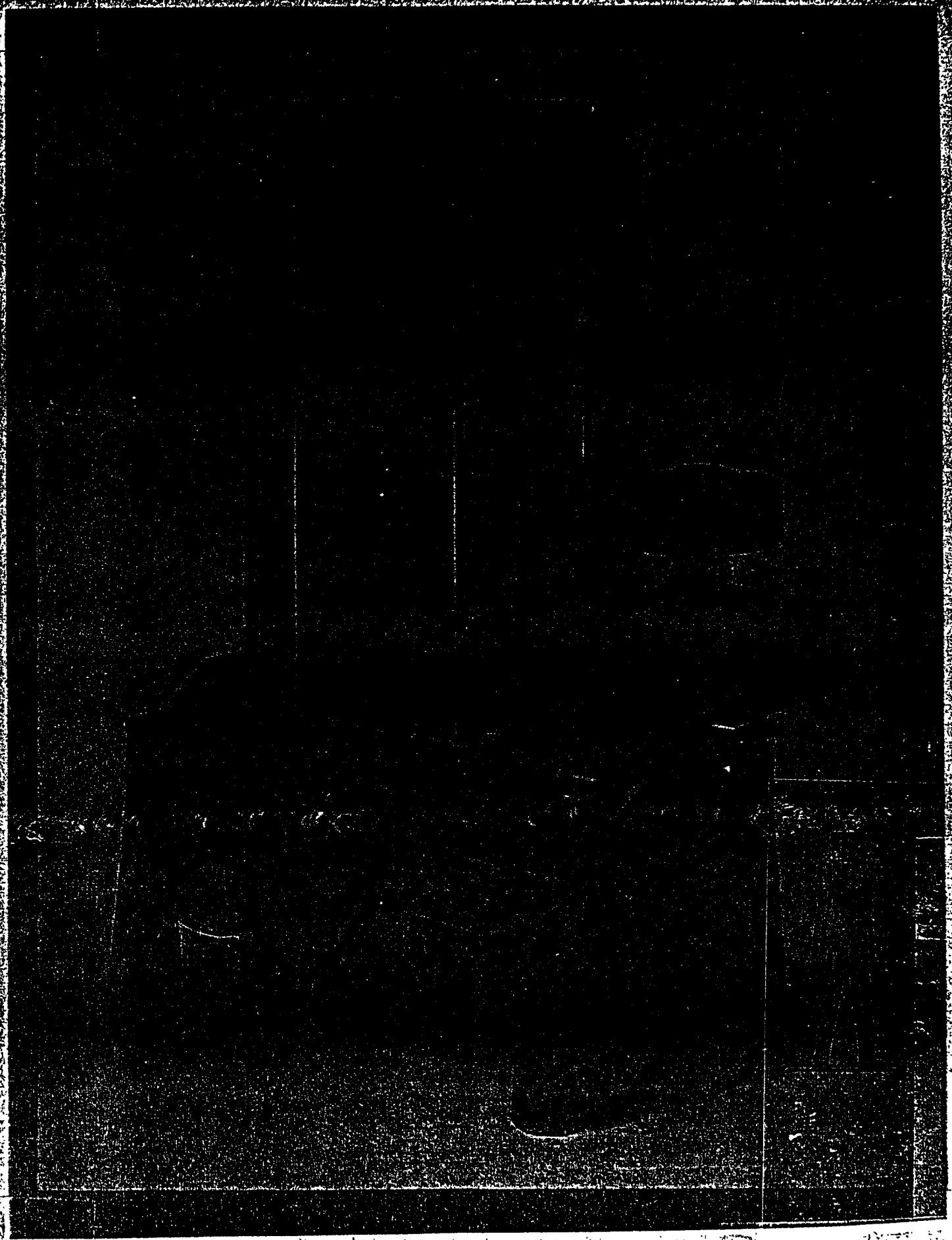


LIGO Facilities

Vacuum Equipment

- Characteristics
  - » mostly standard vacuum equipment
    - – 1st stage roughing atm -> 0.1 torr
    - – 2nd stage roughing 0.1 torr -> 10^{-6} torr
    - – steady state - ion/getter pumps
  - » large gate valves (4 ft diam)
    - – access and flexibility
  - » controls and monitoring

- Status
  - » Science requirements and review 6/94
  - » RFP issued for design contract only
  - » Two competitive contracts awarded (CB&I, PSI)
  - » Final design and manufacturing
    - – down select (6/95) to PSI
    - – CDR approved 10/95
    - – FDR May 96; some prototype/acquisitions now



HFBR 7001-

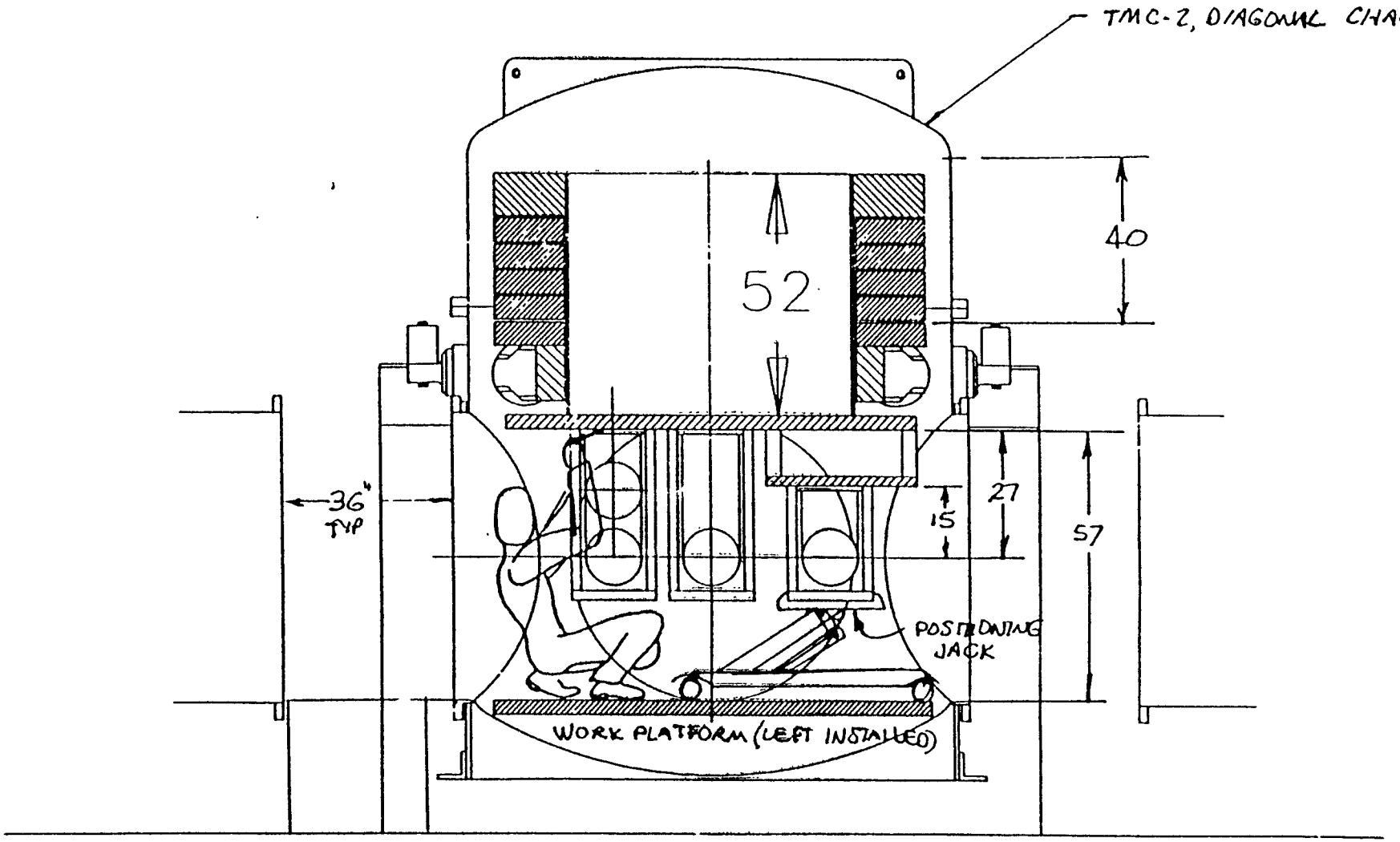
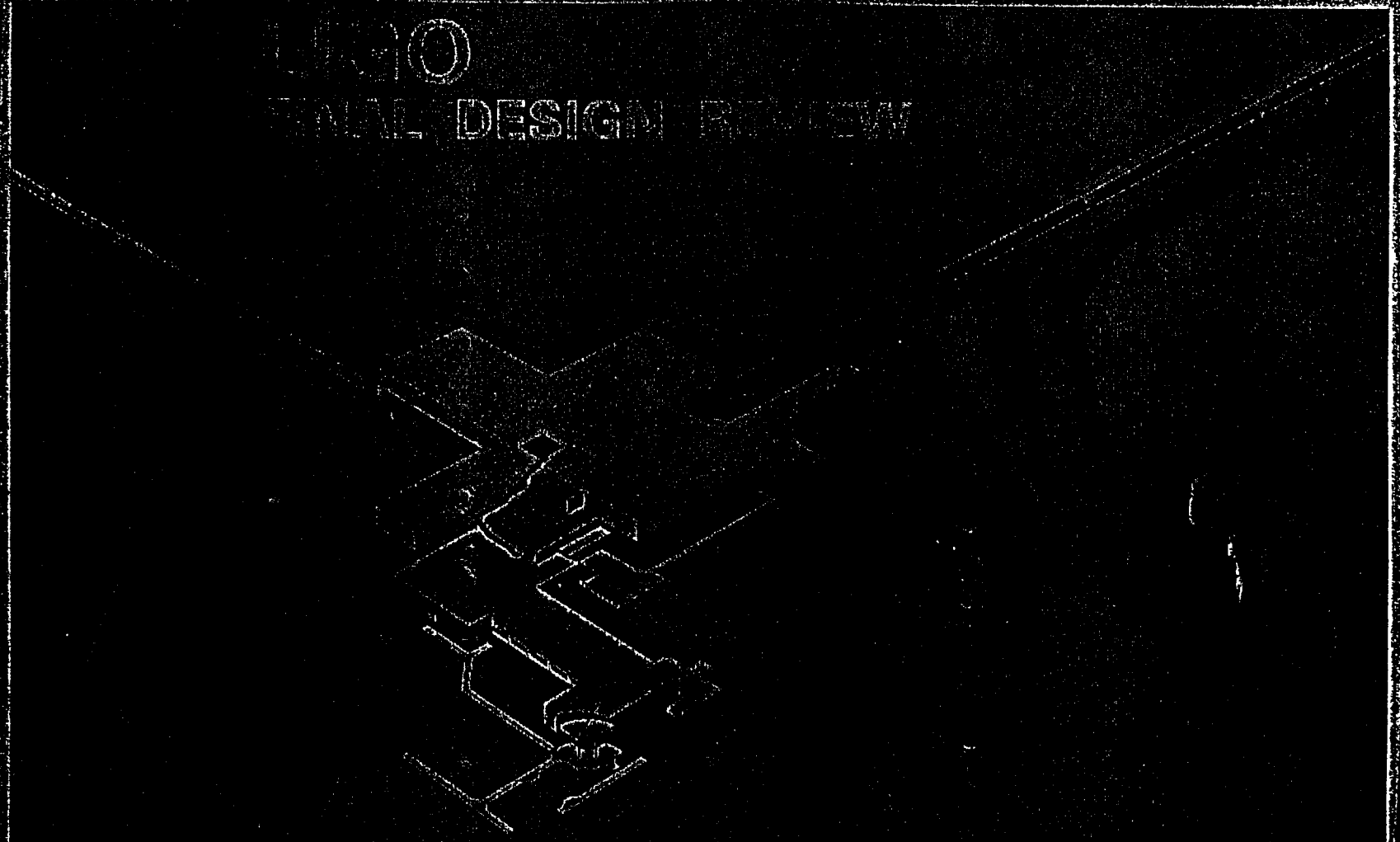


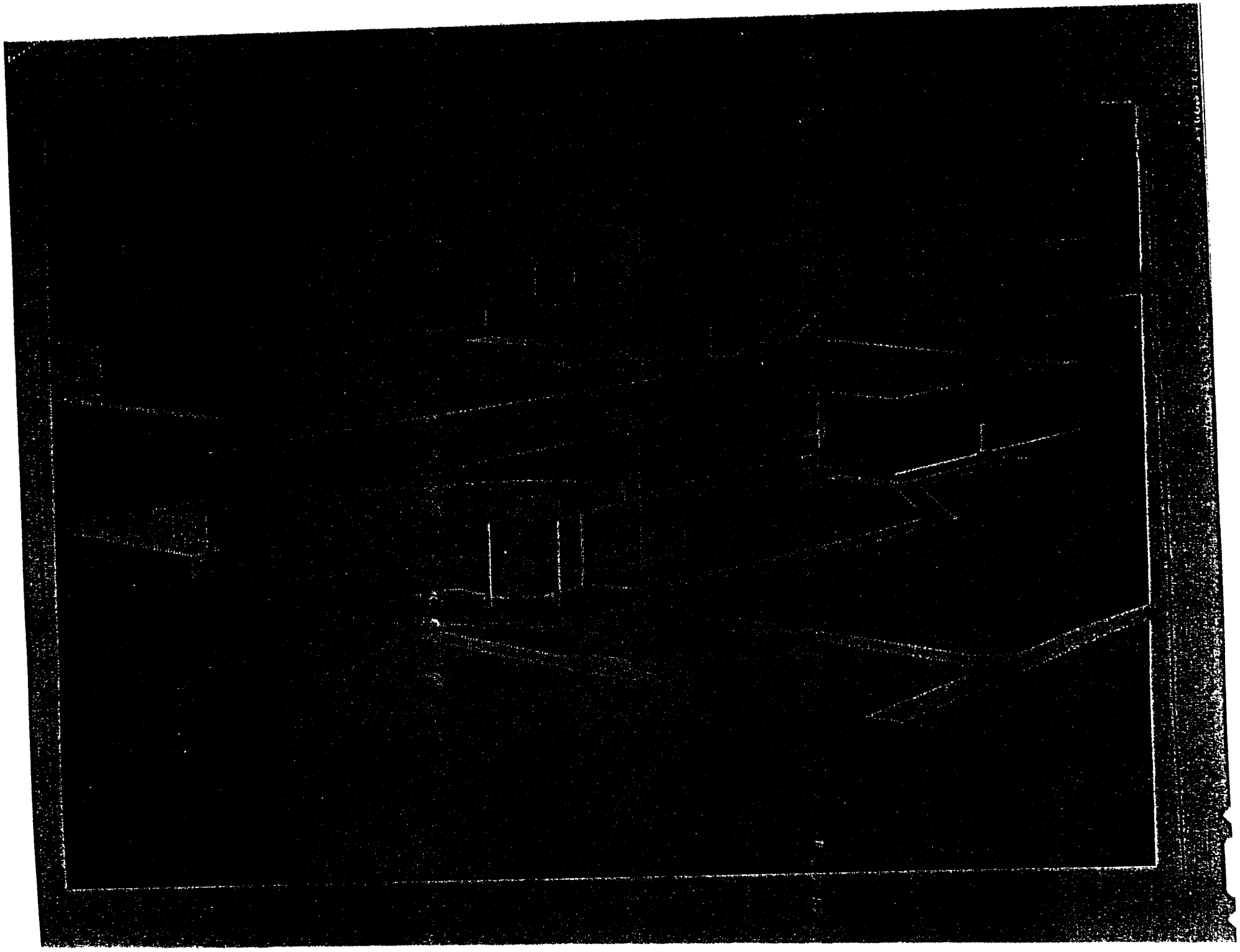
FIG. 3 INTERNAL ACCESS

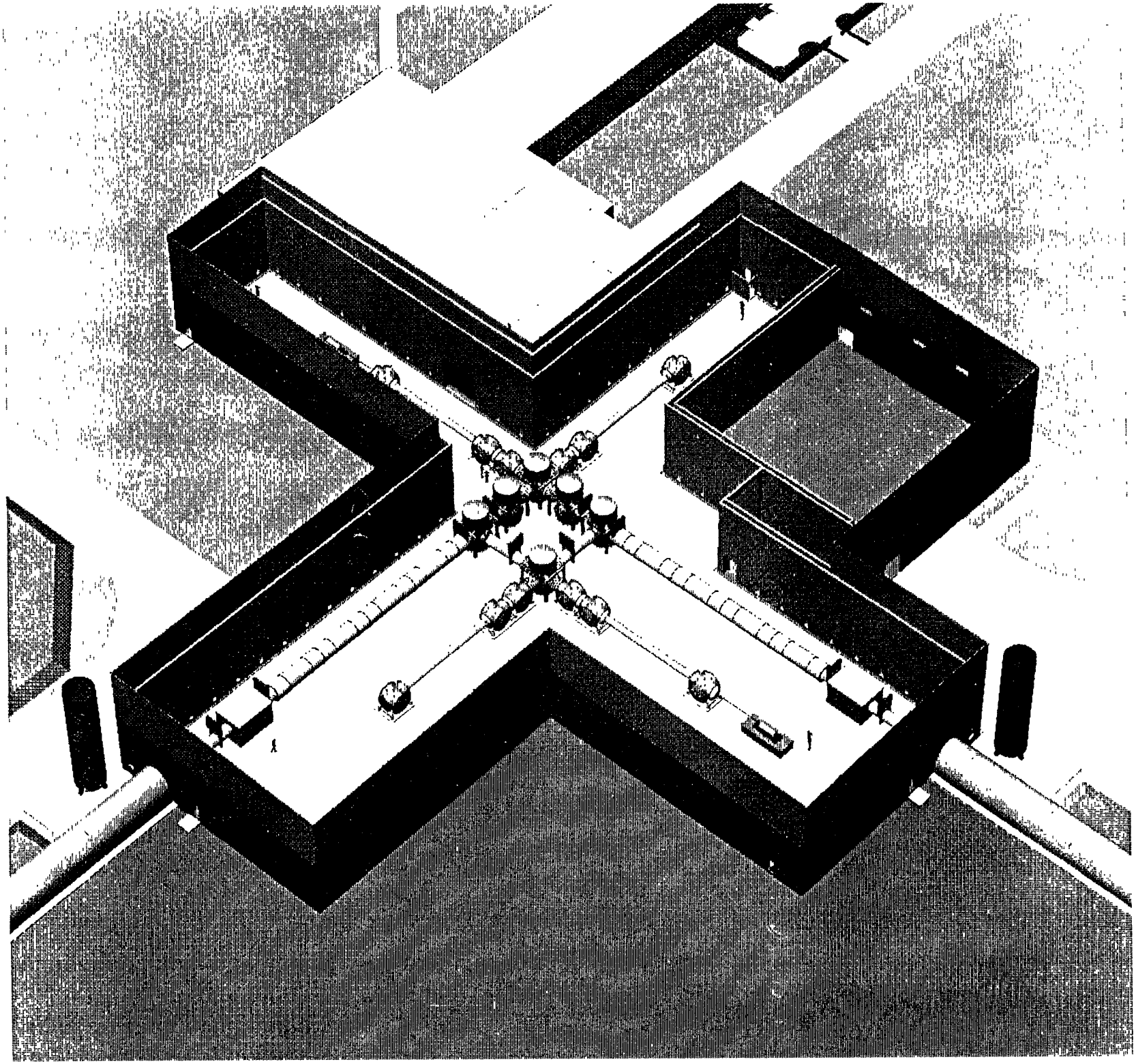
9-2-92

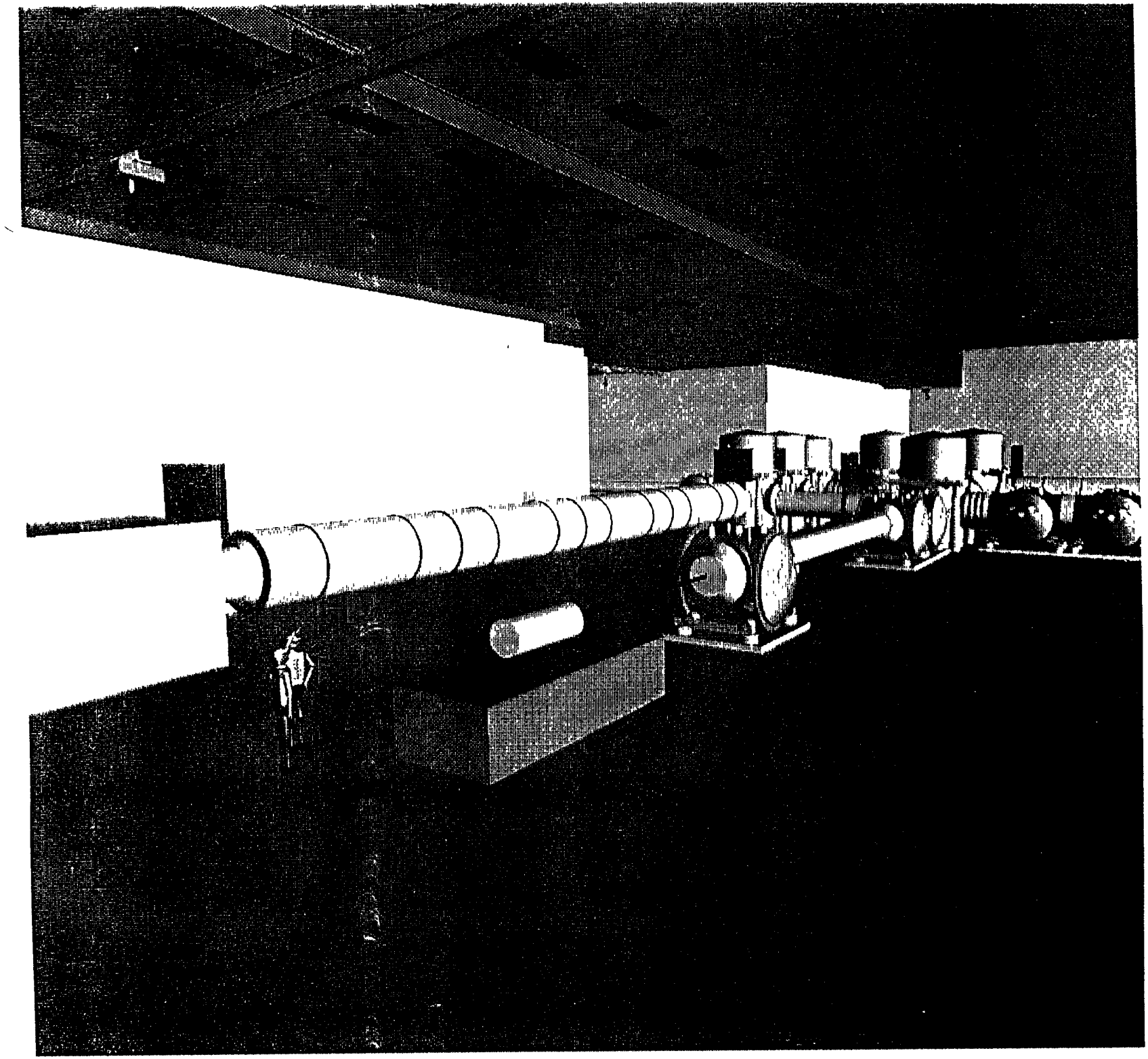
LIGO
FINAL DESIGN REVIEW



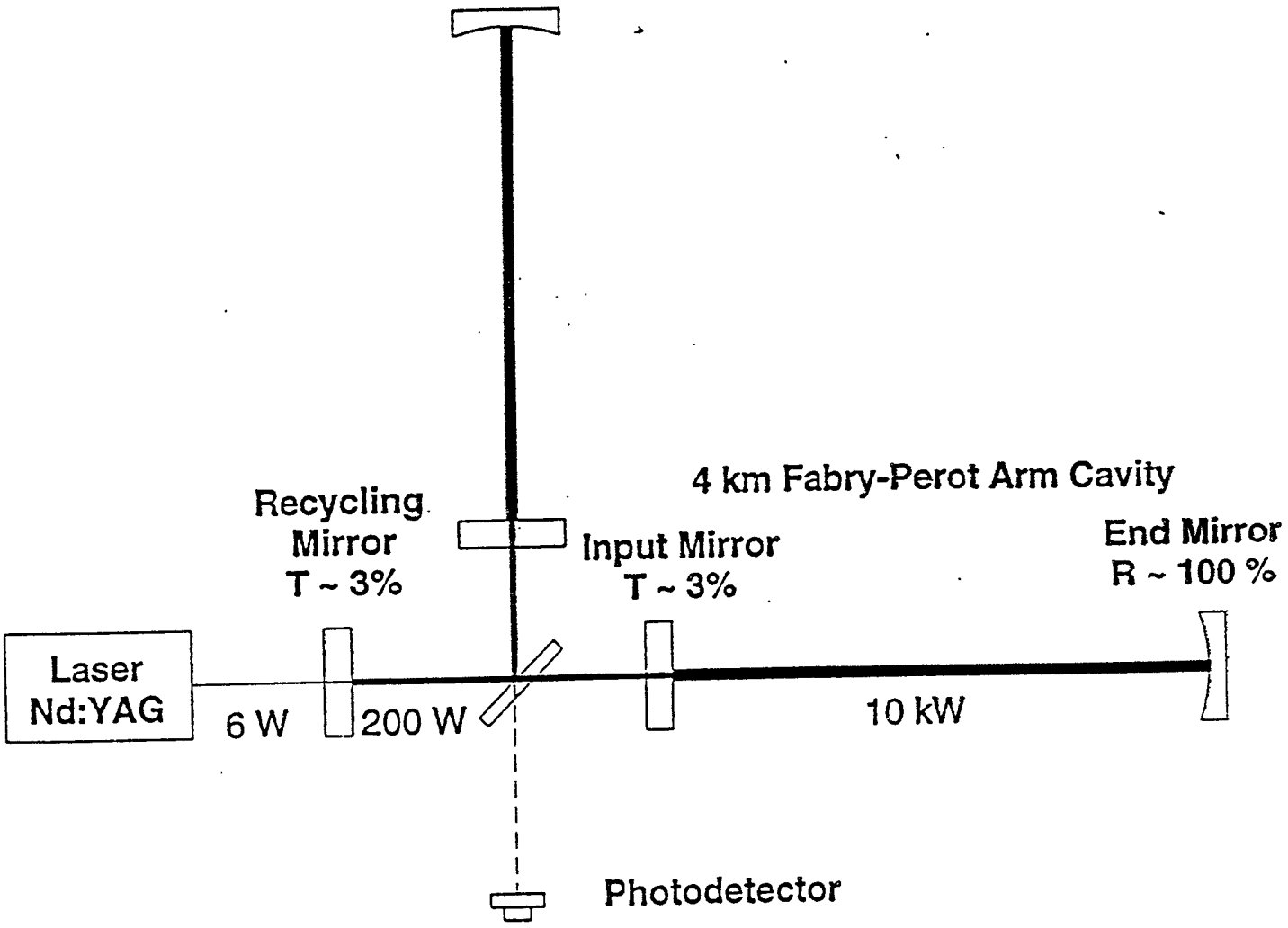
APRIL 1996





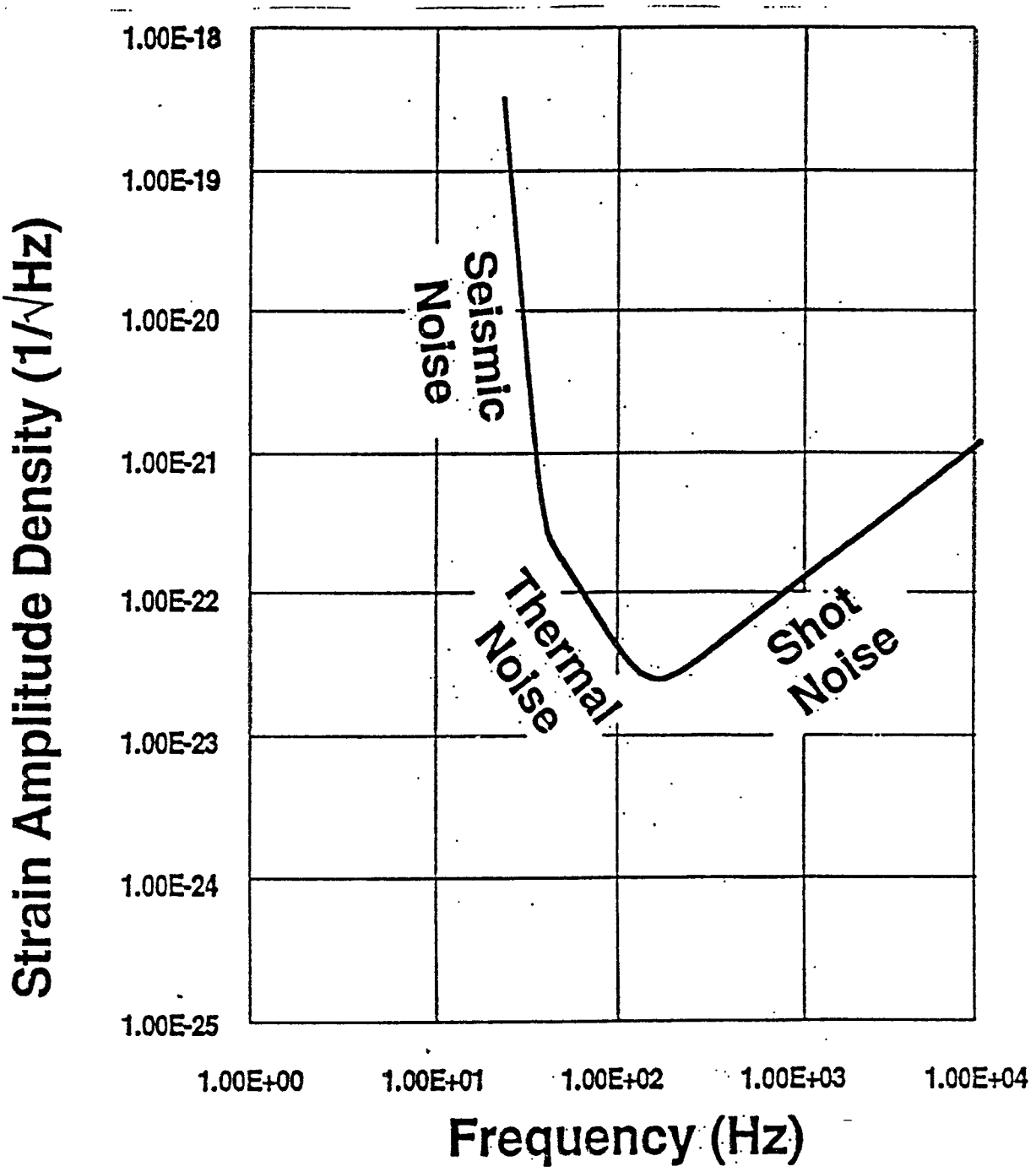


Initial Interferometers
Configuration



Initial Interferometers

Noise Floor



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LIGO Interferometers

Optical Parameters

Optical Characteristics	Nominal Initial Interferometer	Sample Enhanced Interferometer
Arm Length	4000 m	4000 m
Laser Type & Wavelength	Nd:YAG, $\lambda = 1.064$ μm	Nd:YAG, $\lambda = 1.064$ μm
Input Power into Recycling Cavity, P	6W	100W
Contrast Defect, 1-c	3×10^{-3}	3×10^{-3}
Mirror Loss, L_M	1×10^{-4}	1.3×10^{-5}
Power Recycling Gain	30	380
Arm Cavity Storage Time, τ_{Arm}	8.8×10^{-4} s	1.3×10^{-3} s
Cavity Input Mirror Transmission, T	3×10^{-2}	2×10^{-2}
Total Optical Loss, L_T = (Absorption + Scattering)	4×10^{-2}	3×10^{-3}

LIGO Interferometers

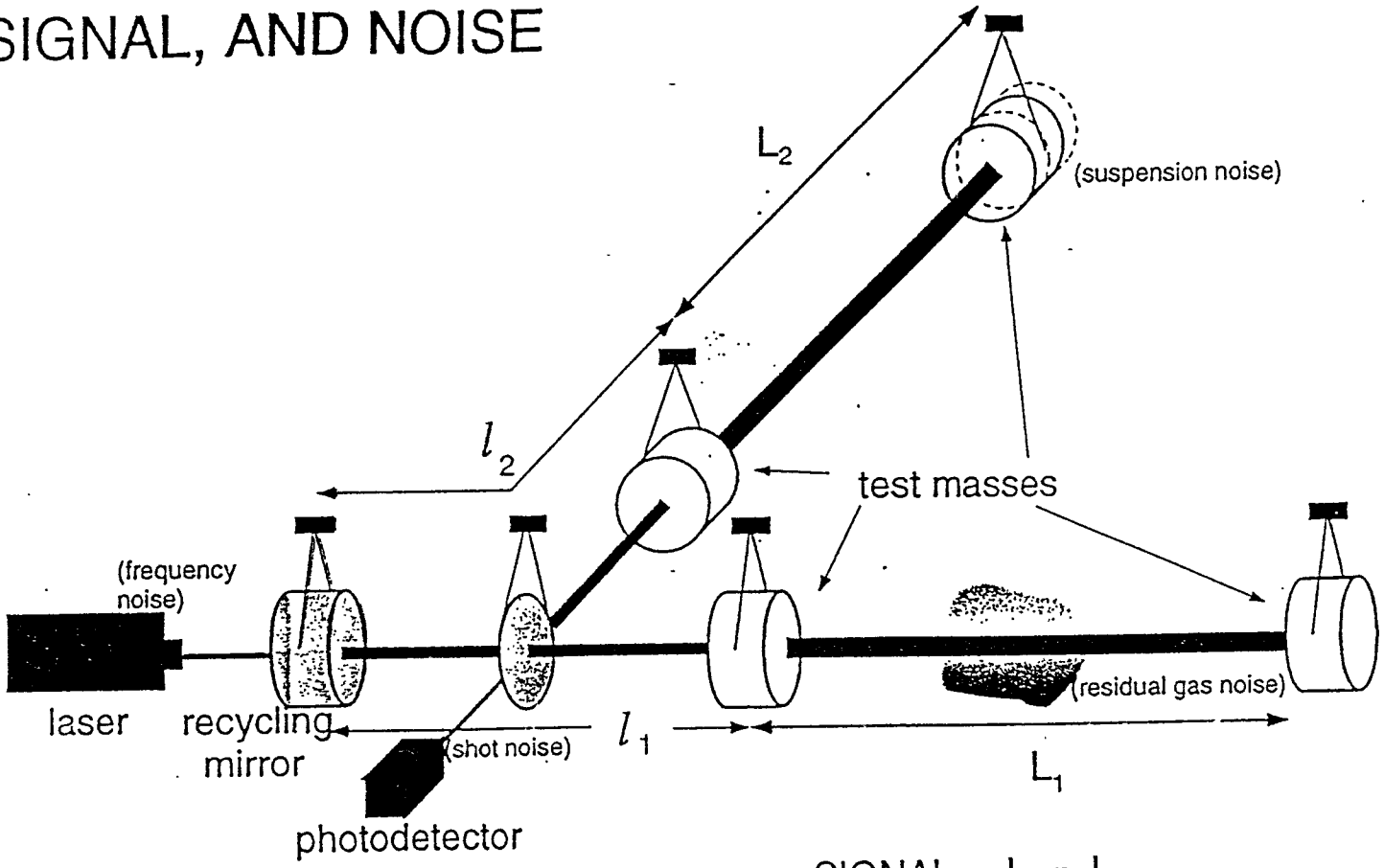
Mechanical Parameters

Mechanical Characteristics	Nominal Initial Interferometer	Sample Enhanced Interferometer
Mirror Mass, M_M	10.7 kg	40 kg
Mirror Diameter, D_M	0.25 m	0.40 m
Mirror Internal Q_M	1×10^6	3×10^7
Pendulum Q_P(damping mechanism)	1×10^5 (material)	1×10^8 (material)
Pendulum Period, T_P	1 s (Single)	1 s (Double)
Seismic Isolation System	T(100 Hz) = -100 dB	T(10 Hz) = -100 dB

Interferometer

Noise Limitations

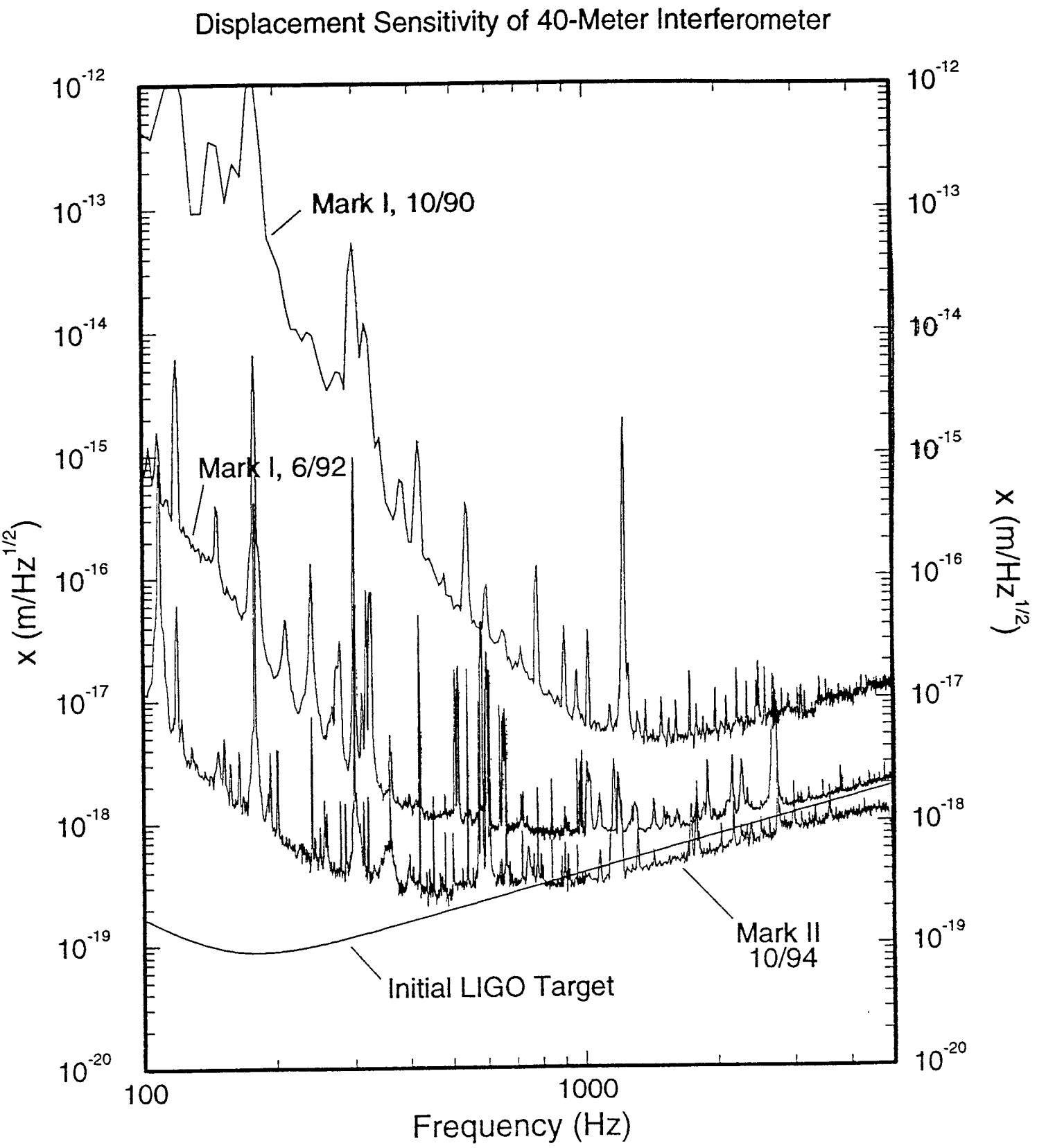
INTERFEROMETER,
SIGNAL, AND NOISE



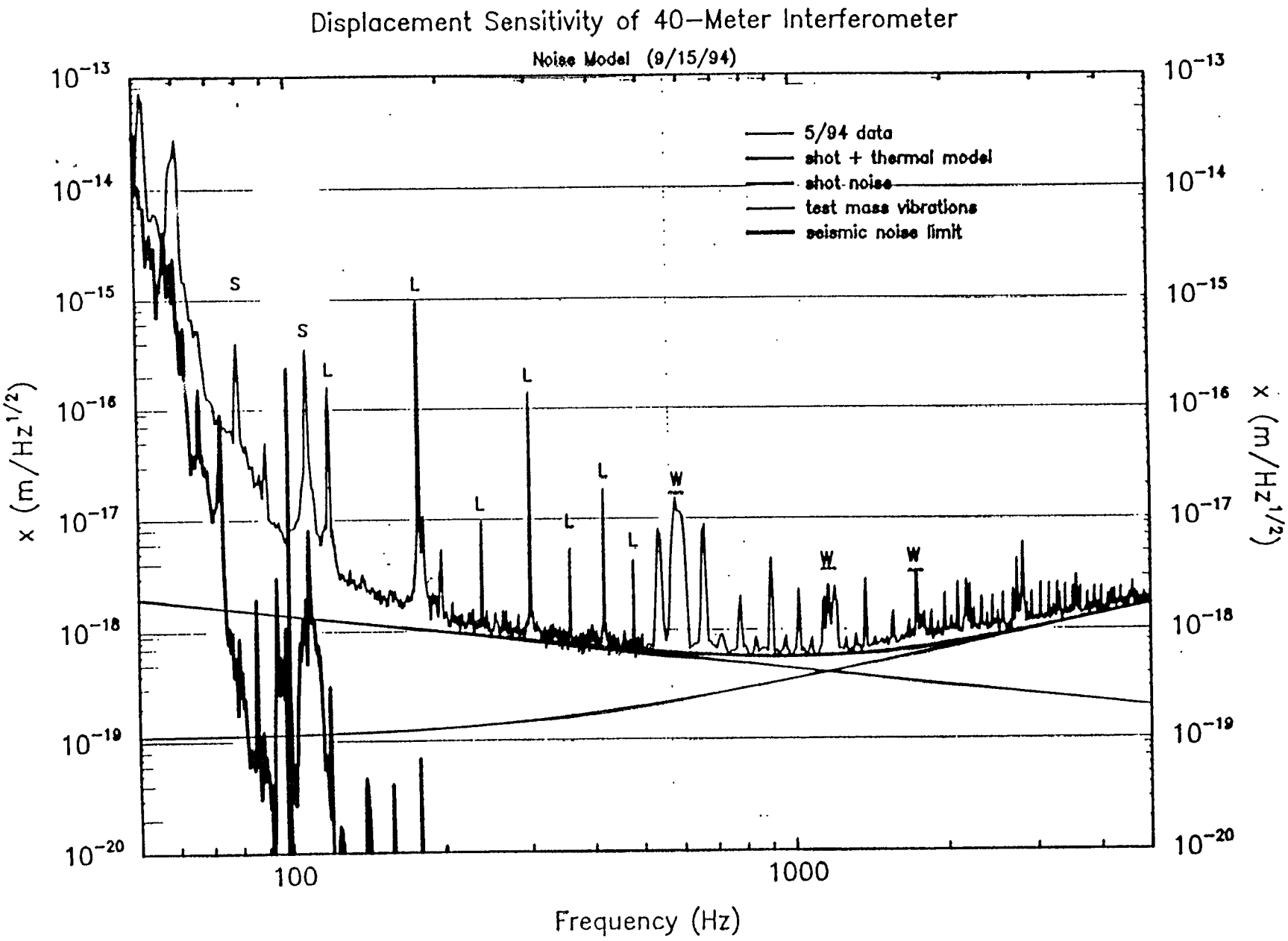
SIGNAL = L_1 - L_2

LIGO
R&D Program

- Sensitivity
  - » main features of 40 m spectrum understood
  - » monolithic test masses improve sensitivity
- Demonstration Experiments
  - » optical recombination demonstrated on 40 m
  - » acquisition locking with LIGO controls
  - » MIT phase noise experiments
- Pre- [detector design freeze][<1998]
  - » Program testing directed at tasks that could effect design over the next two years
- Post- [detector design freeze][>1998]
  - » Advanced R&D program on techniques for improved sensitivity;
  - » understand performance - initial interferometer
  - » gain experience running an interferometer facility (perform search)



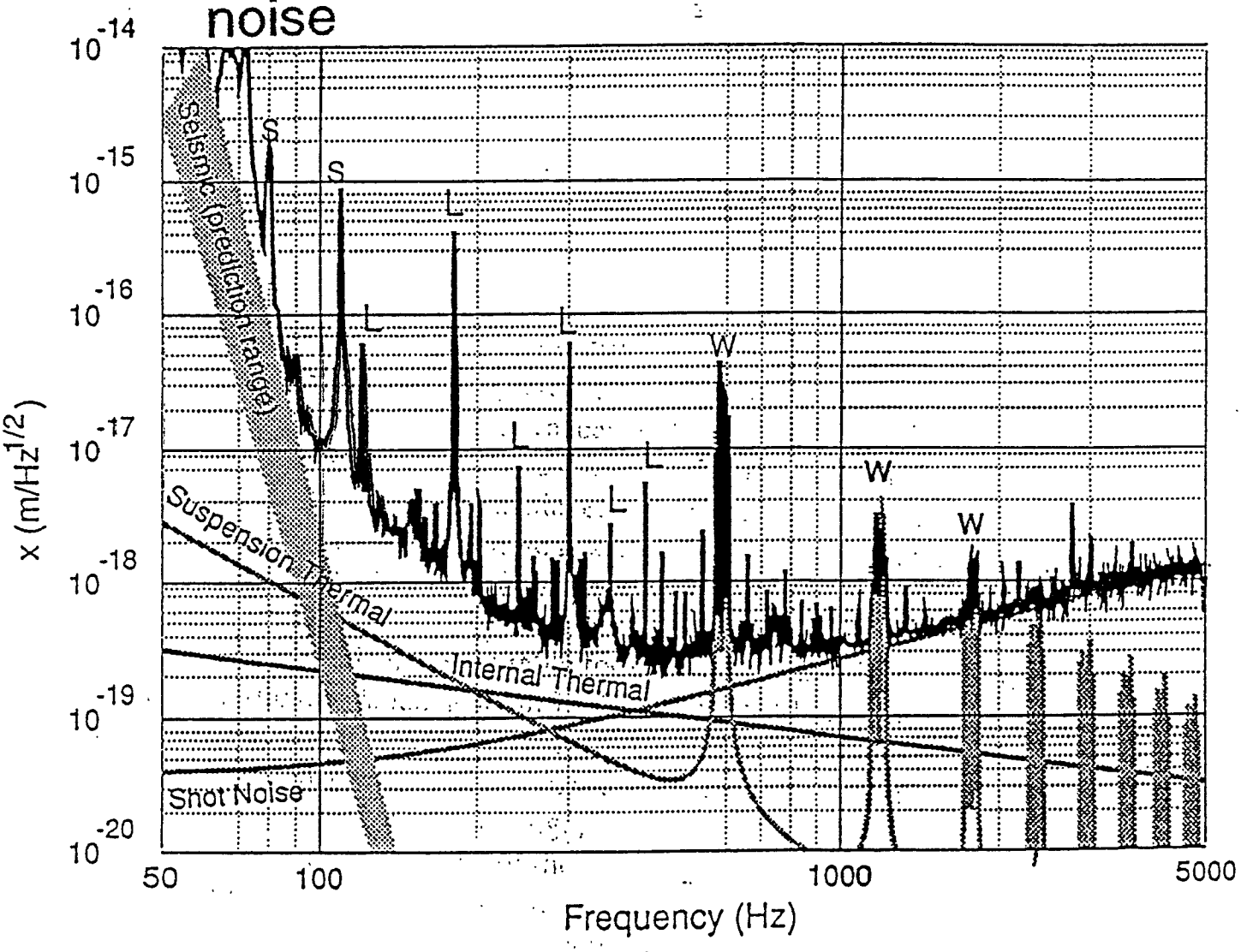
~fjr/fort/mk2/port_90_94.xvgr

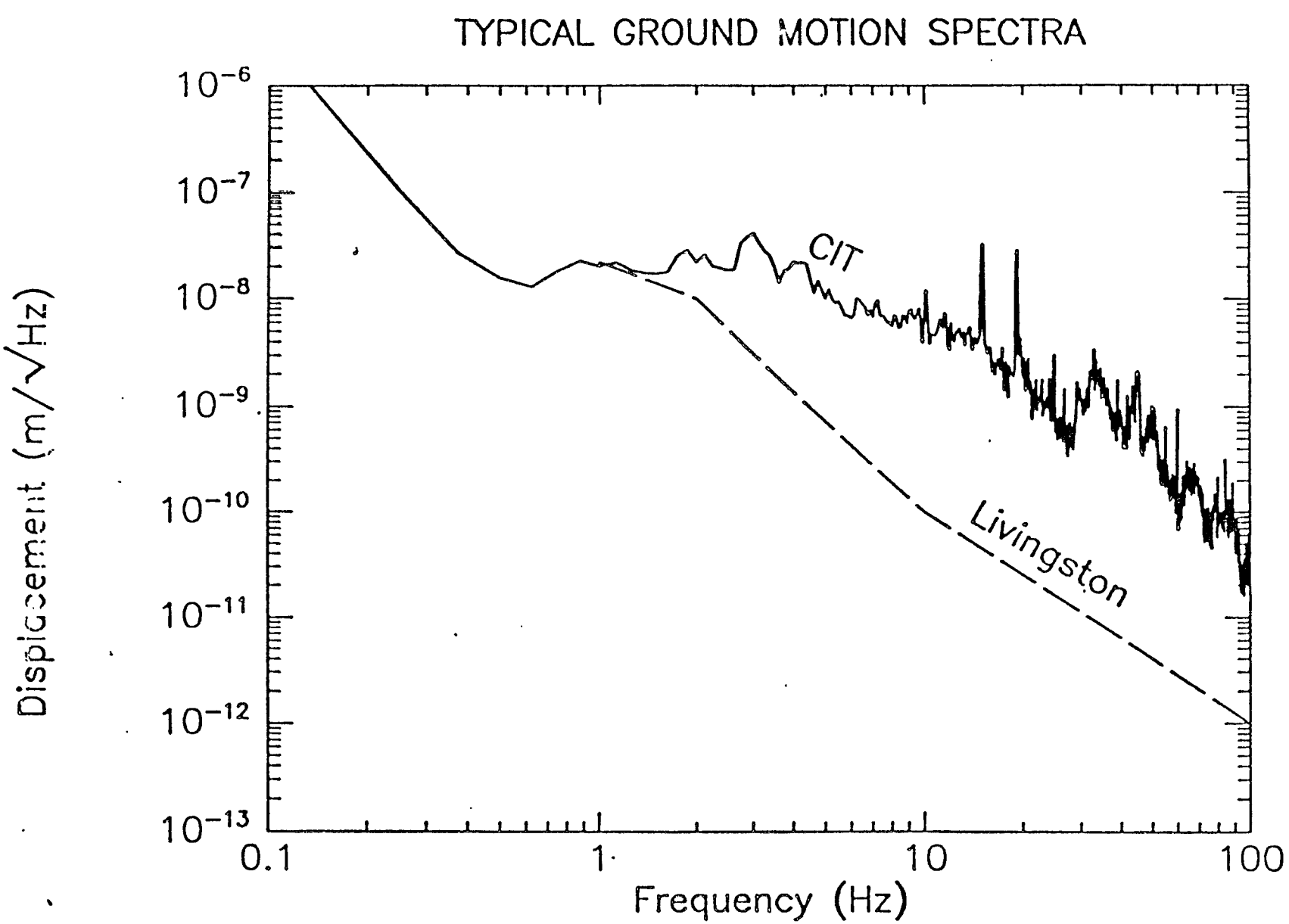

Displacement Sensitivity of 40–Meter Interferometer
Noise Model (9/15/94)
5/94 data
shot + thermal model
shot noise
test mass vibrations
seismic noise limit
S
S
L
L
L
L
L
L
W
W
W
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
x (m/Hz$^{1/2}$)
100
1000
Frequency (Hz)
mk2theory2

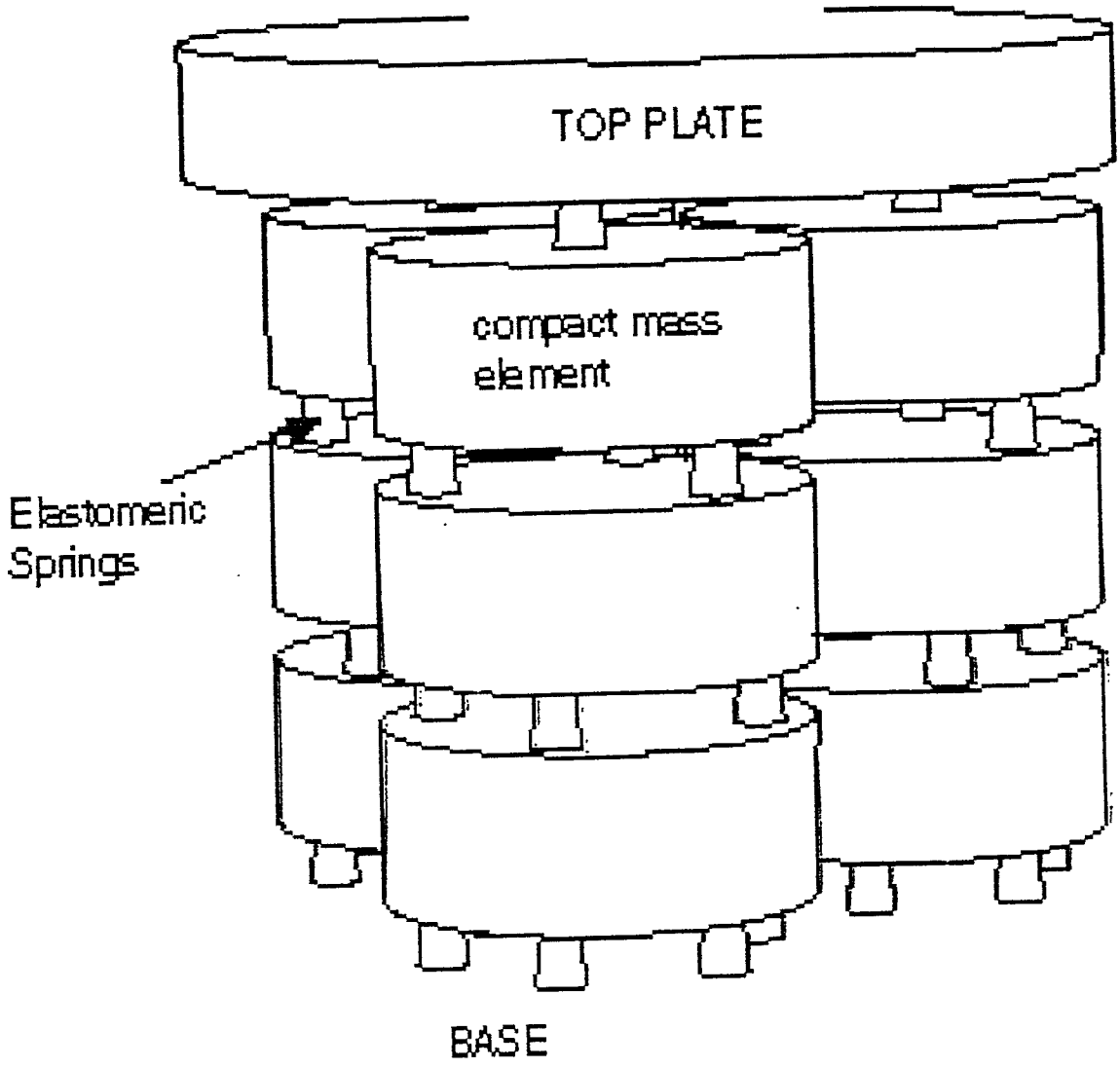
LIGO

40m Prototype

- Measured noise spectrum compared with known broadband sources of noise

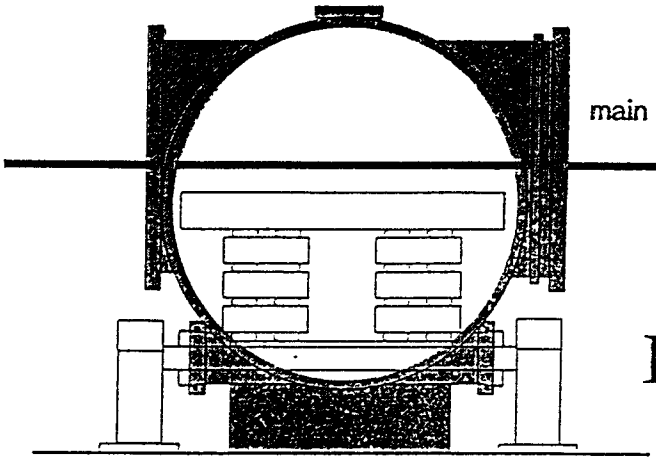



TYPICAL GROUND MOTION SPECTRA
Displacement (m/√Hz)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
0.1
1
10
100
Frequency (Hz)
CIT
Livingston

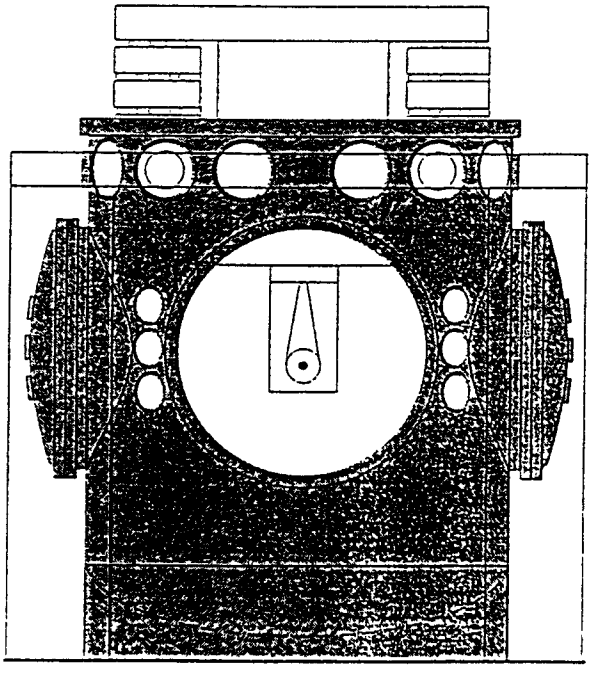


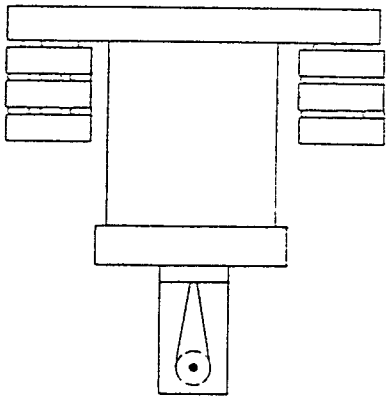
PROTOTYPE ISOLATION STACK

SEI Configuration

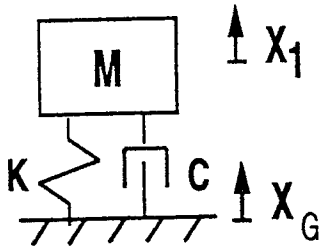


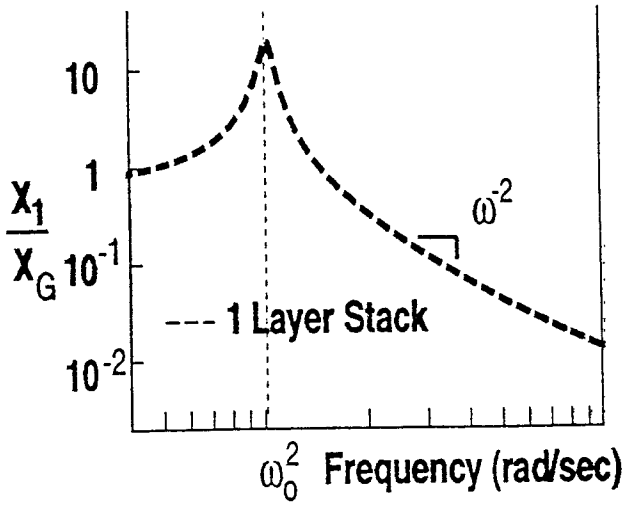
HAM

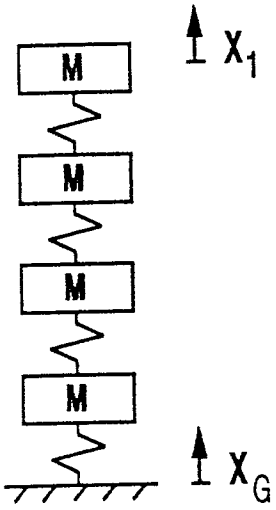




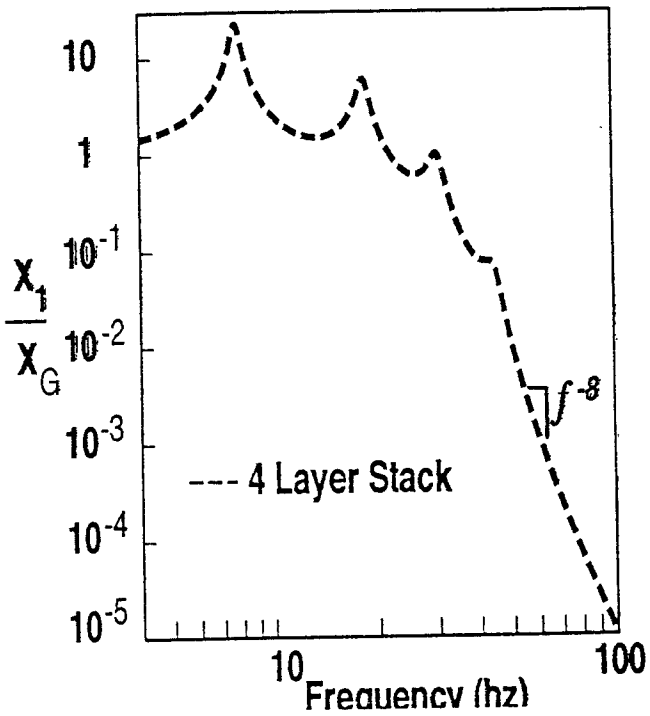
LOC





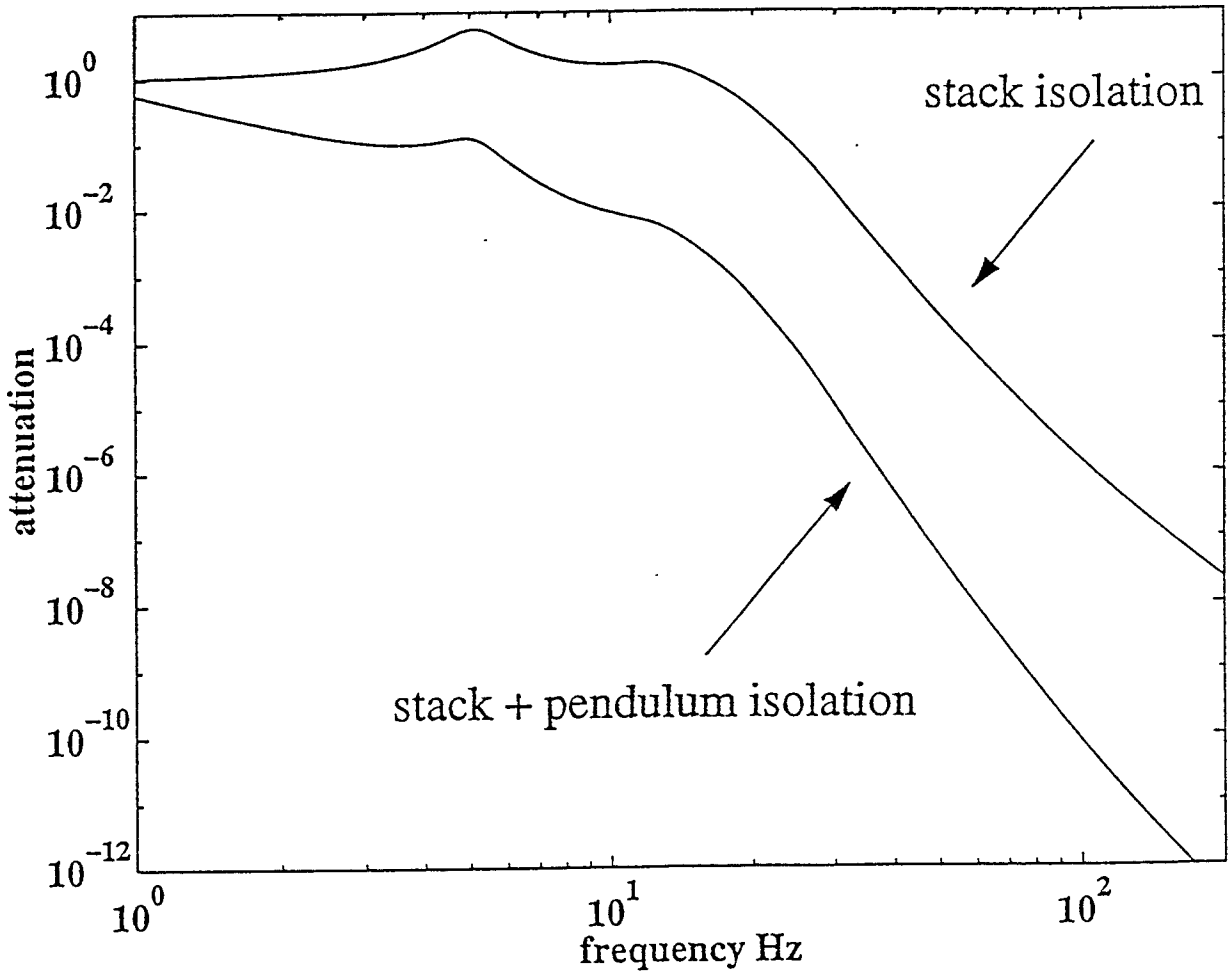


Simple Model of Mark 2
Stack Isolation (vertical)



PASSIVE ISOLATION CONCEPT

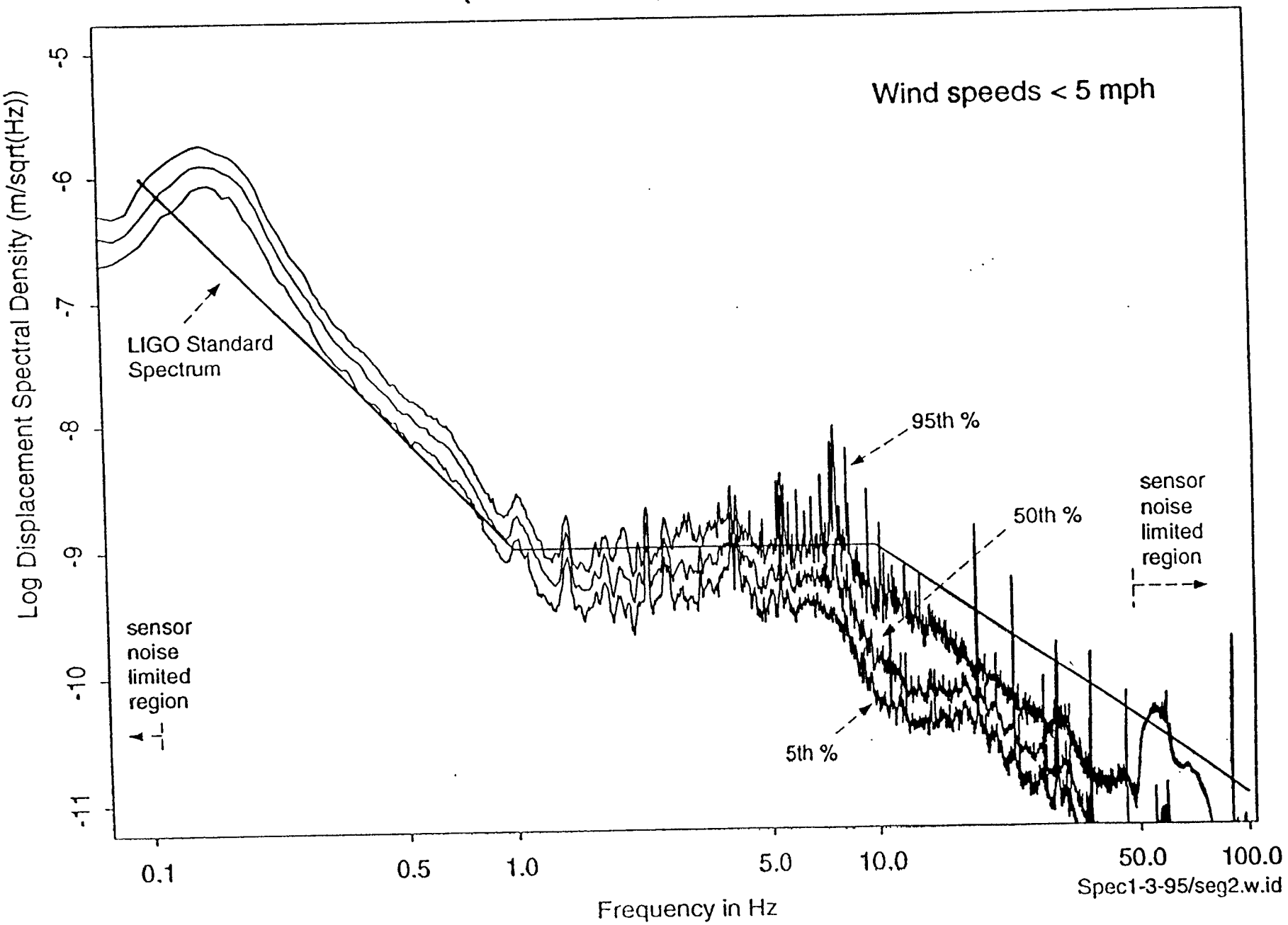
Baseline Isolation Performance



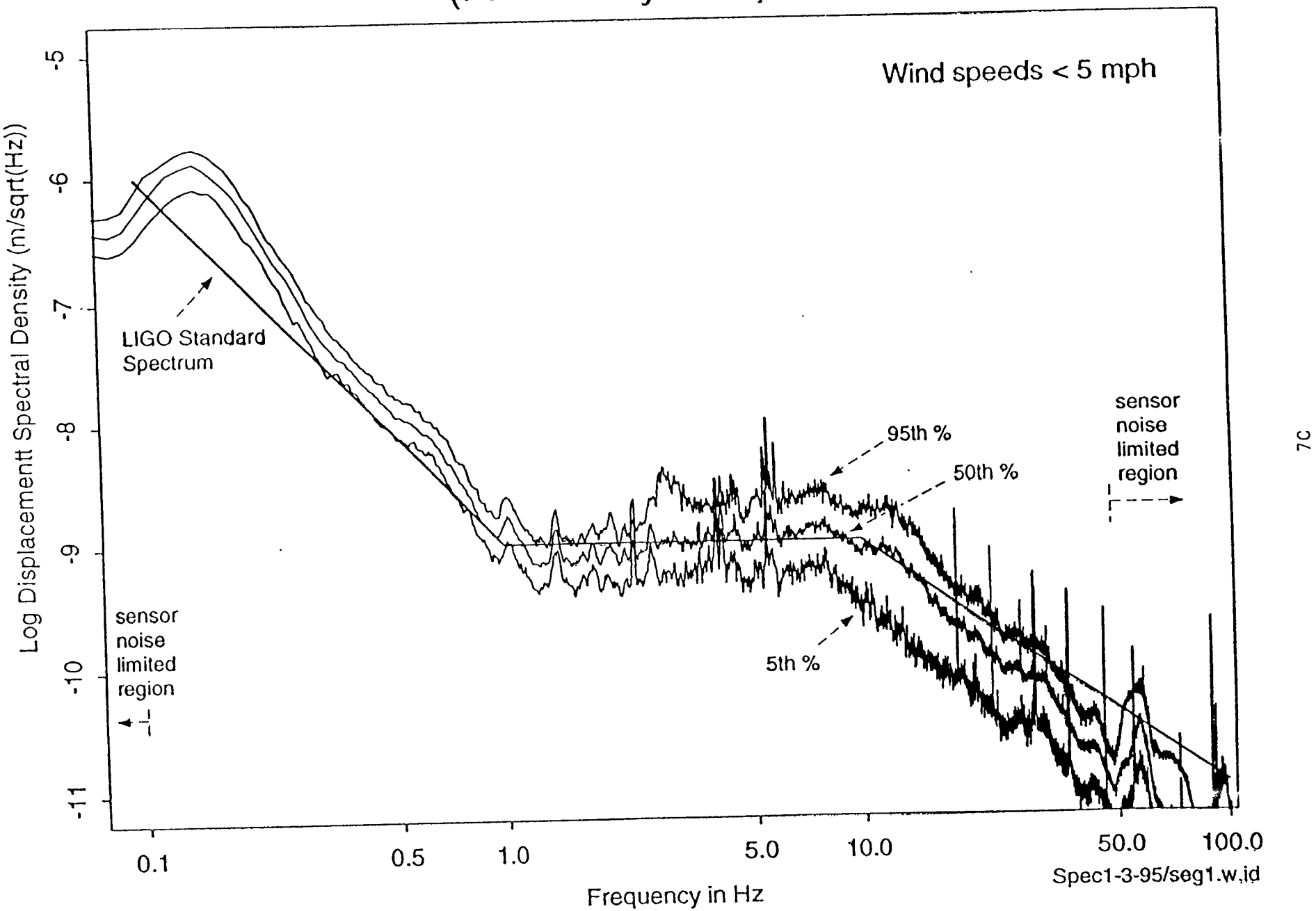
- Displacement noise 10^{-21} m/rHz @ 100 Hz

LIGO

Hanford Corner Station SW Arm Axis, Late Night December 12,1994
(Preliminary Data)



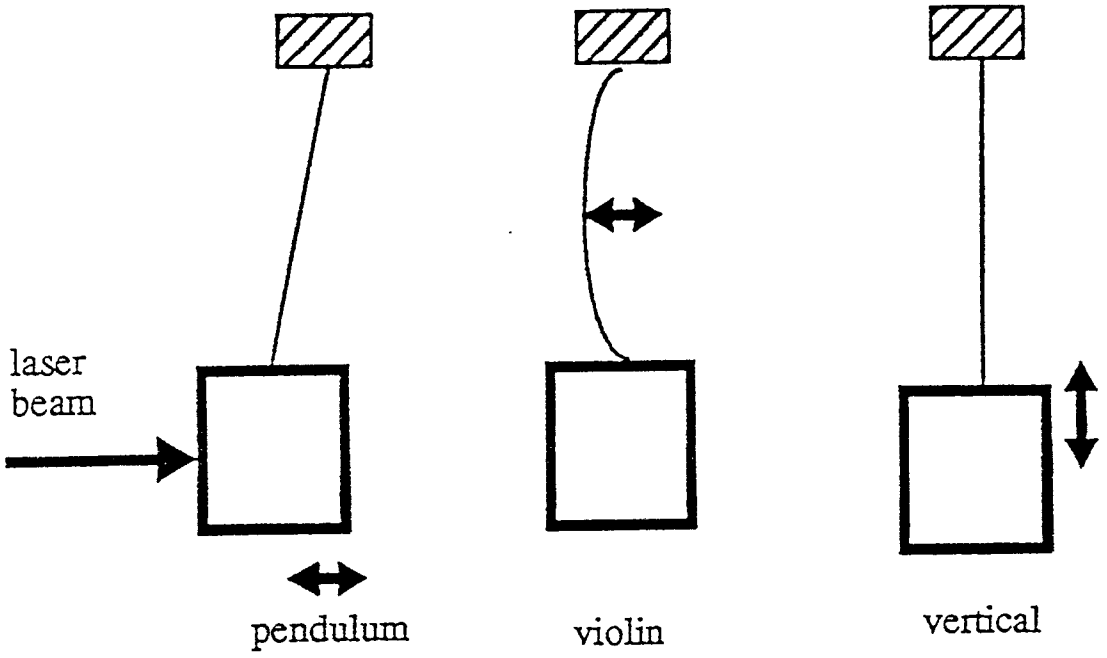
Hanford Corner Station SW Arm Axis, Morning Traffic December 13,1994
(Preliminary Data)



7c

Interferometers

Mechanical Thermal Noise

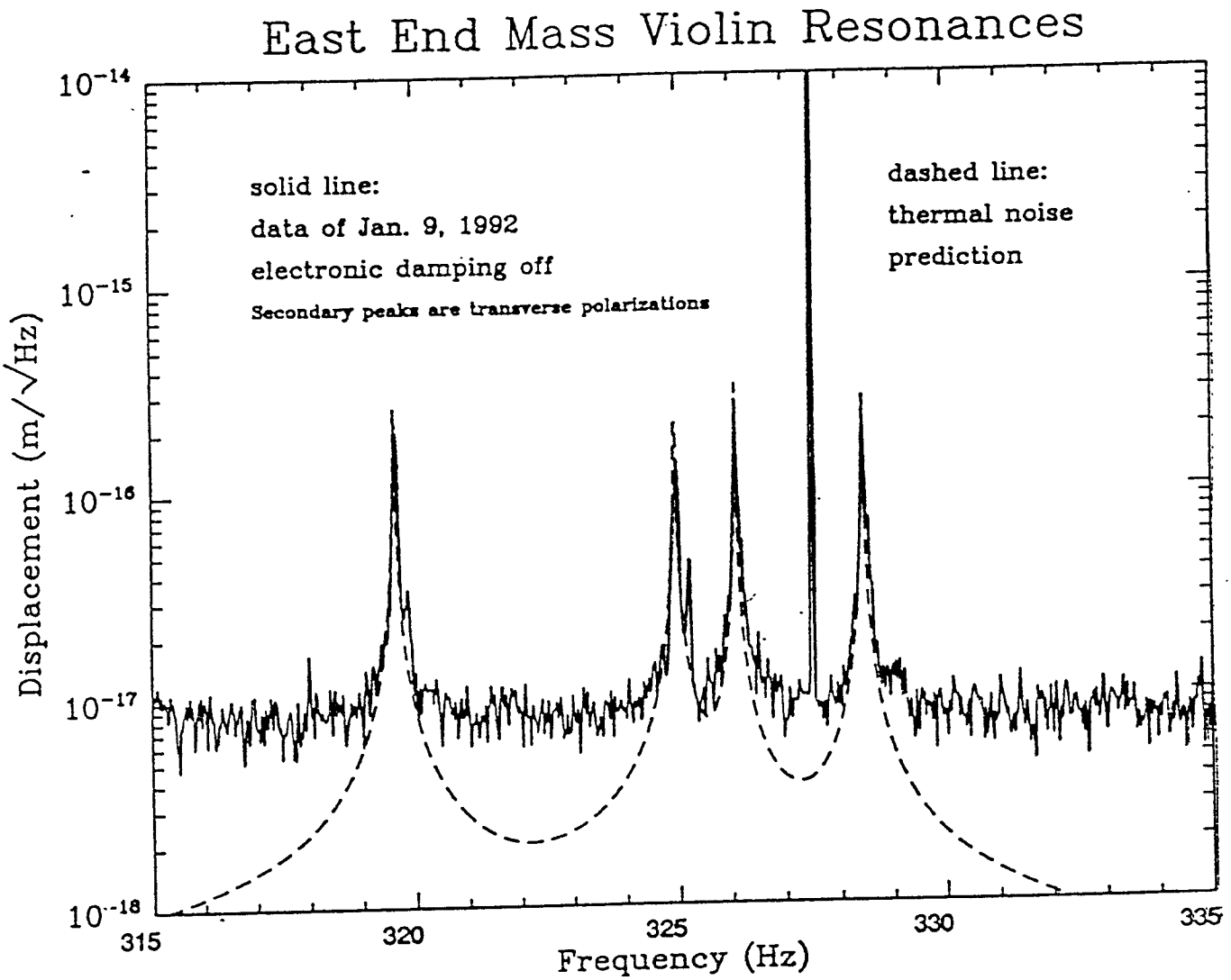


- pendulum noise
  - » $x_{rms} \sim 10^{-11}$ m, $f_0 \sim 1$ Hz
- violin mode
  - » $x_{rms} \sim 5\ 10^{-17}$m; $f_{0n} \sim 600n$ Hz
- test mass vibrational mode
  - » $x_{rms} \sim 5\ 10^{-16}$m, $f_0 > 10$ kHz

LIGO

Suspension Thermal Noise

Observation of Thermal Noise in Violin Modes of 40–m Test Mass Suspensions

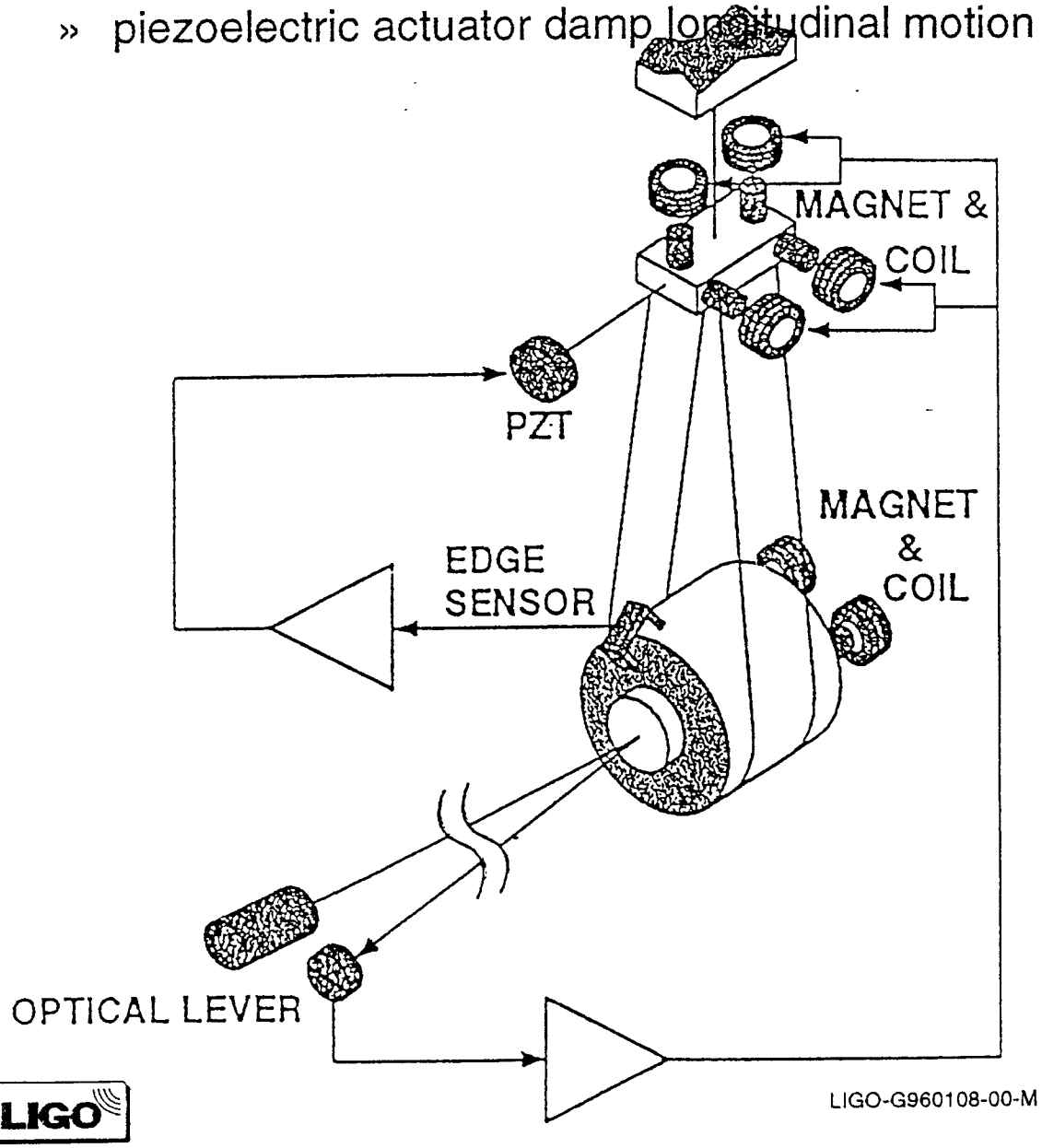


LIGO

LIGO

Suspended Test Mass

- 40 m prototype design
- **Pendulum suspension of test mass**
  - » magnetic/coil actuators damp angular motion
  - » piezoelectric actuator damp longitudinal motion

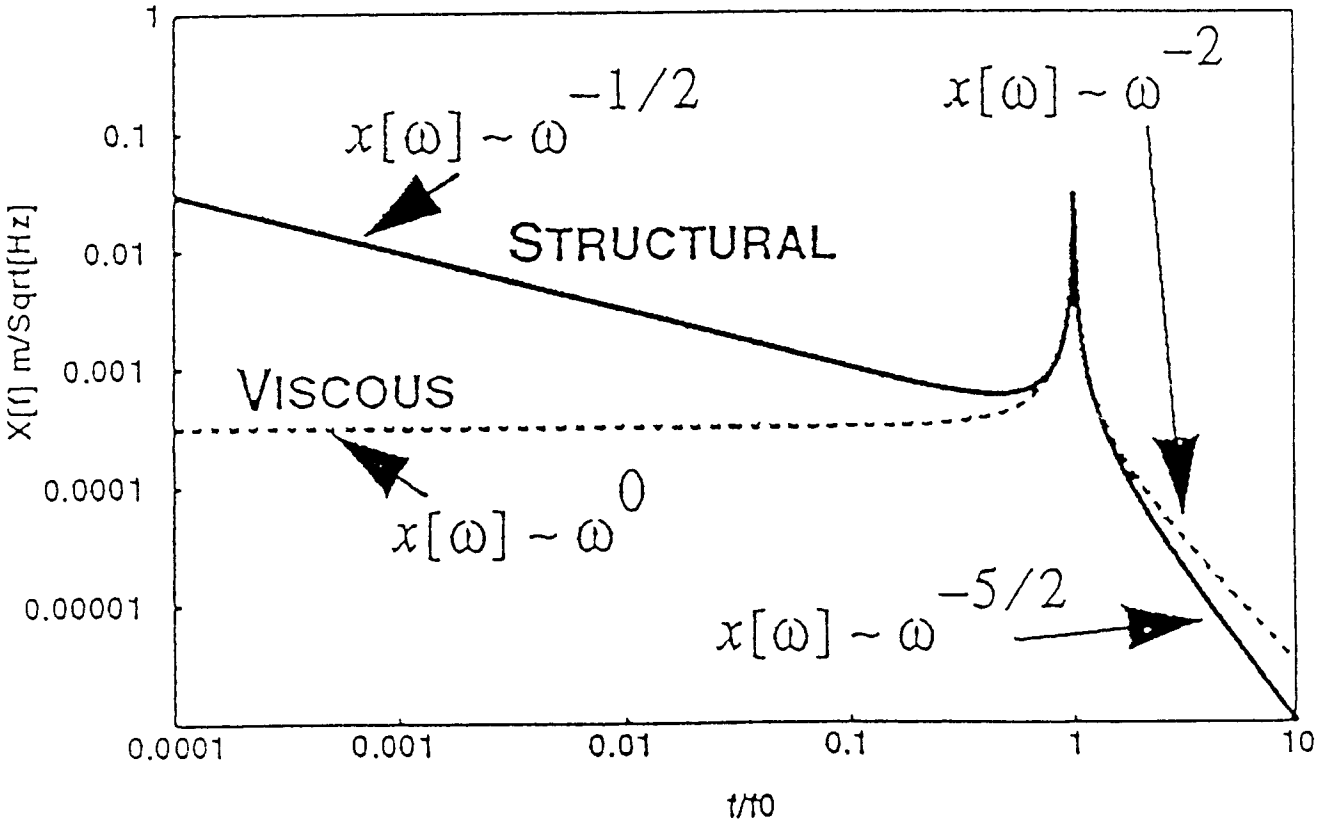


LIGO

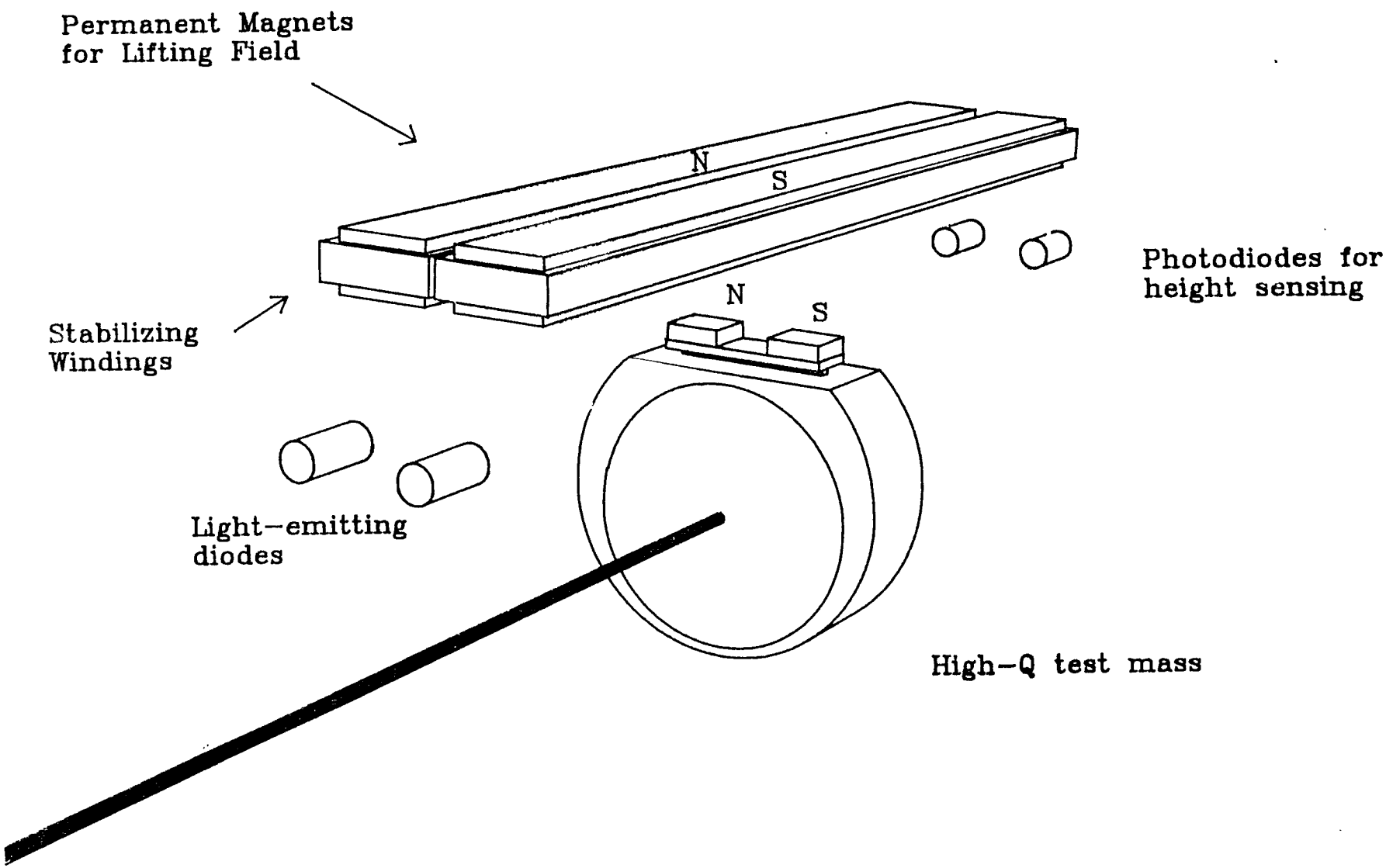
LIGO

Test Masses

- Monollithic fused silica (Q > 10^6)
- Internal resonance ~ 30 kHz
- structural vs viscous damping



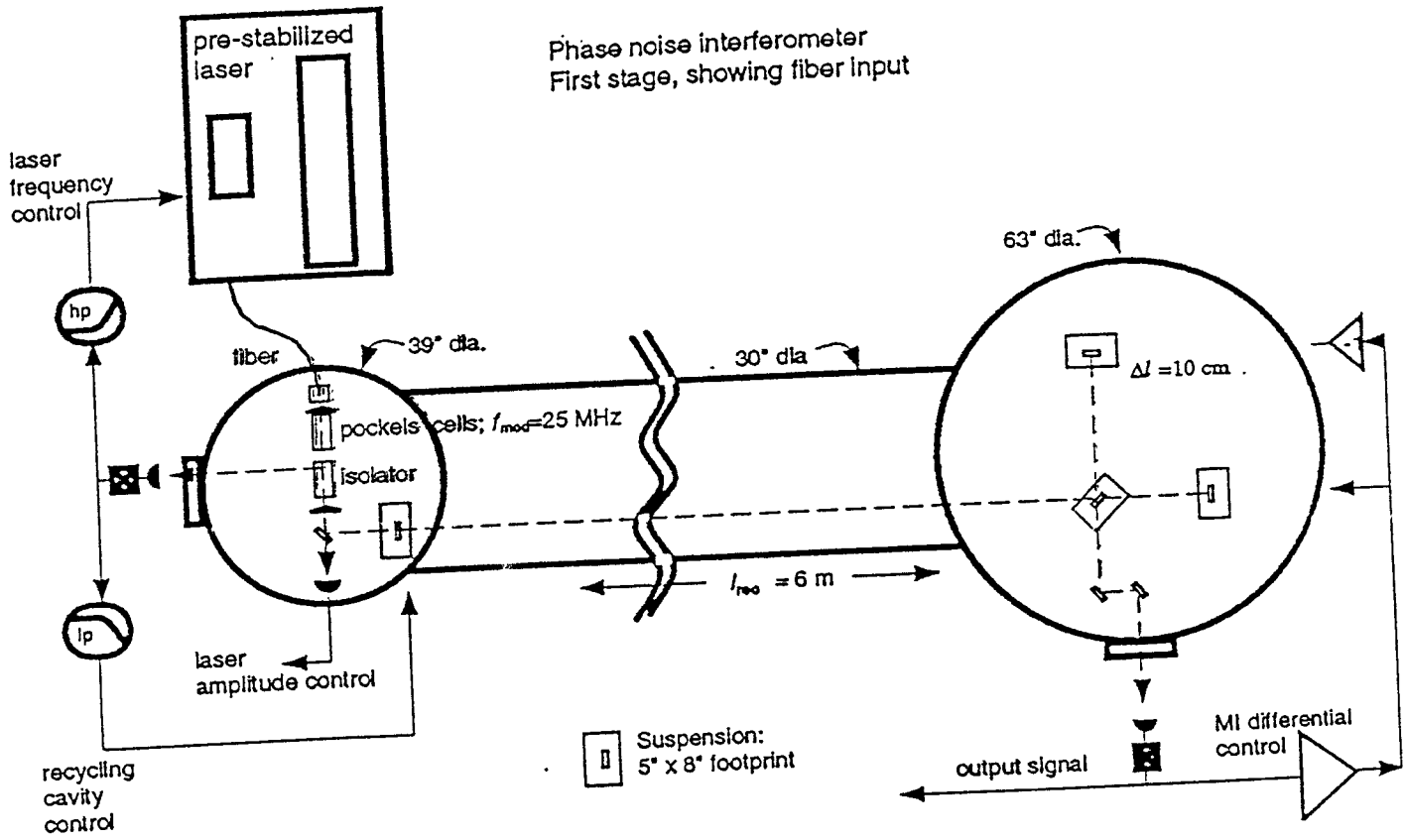
Magnetically Levitated Test Mass



LIGO

Phase Noise

- Phase Noise Interferometer (MIT)
  - » 70 W - recycled configuration
  - » demonstrate phase sensitivity for LIGO



Shot Noise

$$\delta h(f) \approx \frac{1}{L}\left(\frac{\partial \phi}{\partial x}(f)\right)^{-1} \delta\phi(f)$$

PROPERTY OF INTERFEROMETER OPTICAL CONFIGURATION (MIRROR R's, ETC.)

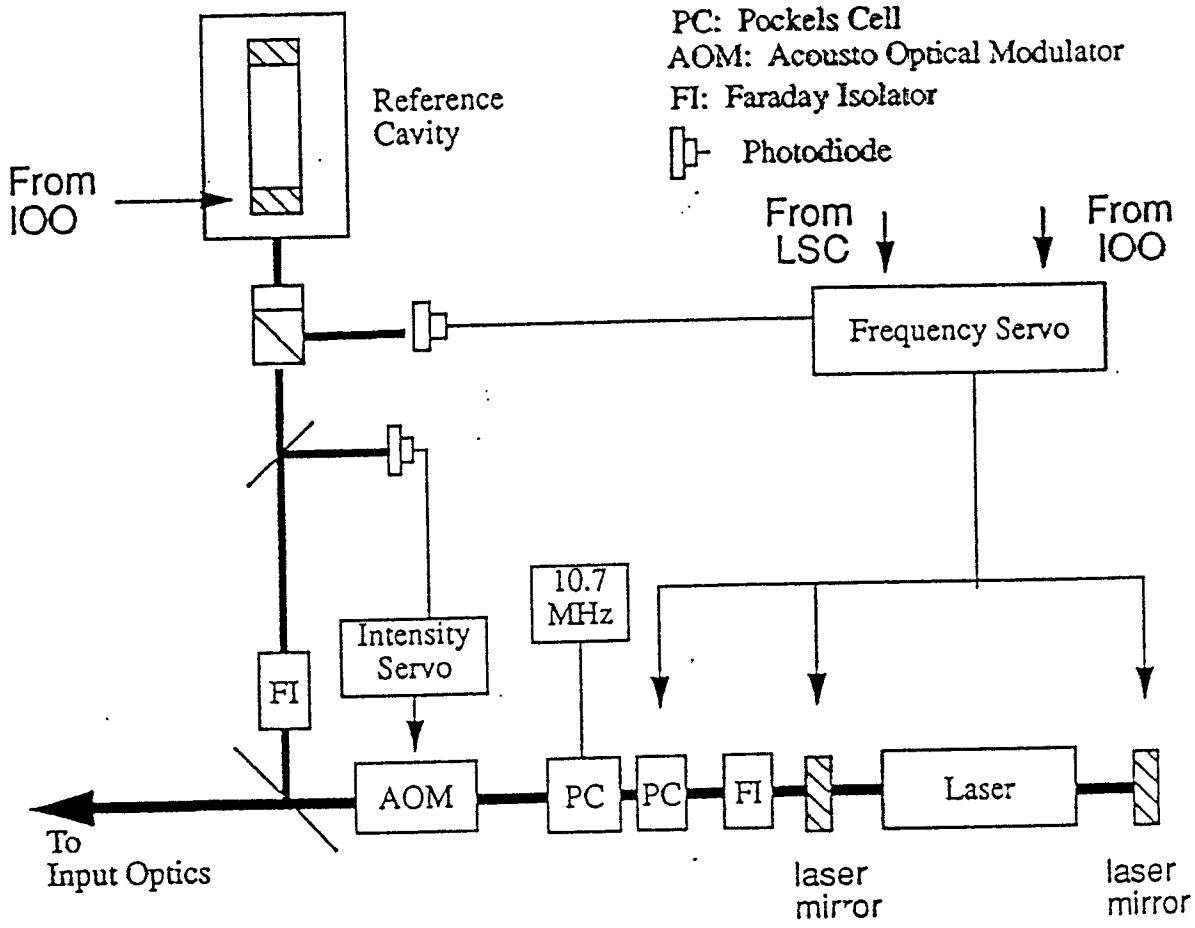
DETERMINED PRIMARILY BY EFFECTIVE OPTICAL POWER

- Achieving Shot-Noise Limited Phase Sensitivity Requires Understanding and Control of All Other Optical Sources of Noise
  - Laser Noise
  - Photodiode Uniformity
  - Modulator-Induced Noise
  - Scattered Light

LIGO Requirement	$10^{-10}\ \mathrm{rad}/\sqrt{\mathrm{Hz}}$
Current 40-m Interferometer	$10^{-8}\ \mathrm{rad}/\sqrt{\mathrm{Hz}}$
MPQ Garching	$10^{-9}\ \mathrm{rad}/\sqrt{\mathrm{Hz}}$

LIGO

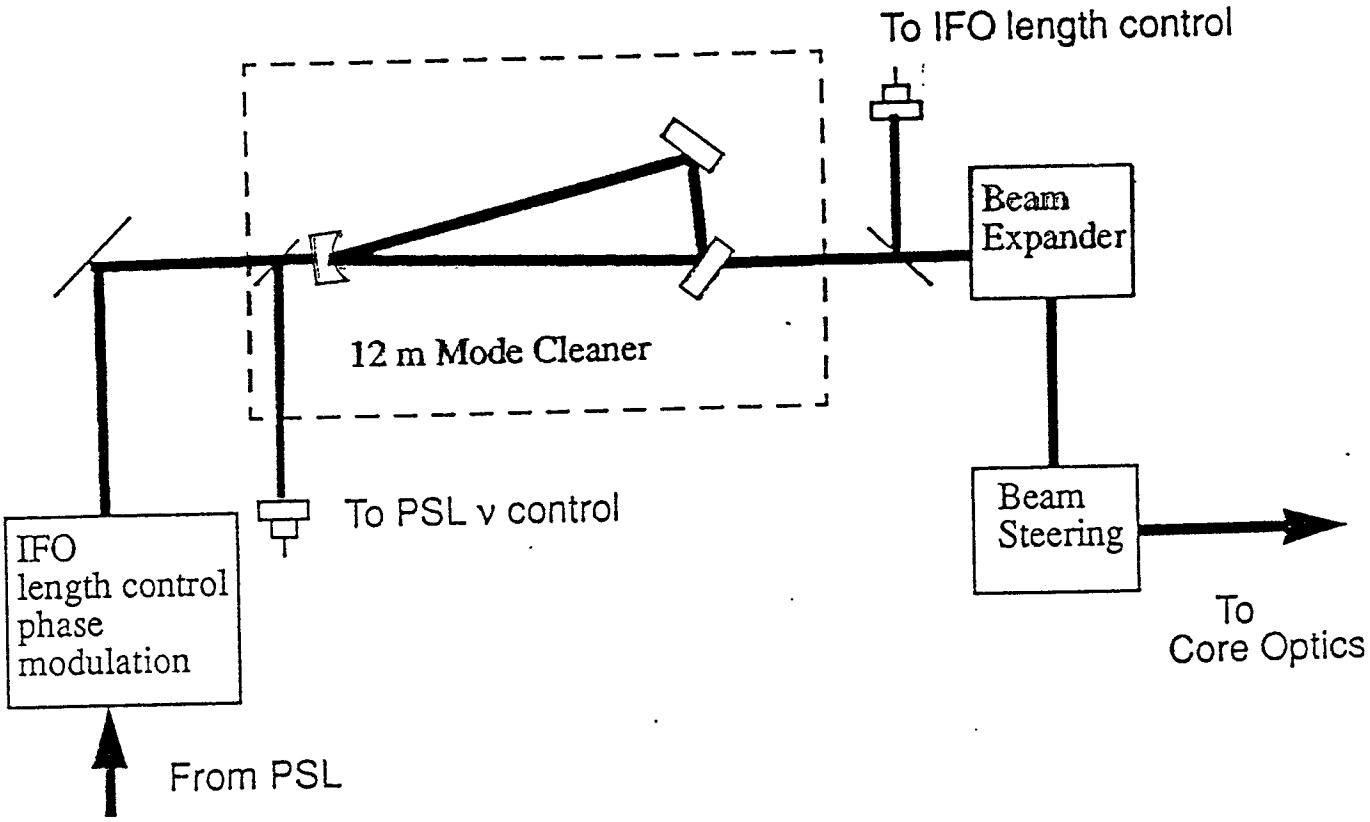
Prestabilized Laser (PSL)



- Power Stabilization $\Delta P / P \sim 10^{-7} / \sqrt{Hz}$
- Frequency Stabilization $\Delta f / f \sim 10^{-15} / \sqrt{Hz}$
- Status: Working LIGO subsystem
  - >>DRR, PDR complete

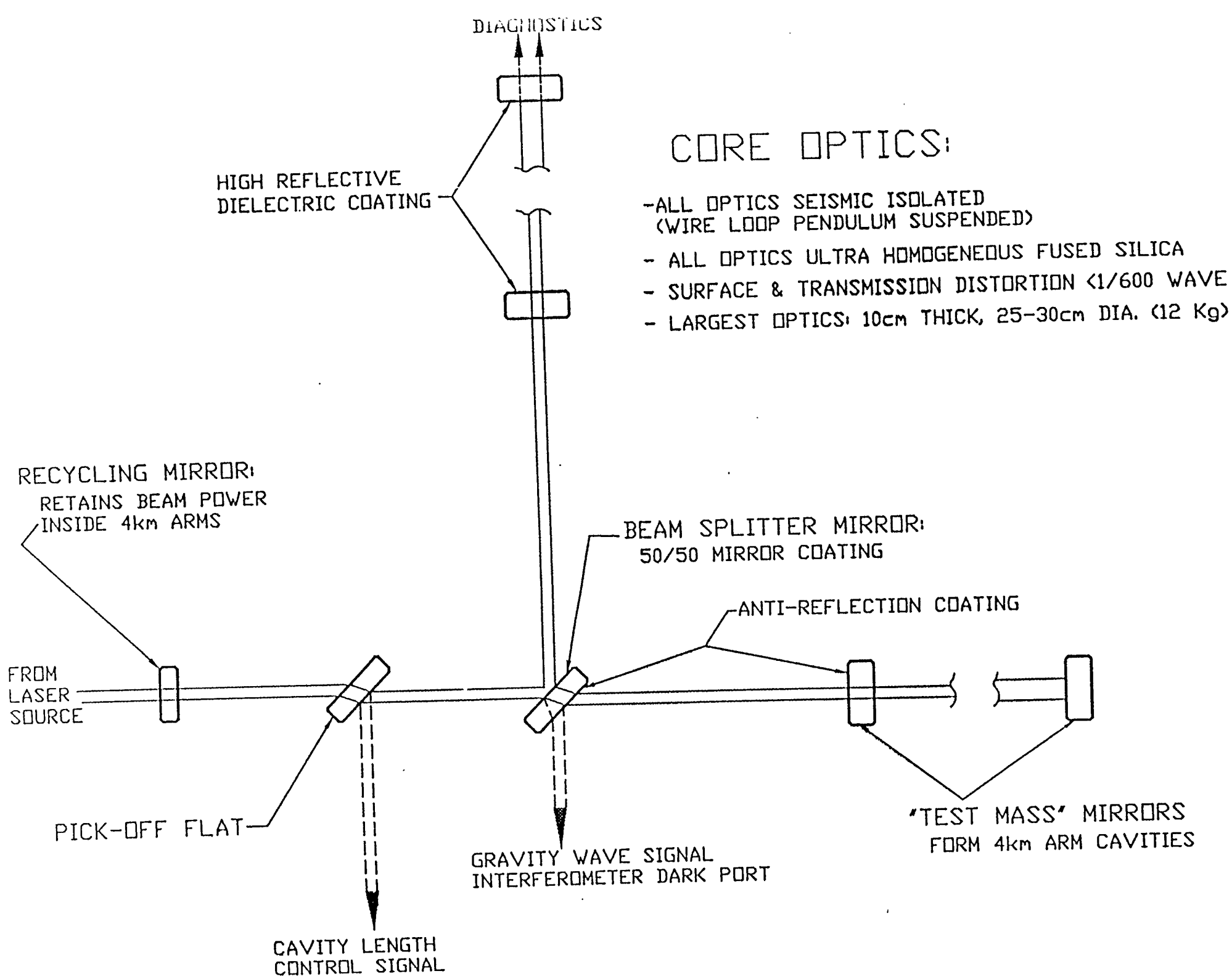
LIGO

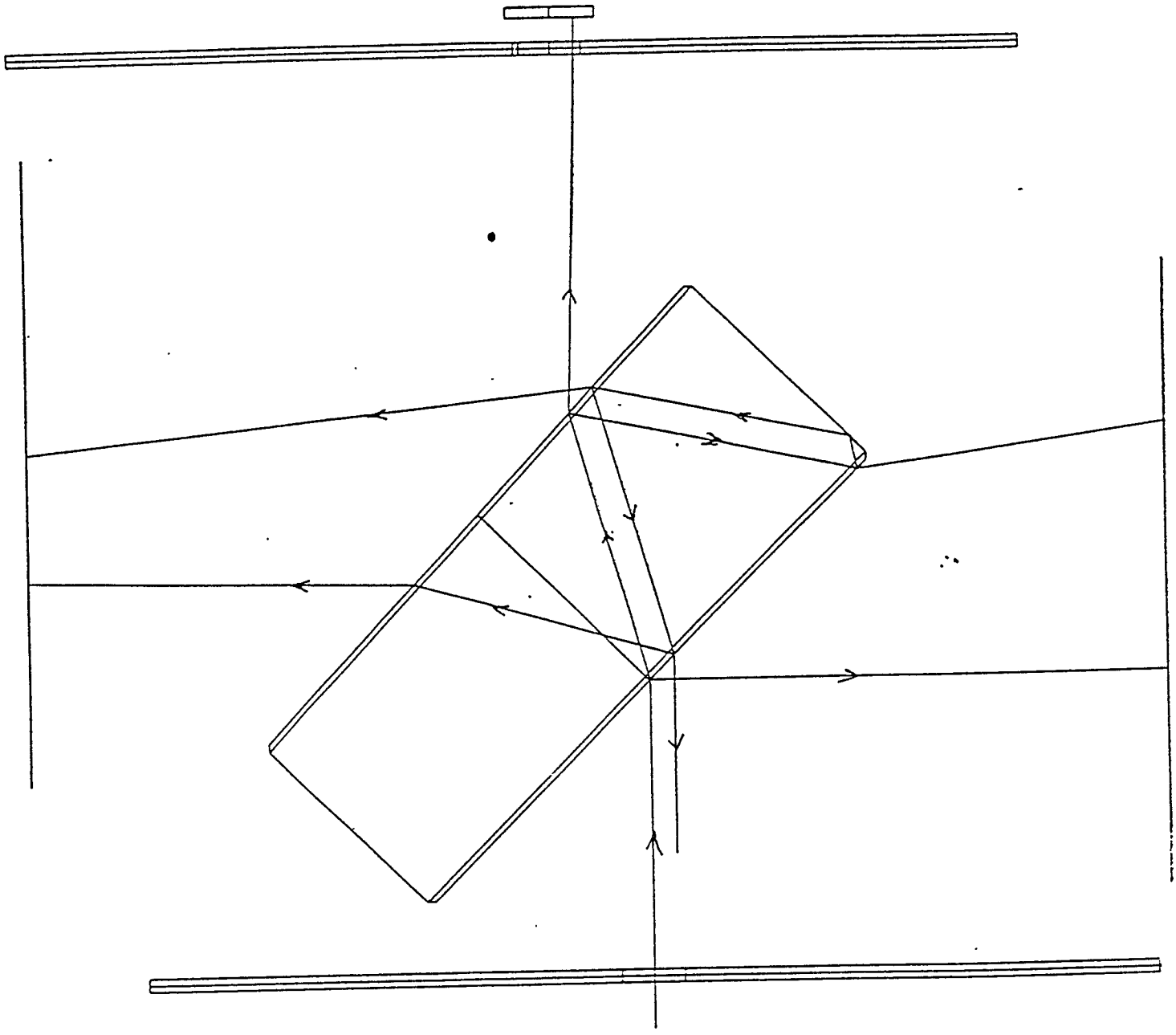
Input Optics

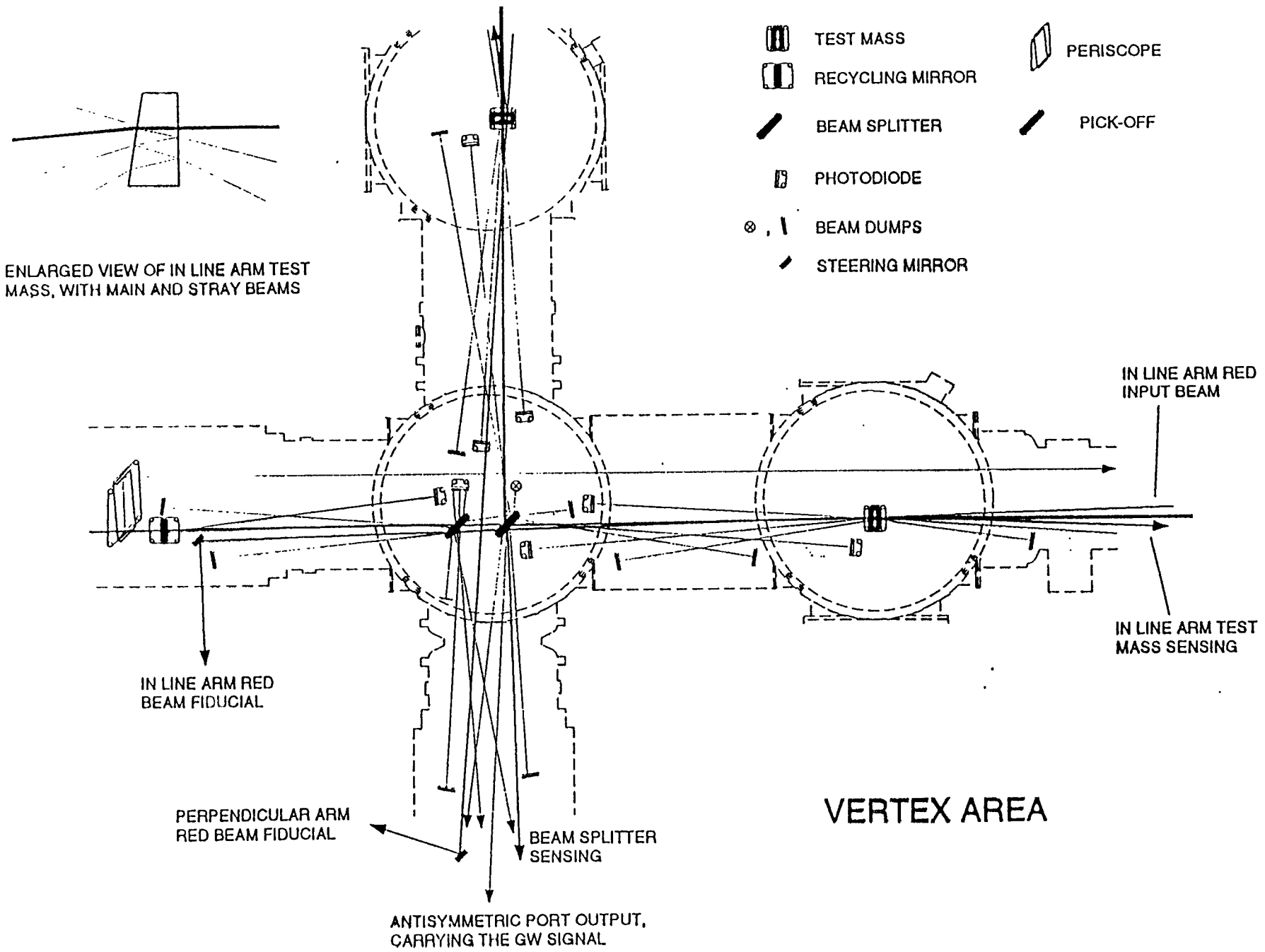


- Phase modulation for IFO length control
- 12 m Mode Cleaner
  - ›› Reduces pointing jitter $\Delta\theta_{out} / \Delta\theta_{in} \sim 10^{-3}$
  - ›› Additional frequency stabilization $\Delta f / f \sim 10^{-18} / \sqrt{\text{Hz}}$
- Mode matching, beam steering to Core Optics
- Status: Conceptual Design Phase

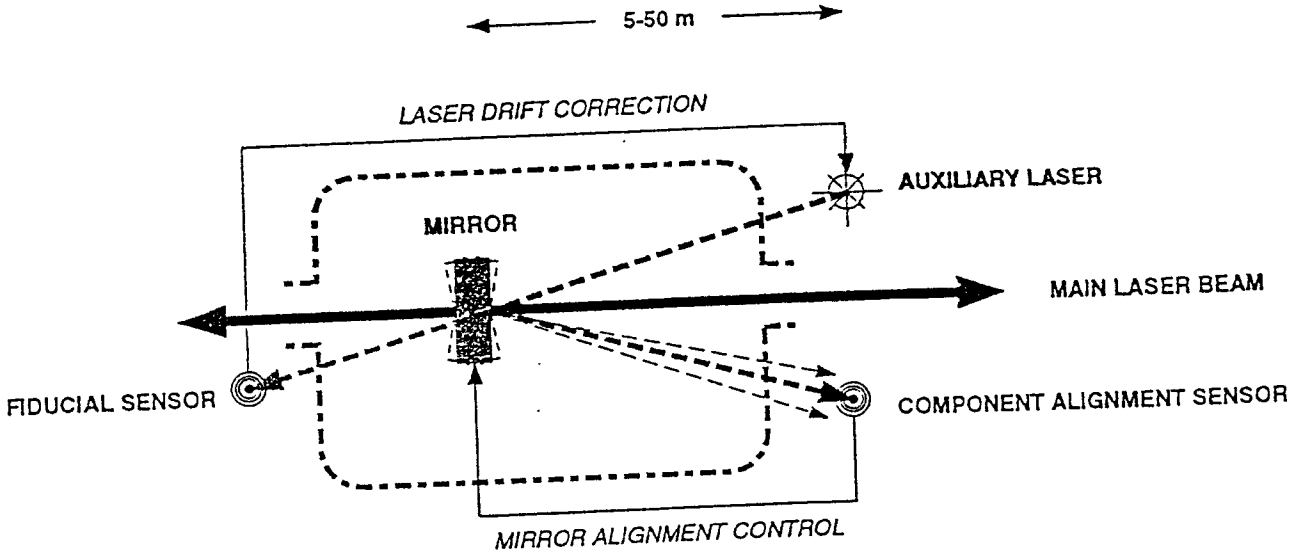
LIGO

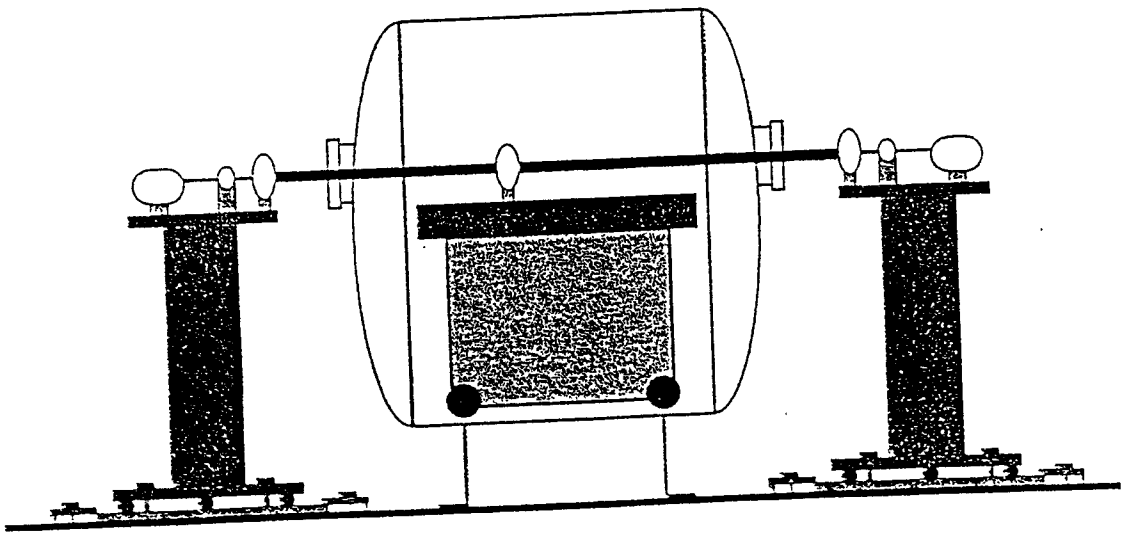

DIAGNOSTICS
HIGH REFLECTIVE
DIELECTRIC COATING
CORE OPTICS:
-ALL OPTICS SEISMIC ISOLATED
(WIRE LOOP PENDULUM SUSPENDED)
- ALL OPTICS ULTRA HOMOGENEOUS FUSED SILICA
- SURFACE & TRANSMISSION DISTORTION <1/600 WAVE
- LARGEST OPTICS: 10cm THICK, 25-30cm DIA. (12 Kg)
RECYCLING MIRROR:
RETAINS BEAM POWER
INSIDE 4km ARMS
BEAM SPLITTER MIRROR:
50/50 MIRROR COATING
ANTI-REFLECTION COATING
FROM
LASER
SOURCE
PICK-OFF FLAT
GRAVITY WAVE SIGNAL
INTERFEROMETER DARK PORT
"TEST MASS" MIRRORS
FORM 4km ARM CAVITIES
CAVITY LENGTH
CONTROL SIGNAL




TEST MASS
RECYCLING MIRROR
BEAM SPLITTER
PHOTODIODE
BEAM DUMPS
STEERING MIRROR
PERISCOPE
PICK-OFF
ENLARGED VIEW OF IN LINE ARM TEST MASS, WITH MAIN AND STRAY BEAMS
IN LINE ARM RED INPUT BEAM
IN LINE ARM TEST MASS SENSING
IN LINE ARM RED BEAM FIDUCIAL
PERPENDICULAR ARM RED BEAM FIDUCIAL
BEAM SPLITTER SENSING
ANTISYMMETRIC PORT OUTPUT, CARRYING THE GW SIGNAL
VERTEX AREA

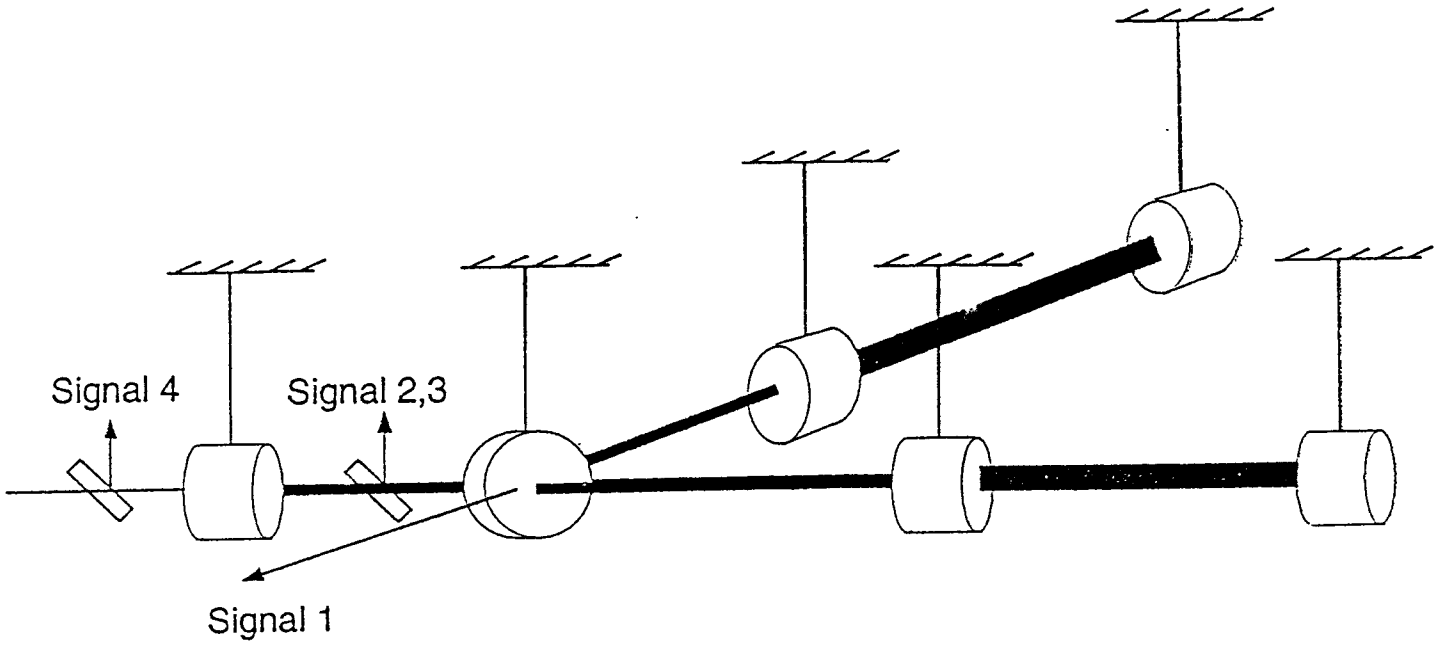
Three-Point Optical Lever





LIGO

Length Sensing/Control System



LIGO Recycled/Recombined Interferometer

- 4 signals used for controlling 4 degrees of freedom
- Important degrees of freedom: 2 arm cavity lengths and 2 recycling cavity lengths

Control Design for 2 Modes of Operation

- Operations Mode (linear dynamic model)
- Lock Acquisition (highly nonlinear dynamic model)

Model Development for Control Design

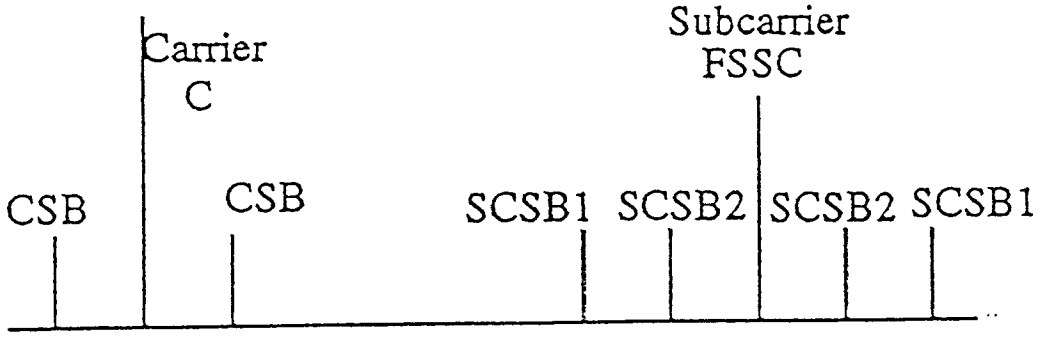
- Operations Mode model complete
- Acquisition Mode model complete for coupled cavity interferometer

LIGO

Length Sensing

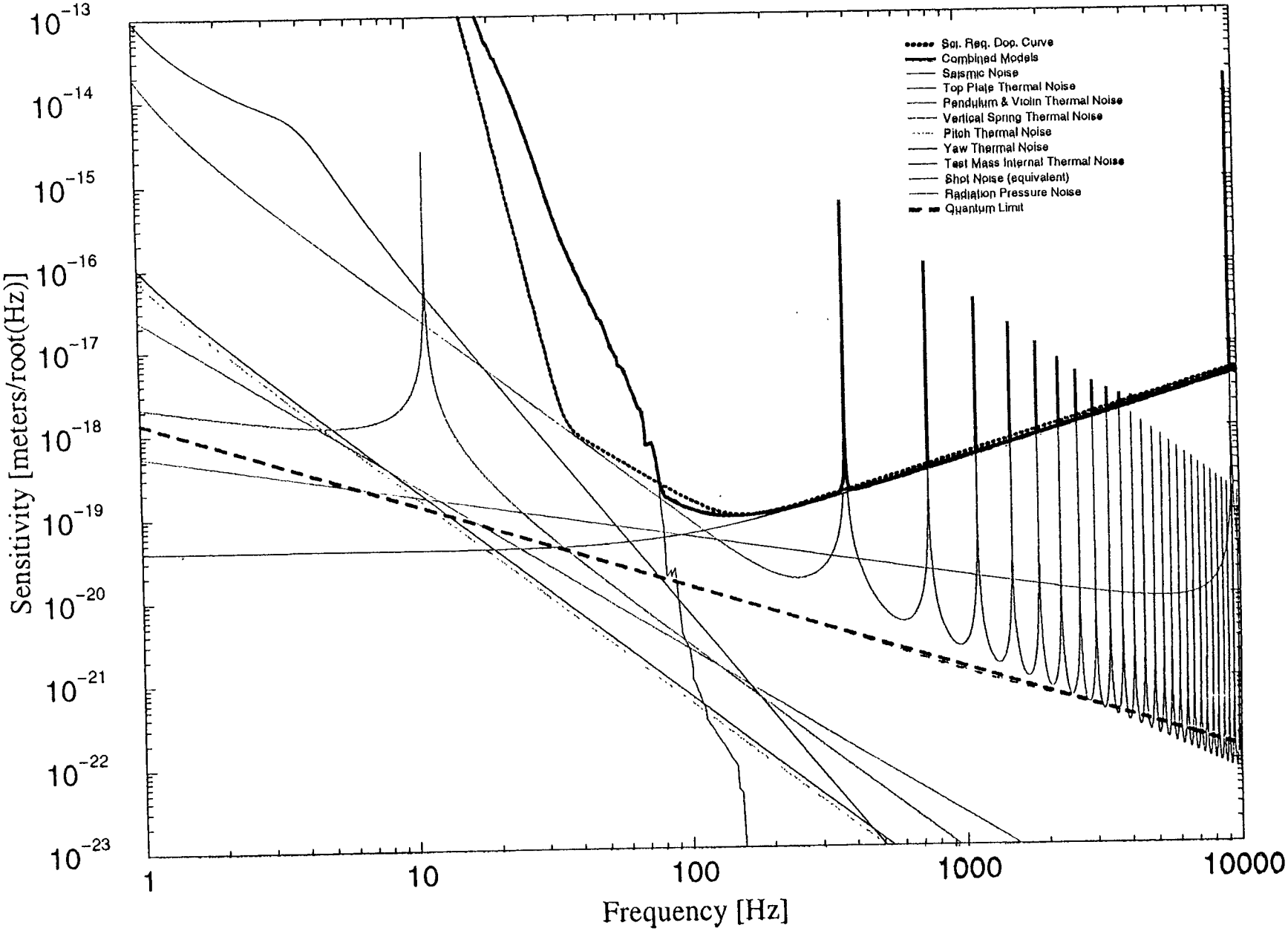
- Signals sensitive to length degrees of freedom

INTERFERING FIELDS	SIGNAL LOCATION	DEGREE OF FREEDOM
C and CSB	anti-symmetric port	L_1-L_2, differential arm cavity length
C and CSB	reflected from recycling mirror	L_1+L_2, common mode arm cavity length
FSSC and SCSB1	anti-symmetric port	l_1-l_2, differential mode Michelson length
FSSC and SCSB2	reflected from recycling mirror	l_1+l_2, common mode Michelson length

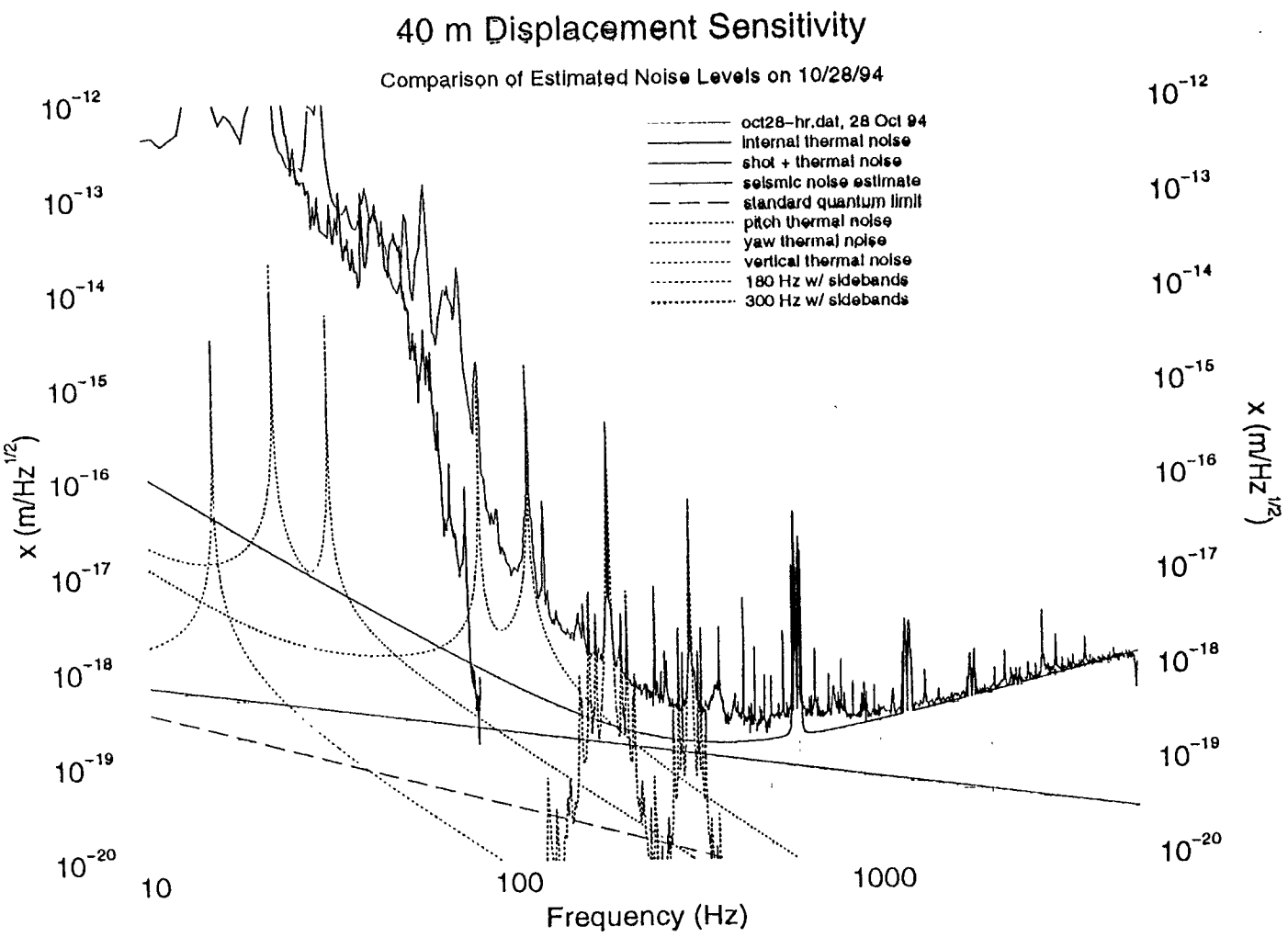


Initial LIGO Noise Sources

(April 8th 1996 Parameter Set)

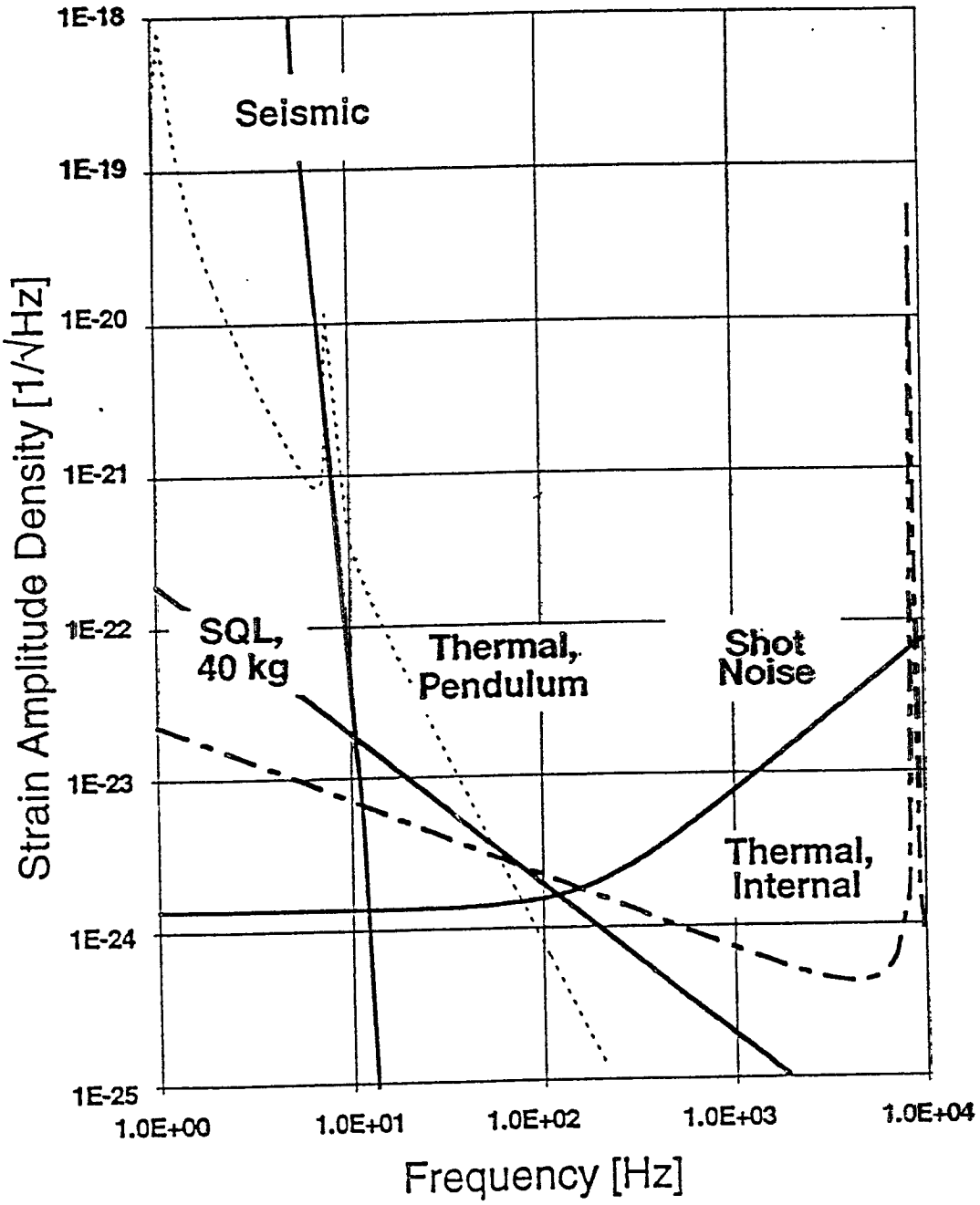


40 m Lab


40 m Displacement Sensitivity
Comparison of Estimated Noise Levels on 10/28/94
oct28-hr.dat, 28 Oct 94
internal thermal noise
shot + thermal noise
seismic noise estimate
standard quantum limit
pitch thermal noise
yaw thermal noise
vertical thermal noise
180 Hz w/ sidebands
300 Hz w/ sidebands
x (m/Hz^1/2)
x (m/Hz^1/2)
10^-12
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
10
100
1000
Frequency (Hz)

Enhanced Interferometer

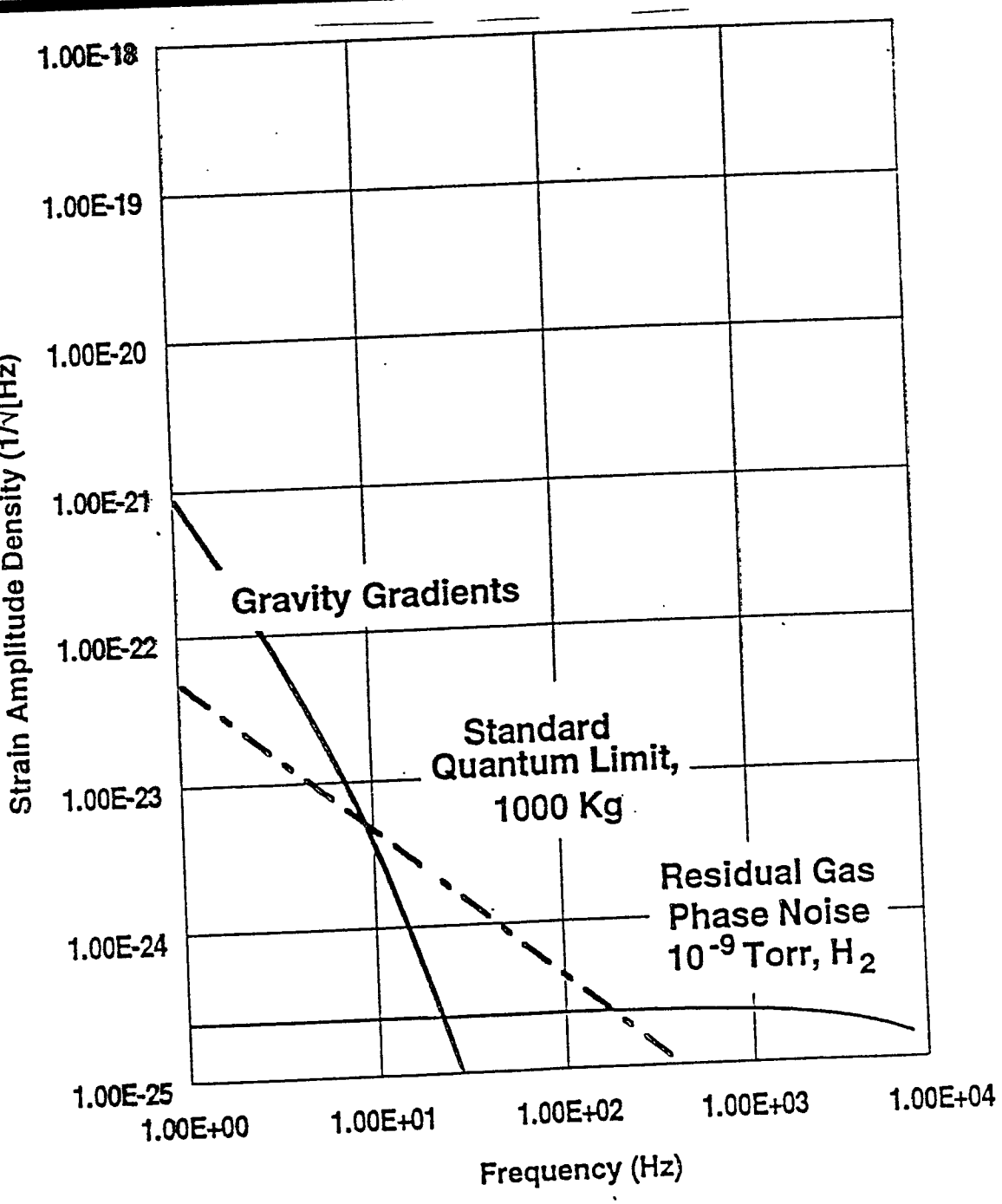
Noise Budget



LIGO

LIGO Facilities

Limiting Noise Floor



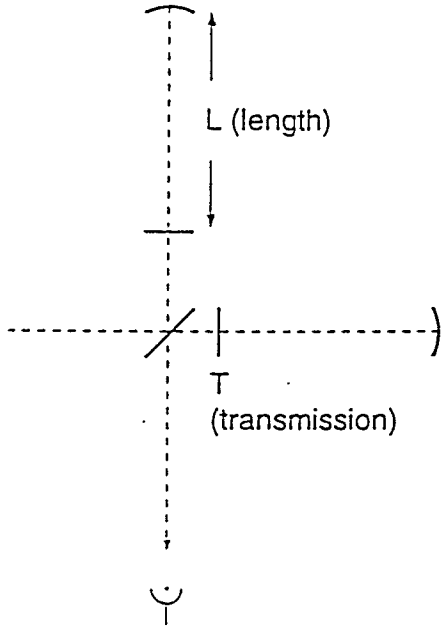
LIGO

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

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



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

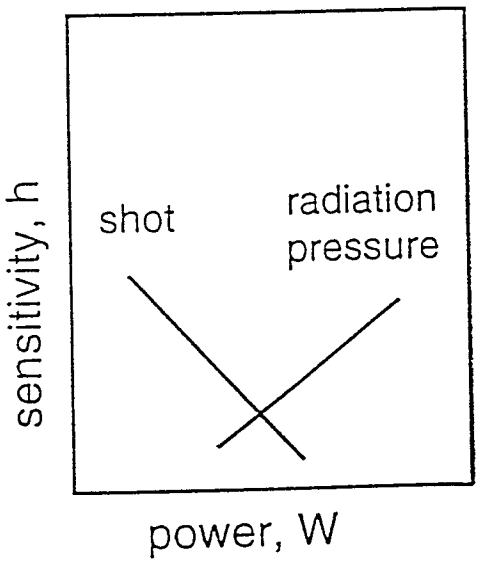
$$\tilde{h} = \frac{4}{cTLm\omega^2}\sqrt{Ph\nu}$$

- minimum for

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

- gives quantum limited sensitivity of

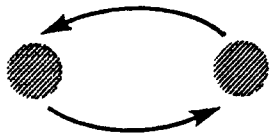
$$\tilde{h}_{\text{QL}}(f) = \frac{1}{2\pi Lf}\sqrt{\frac{4h}{\pi m}}$$



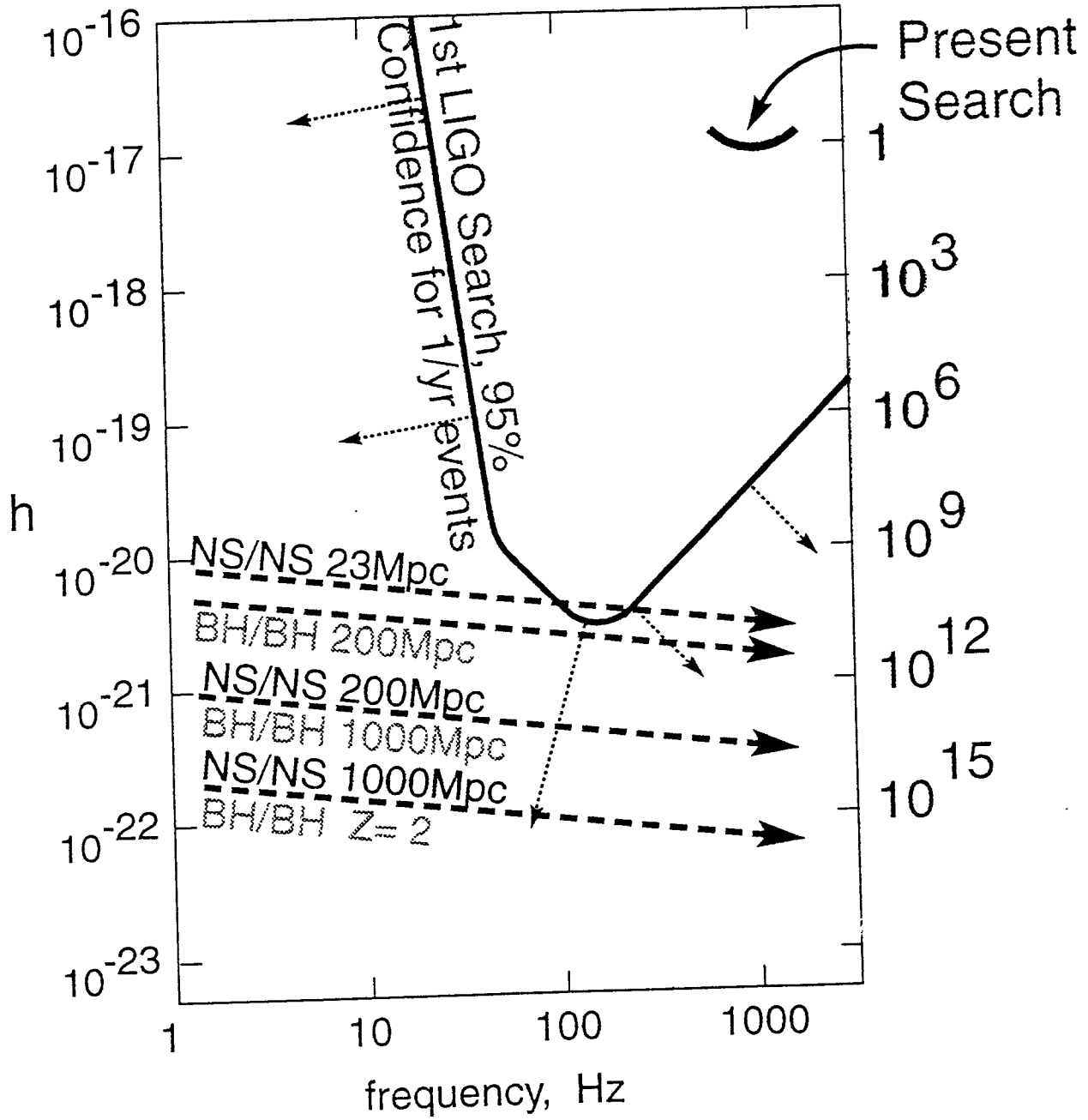
$\tilde{h}_{\text{QL}} = 5\times10^{-24}$ Hz$^{-\frac{1}{2}}$ for $L = 4$ km, $f = 100$ Hz,
$m = 10$ kg, $\lambda = 514$ nm, $P = 7$kW;
a problem for second (or third?) generation antennas.

For now, wish to maximize circulating power.

NEUTRON STAR BINARIES



["Near-Guaranteed" source]

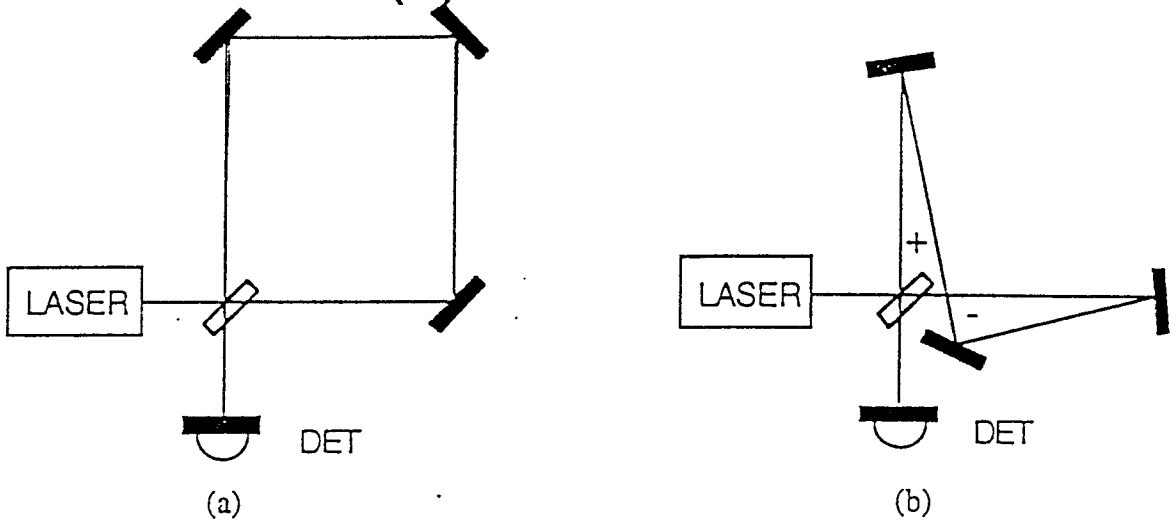


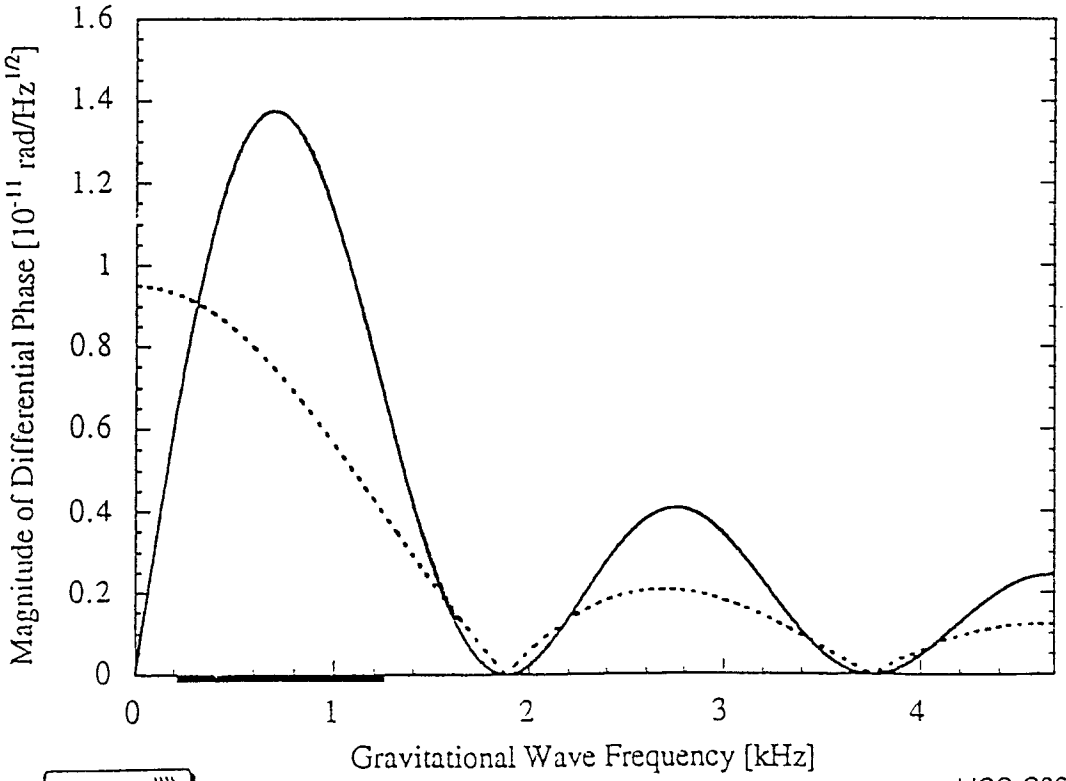
- *15 minutes &10,000 orbits in LIGO band*
- *Rich information in waveforms:*
  masses, spins, distance, direction,
  nuclear equation of state

Interferometers

Sagnac

- Stanford (b) for advanced detectors



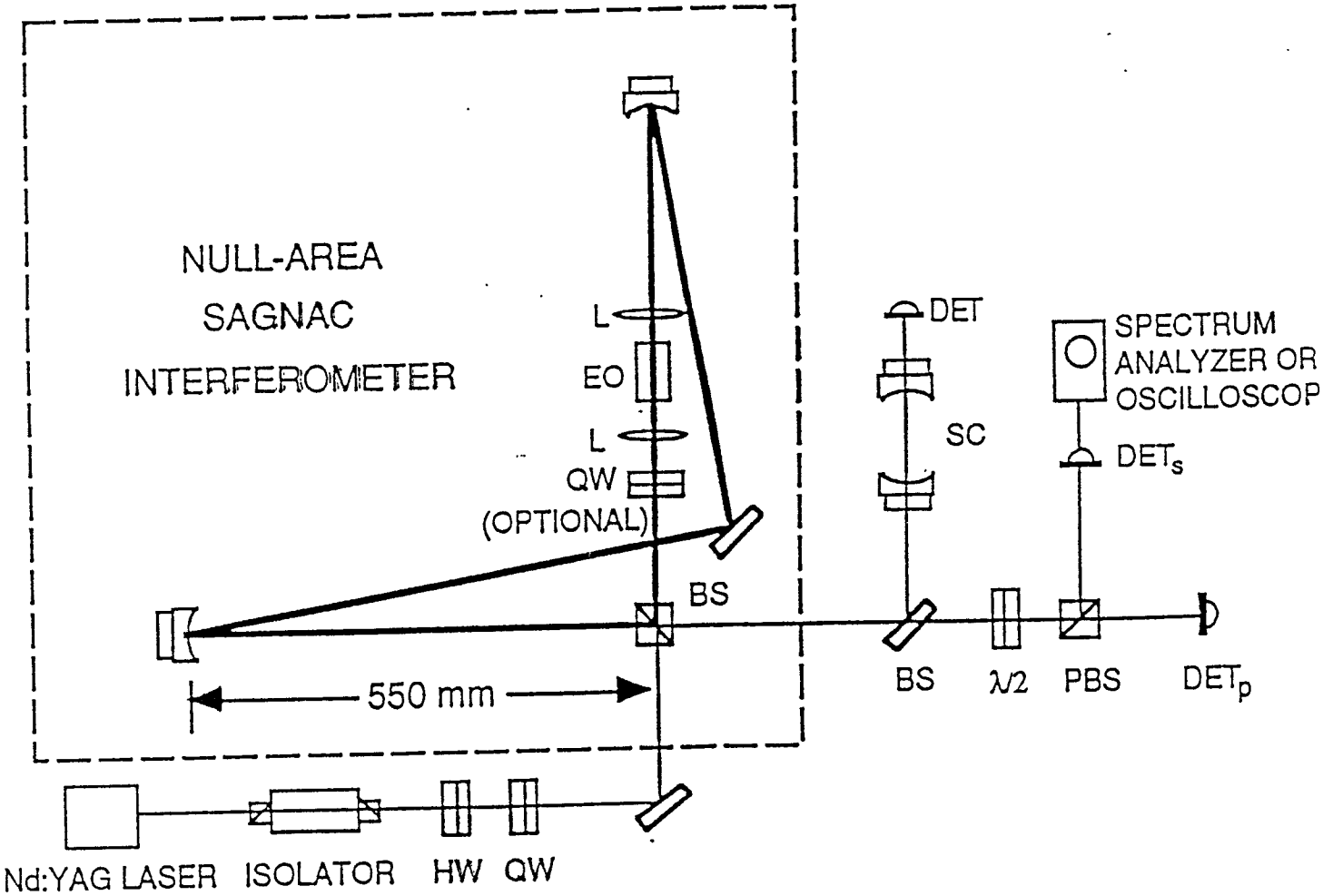


LIGO

Interferometers

Sagnac

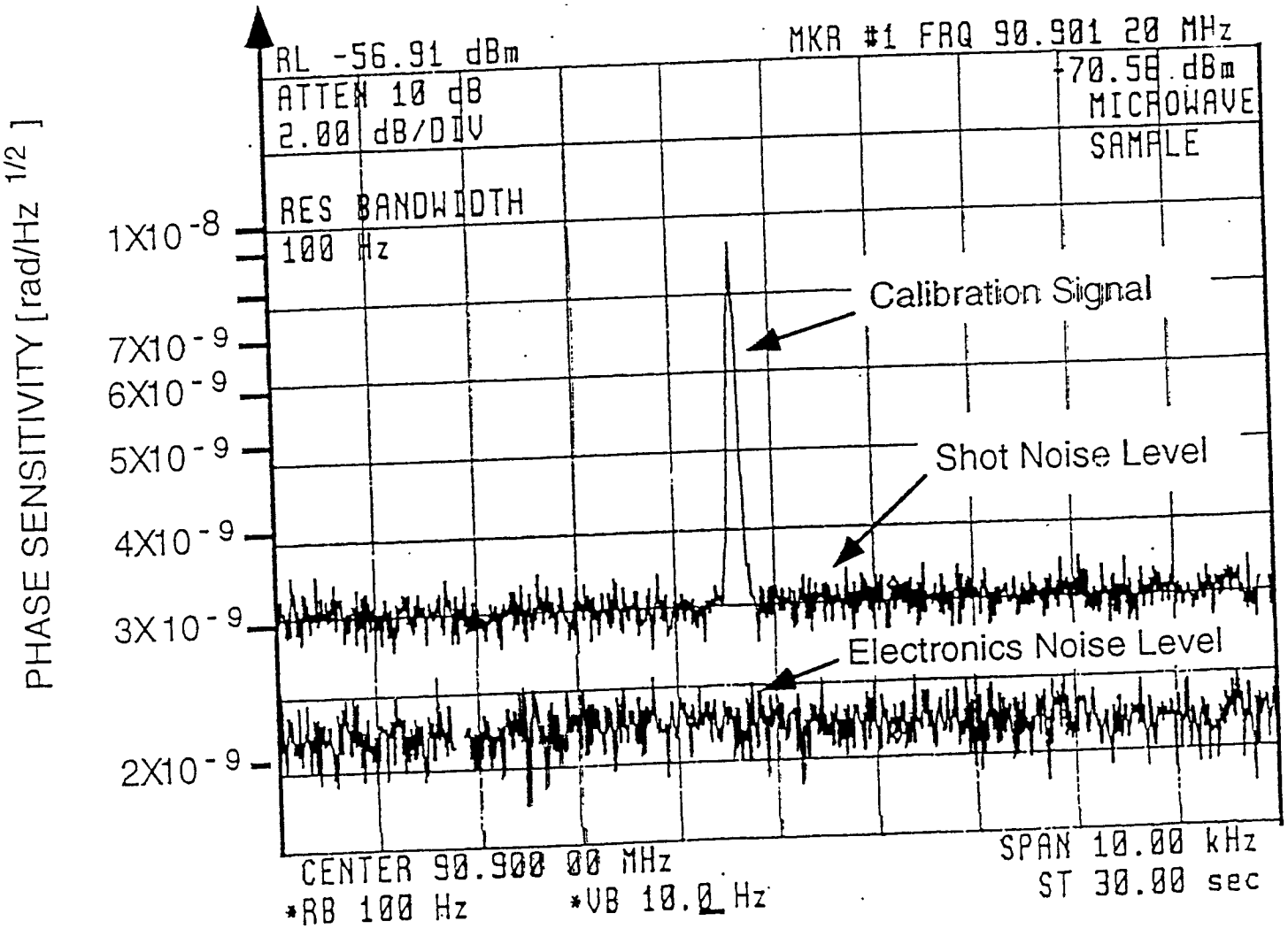
- Stanford test Sagnac



Interferometers

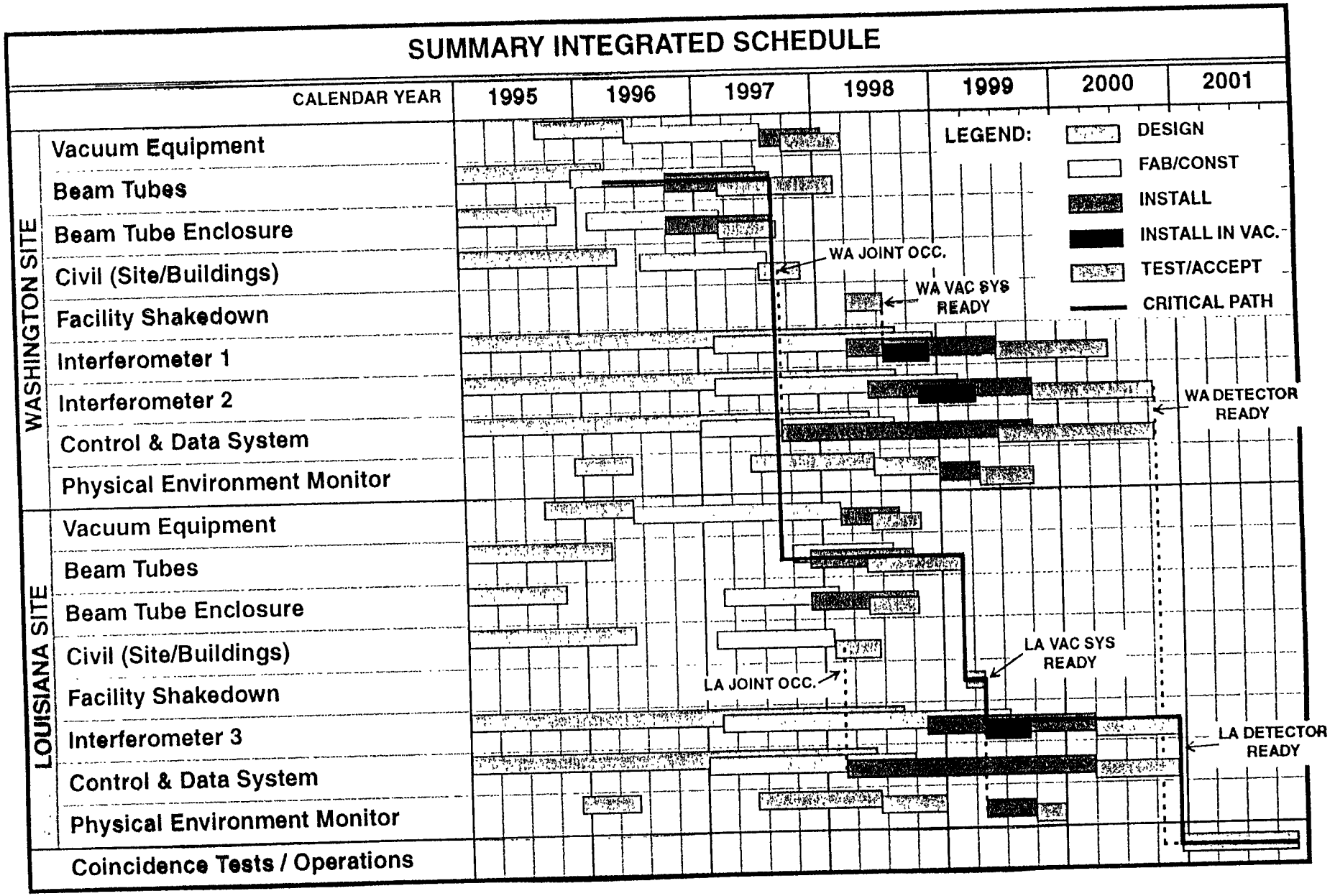
Sagnac

- Shot Noise Phase Sensitivity Measurement
- Phase Sensitivity = 3 10^{-9} rad/$Hz^{1/2}$
  - » (within 3 db of shot noise limit)



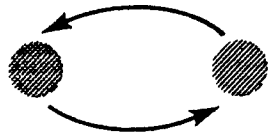
LIGO

SUMMARY INTEGRATED SCHEDULE

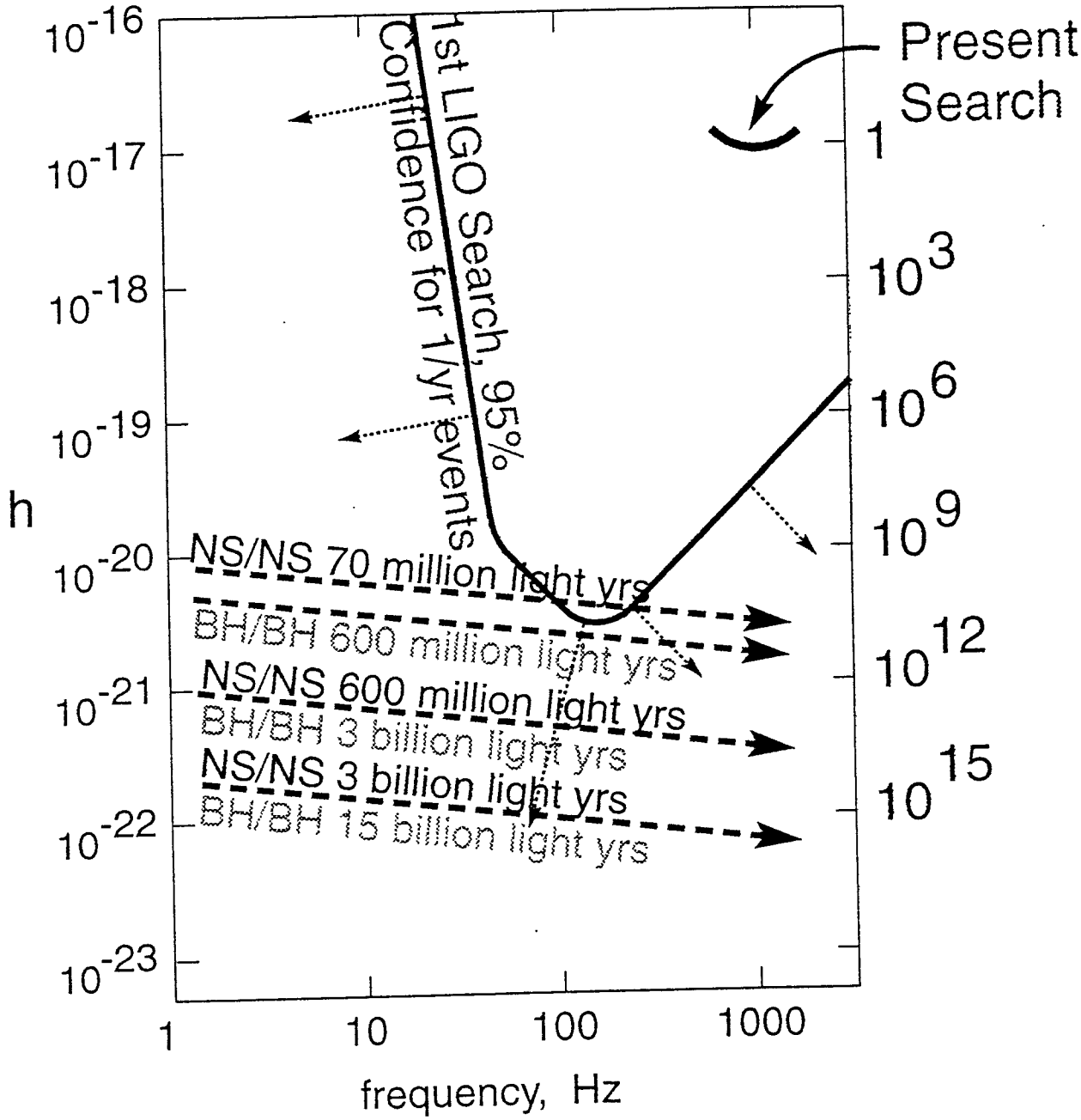


LIGO-G960000-00-M

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*

Conclusions

- LIGO Construction is well Underway

- Direct Detection of Gravitational Waves Appears Realistic within 10 years

- Ultimate Sensitivities Capable of Opening a New Field of Observational Astronomy with Gravitational Waves is the Long Term Goal.