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LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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LIGO Presentation to NSF Panel on Long Range uses of LIGO

B. Barish, A. Lazzarini, R. Weiss

Distribution of this draft:

LIGO

This is an internal working note
of the LIGO Project.
NOTE: Two LIGO DCC are included in this material.

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LIGO

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

PRESENTATION TO THE

PANEL ON THE LONG RANGE USE OF LIGO

NATIONAL SCIENCE FOUNDATION
24,25 JUNE 1996
ARLINGTON, VA 22230

BARRY BARISH - CALTECH
LIGO PROJECT PRINCIPAL INVESTIGATOR

ALBERT LAZZARINI - CALTECH
LIGO PROJECT INTEGRATION MANAGER

RAINER WEISS - MIT
LIGO PROJECT INTEGRATION SCIENTIST

OVERVIEW

- **LIGO SCIENCE - B. Barish**
- **LIGO DESIGN - A. Lazzarini**
- **MAJOR LIGO SYSTEMS - A. Lazzarini**
    - CIVIL CONSTRUCTION
    - BEAM TUBE SYSTEM
    - VACUUM EQUIPMENT
    - DETECTOR/R&D
- **LIGO R&D - R. Weiss**
    - PRESENT
    - ADVANCED
- **LIGO COLLABORATIVE RESEARCH - B. Barish**

LIGO
The Science

Barry Barish
NSF Panel
"Future Uses of LIGO"
June 24-25, 1996

LIGO
The Project

- Joint Caltech/MIT Project funded by the National Science Foundation

- Under Construction 1995-1999
  - » Two Sites -- Louisiana and Washington

- **DIRECT** Detection of Gravitational Waves
  - » Fundamental Physics (GR)
    - – test General Relativity in strong field and high velocity limit
    - – measure polarization and propagation speed
  - » Astrophysics
    - – compact binary systems
    - – stellar collapse
    - – early universe

Gravitational Waves

International Effort

- Techniques
  - » Resonant Bar Detectors (LSU, Rome, etc)
    - – narrow band
  - » Large Scale Interferometers
    - – broad band

- International Interferometer Effort
  - » U.S. -- LIGO (Two Sites)
    - – Caltech & MIT (Wash and Louisiana)
  - » Europe -- VIRGO (One Site)
    - – French and Italian (near Pisa)
  - » Smaller efforts
    - – Germany, Japan, Australia

- Time Scale (Interferometers)
  - » Approximately year 2000

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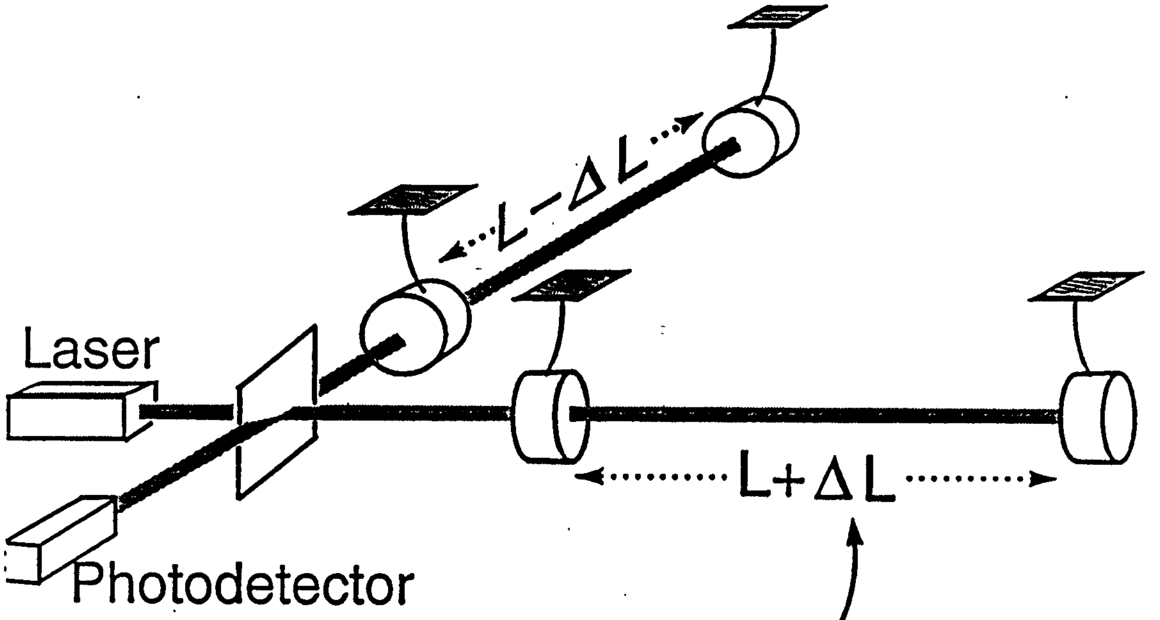
Interferometers



$$\Delta L = \underset{10^{-21}}{h}\,\underset{4\ \text{km}}{L} = 4 \times 10^{-16}\ \text{cm}$$

- 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 $h_\times$, which depends on interferometer's orientation

Gravitational Waves

General Relativity

- Non-spherically symmetric accelerations of mass
- Main term - time dependence of quadrupole moment
  - binary systems always radiate
  - non-sherically symmetric supernova collapse
  - non-axisymmetric rotations
- Types of waves
  - bursts, periodic or quasi-periodic waves
  - stochastic background from compact binaries, primordial waves and cosmic strings or phase transitions

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Long Range Goals

- Inspiral of Compact Binary ***[chirps]***
  - 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 ***[bursts]***
  - Axisymmetric in our galaxy
  - Non-axisymmetric ~300MLyr
- Pulsars ***[periodic]***
  - rotating non-axisymmetric neutron stars
- Early Universe ***[stochastic]***
  - Vibrating Cosmic Strings
  - Vacuum Phase Transitions
  - Vacuum Fluctuations from Planck Era
- Unknown Sources ***[??]***

NEUTRON STAR BINARIES

[“Guaranteed” source]

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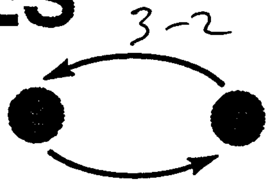
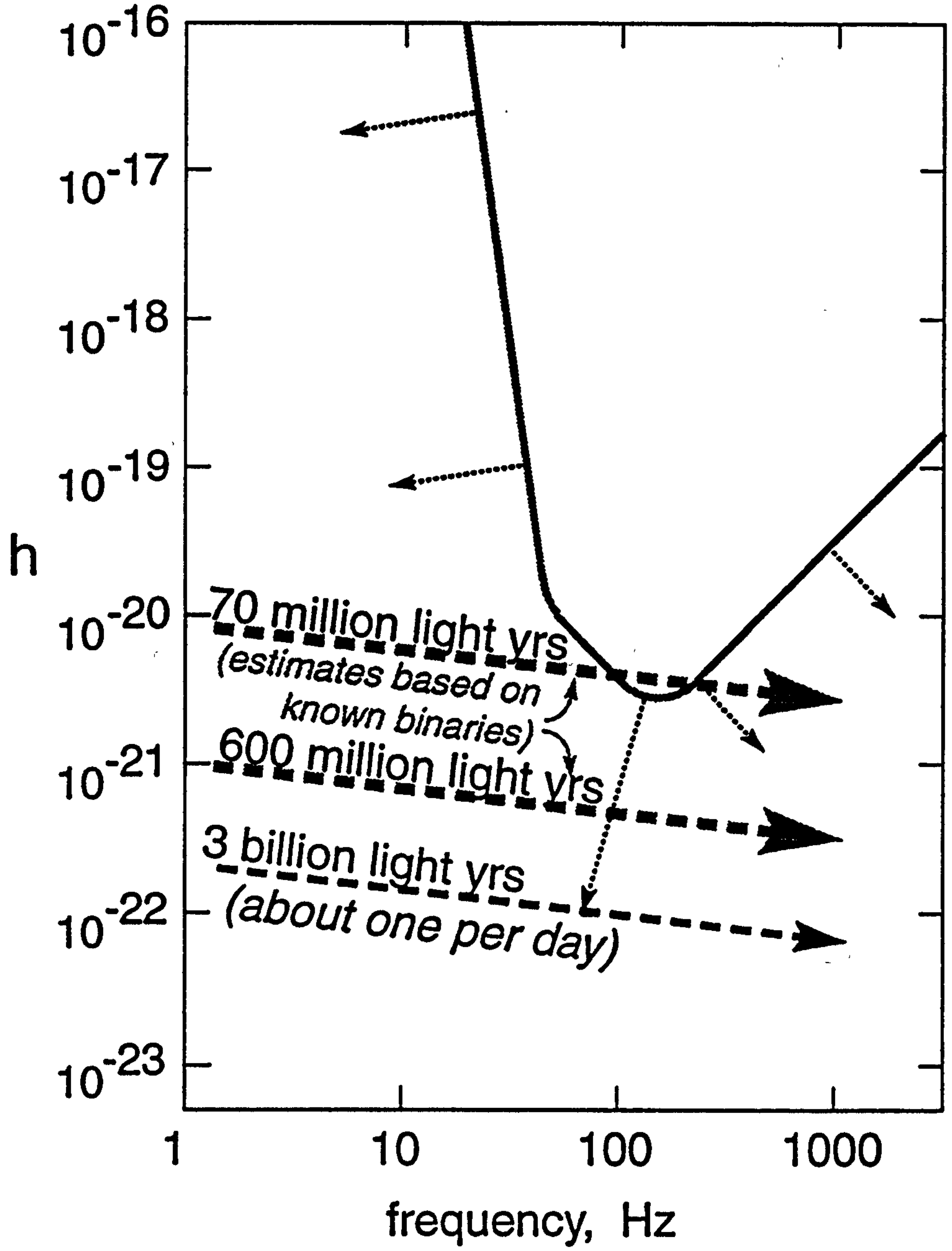
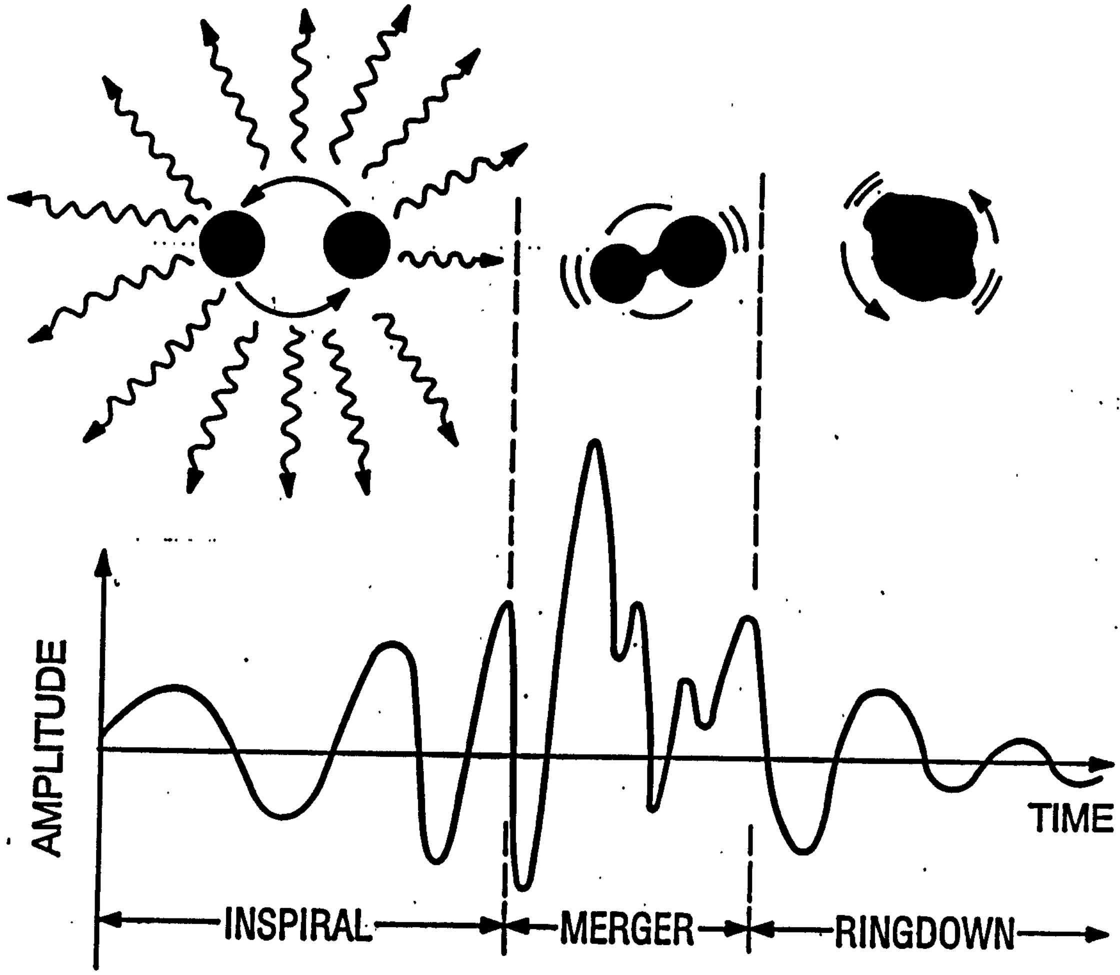




- *15 minutes &10,000 orbits in LIGO band*
- *Rich information in waveforms: masses, spins, distance, direction, nuclear equation of state*

Binary Sources

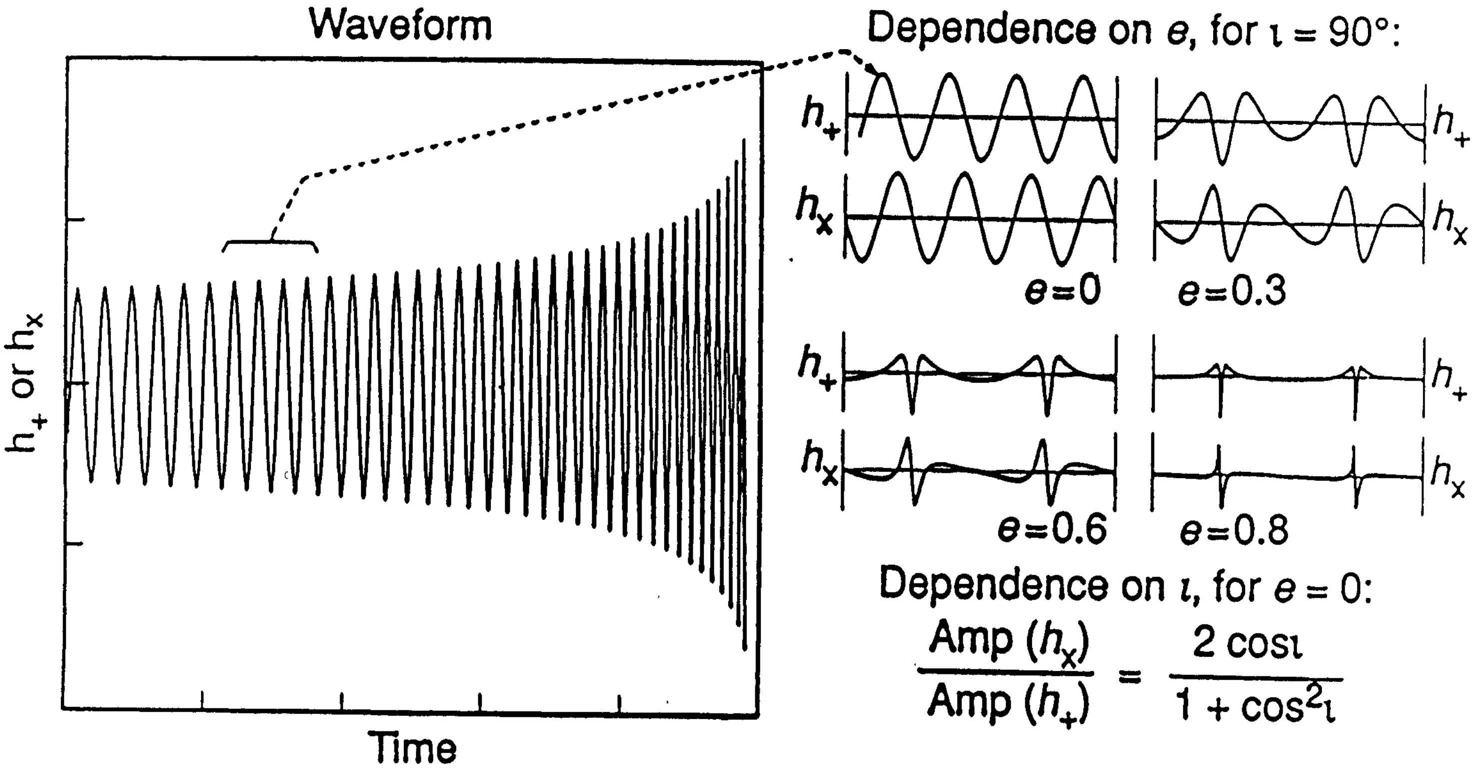
Inspiral and Coalescence



Gravitational Waveforms

binary inspiral

- can determine
  - » distance from the earth r
  - » masses of the two bodies
  - » orbital eccentricity e and orbital inclination i

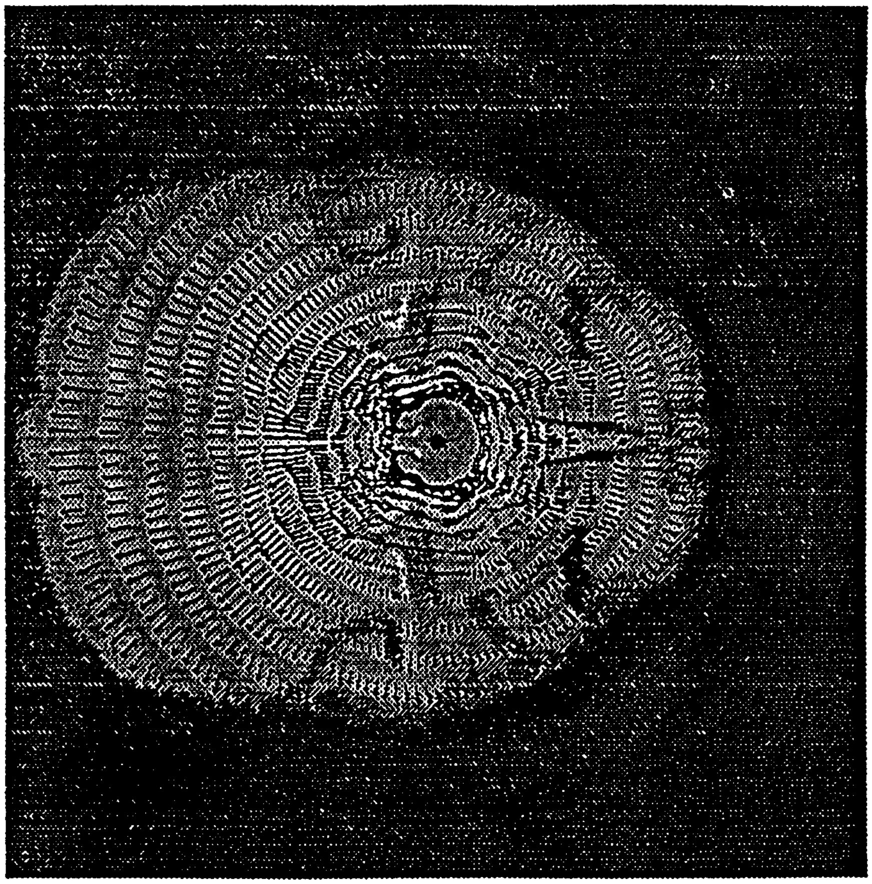


Dependence on ι, for $e = 0$:

$$\frac{\mathrm{Amp}\,(h_\times)}{\mathrm{Amp}\,(h_+)} = \frac{2\cos\iota}{1+\cos^2\iota}$$

Supernovae
simulation

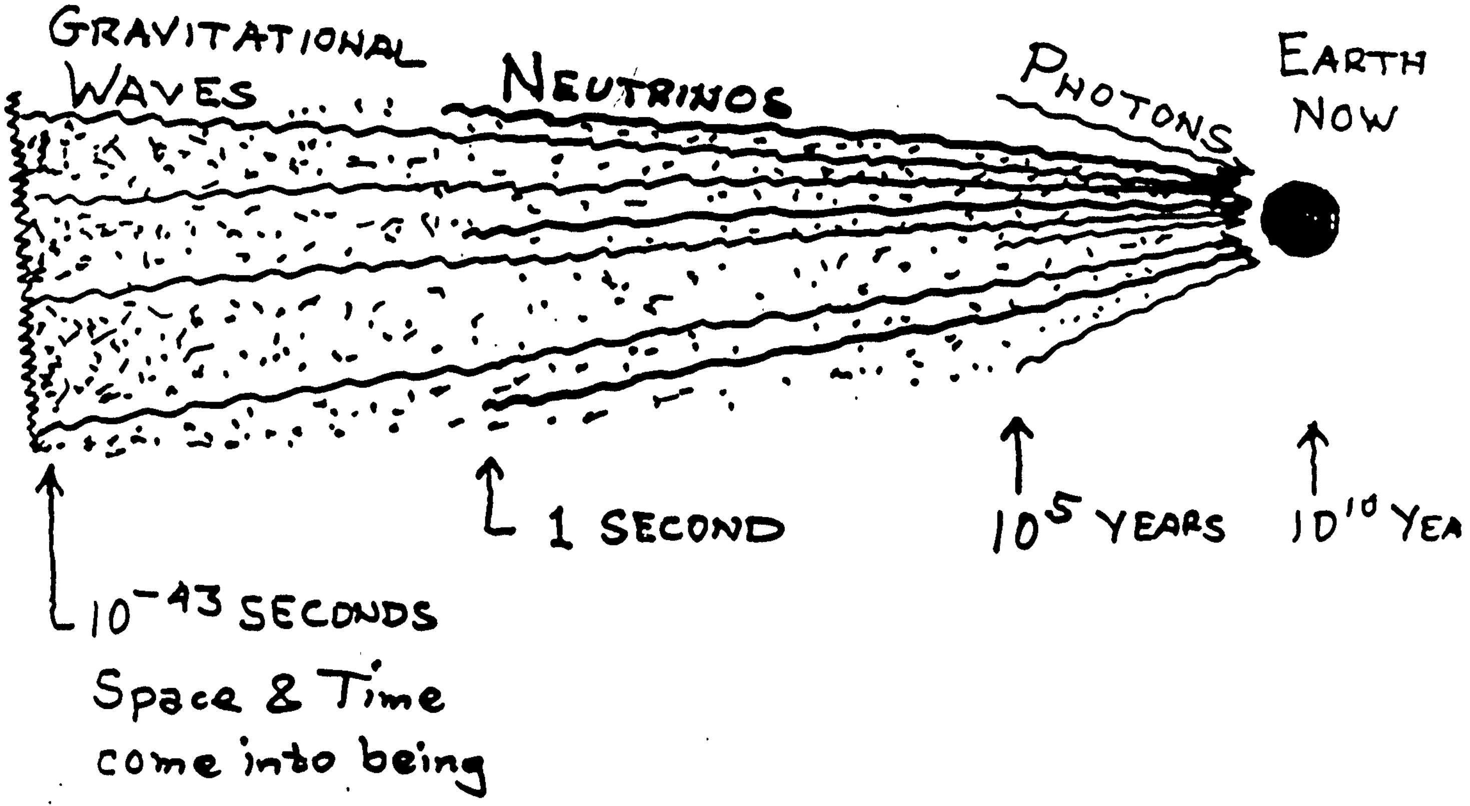
- A. Burrows
  - » 2 - dim model
  - » 50 msec into the explosion



The Early Universe

Stochastic Background

- The Big Bang Singularity

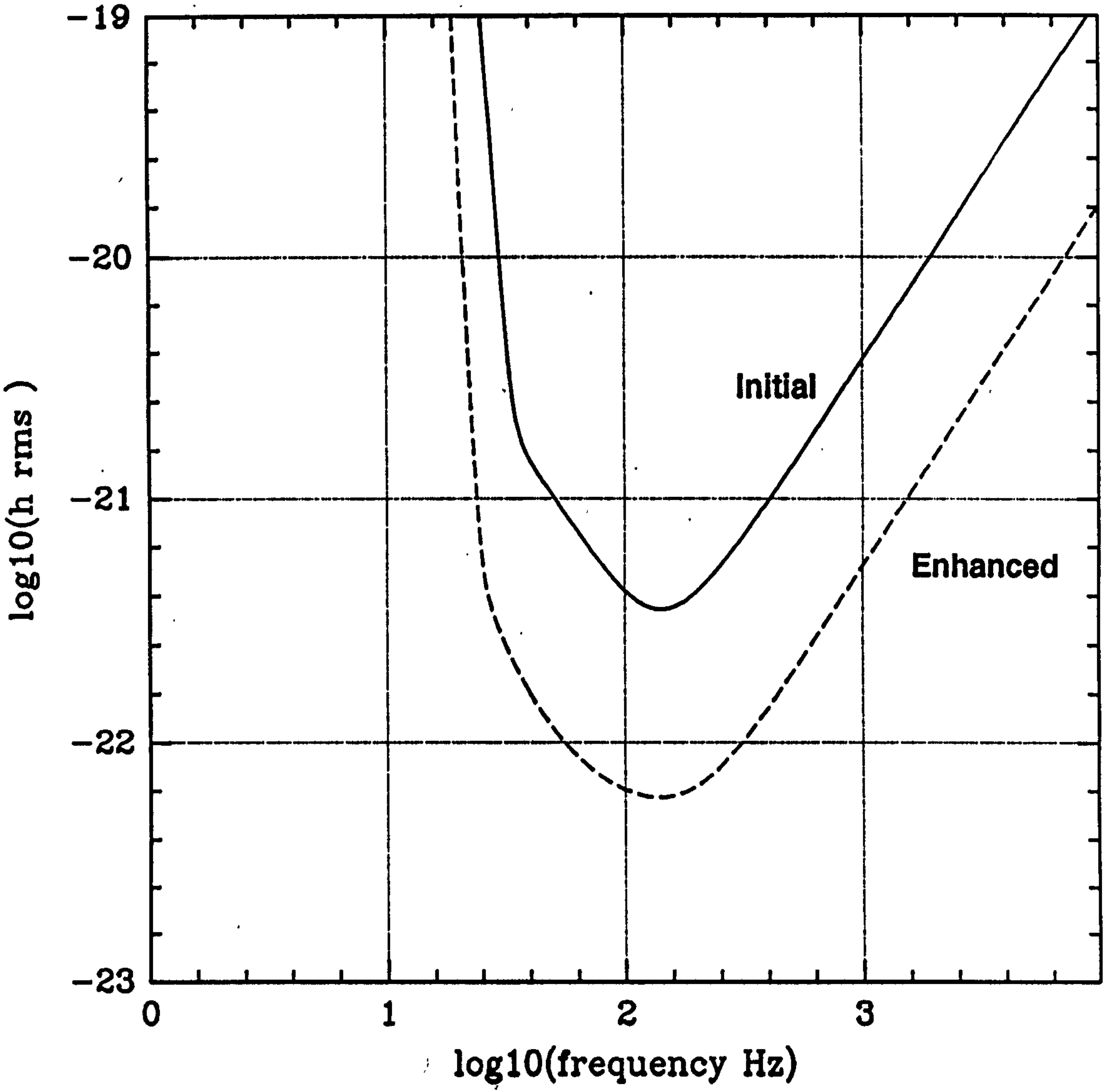


- LIGO
  - » time ~10^{-22} sec
  - » temp ~ 10^6 GeV
  - » graviton ~ 10 MeV

Detectors

Capability

- Initial Detector - end of 2001
- Fully Enhanced - about 2007 ?



LIGO DESIGN

• OBSERVATORY CHARACTERISTICS

- Two Sites:
  - **Hanford, Washington**
  - **Livingston, Louisiana**
  - **$L_{12}/c = 10$ msec.**
- Three Instruments:
  - **Two 4 km interferometers (WA/LA)**
  - **One 2 km interferometer (Hanford)**
- Arms oriented "parallel" to one another
- Coincident observations among all three interferometers
  - **$R_{3x}^{BKGND} \approx (\tau_P + 2L_{12}/c)\tau_P R_{12} R_{23} < 1/\text{year}$**
- Initial Sensitivity: $h_{rms} \leq 10^{-21}$ within 100 Hz band centered at maximum sensitivity
  - **$f_{GW} \approx 100$ Hz; $\lambda_{GW} \approx 3 \times 10^6$ m;**
- Observatory Extensibility:
  - Eventual expansion to 8 interferometers
  - Limiting sensitivities:
    - Naturally occurring gravity gradients (at lowest frequencies)
    - Scattered light phase noise (in the mid-frequency range)
    - Residual gas phase noise (at the highest high-frequencies)

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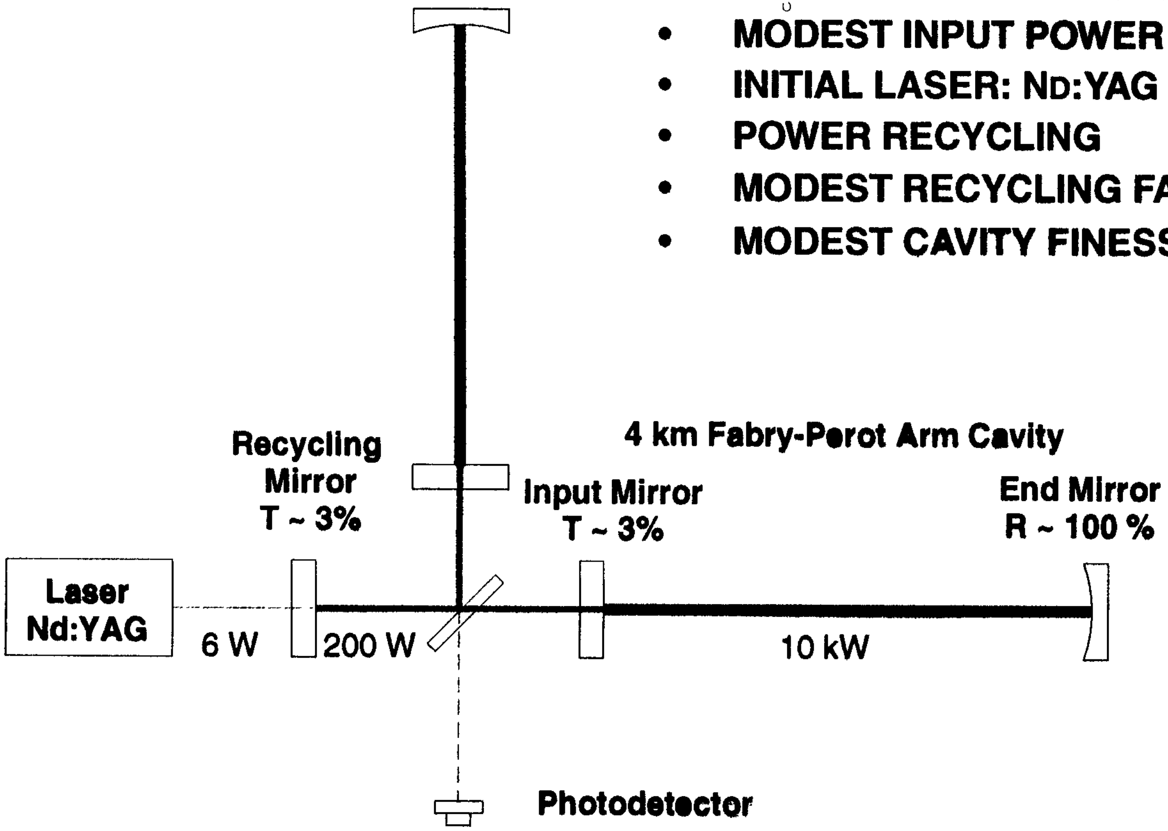
INITIAL INTERFEROMETER CONFIGURATION

- **FABRY-PEROT ARM CAVITIES**
- **MODEST INPUT POWER (6 W)**
- **INITIAL LASER: ND:YAG** $\lambda = 1.06\ \mu\text{m}$
- **POWER RECYCLING**
- **MODEST RECYCLING FACTOR** ($\mathcal{R} \sim 30X$)
- **MODEST CAVITY FINESSE** ($\mathcal{F} \sim 50$)



Interferometer Response Function:

$$\varphi = h \frac{\omega L}{c} \frac{2F}{\pi \sqrt{1 + (\Omega\tau)^2}}$$

where

$\delta\varphi$ = optical light phase change
ω = laser frequency
Ω = GW frequency
c = speed of light
h = strain amplitude
L = arm length
F = Fabry-Perot finesse
τ = Fabry-Perot time constant

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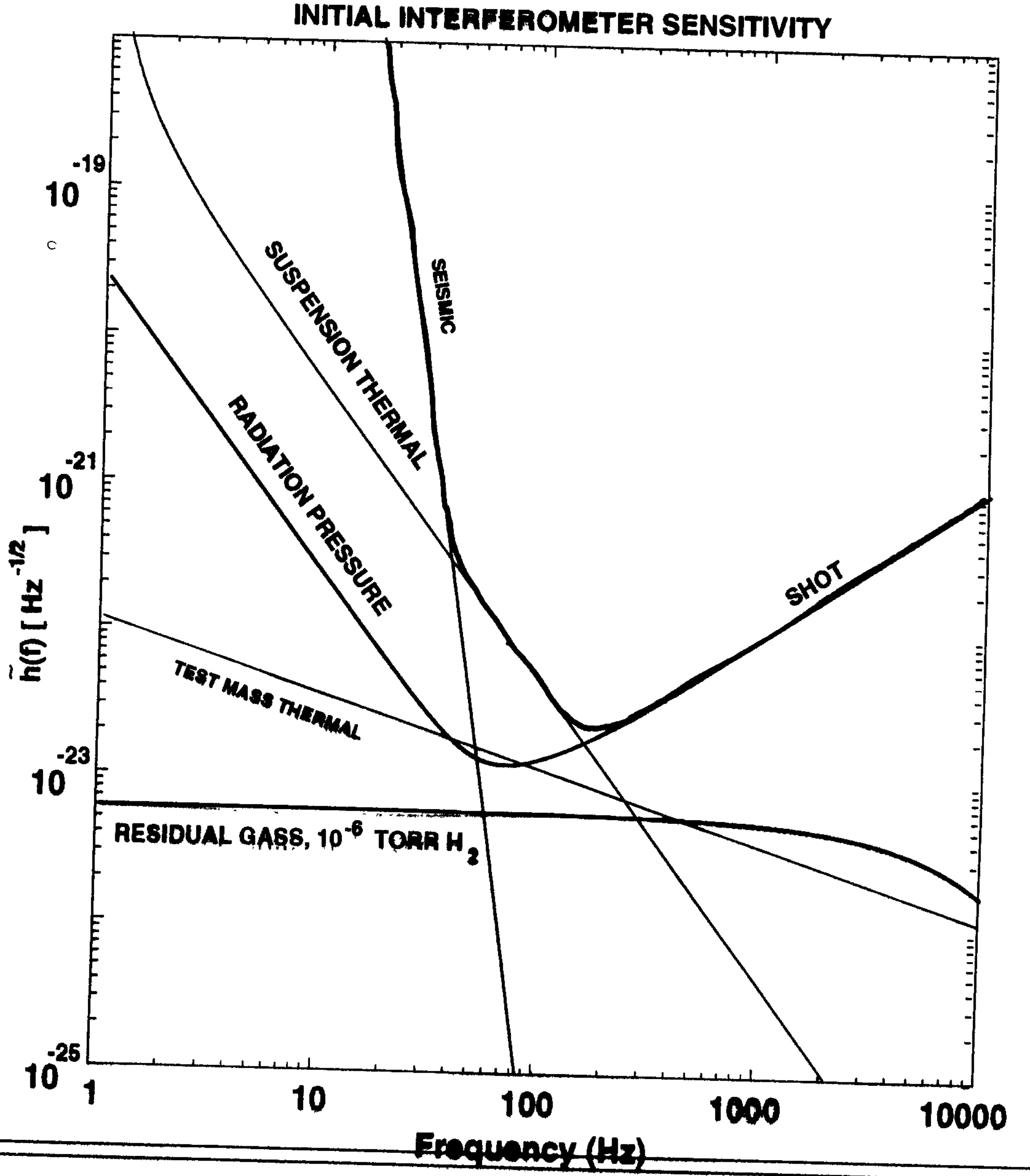
LIGO

2/4-9/96

INITIAL INTERFEROMETER DESIGN PERFORMANCE GOAL



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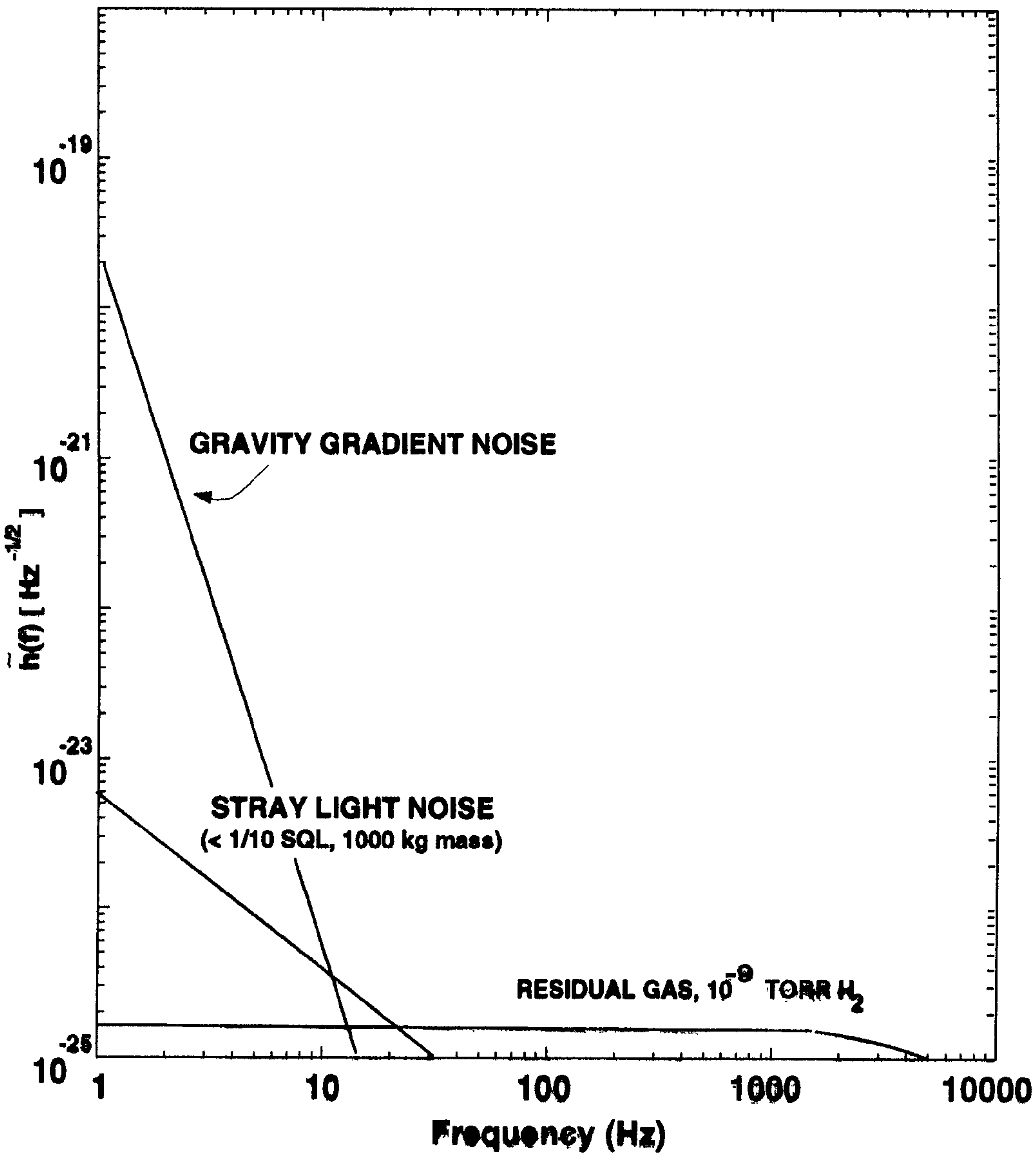
LIGO

2/4-9/96

LIMITING PERFORMANCE DUE TO FACILITIES



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LIGO DESIGN (cont.)

- OBSERVATORY EXTENSIBILITY (CONT.):
  - EXTREME CARE IN DESIGNING QUIET FACILITIES
    - site selection
    - design considerations
  - APERTURE & BAFFLING DESIGNED TO MINIMIZE SCATTERED STRAY LIGHT
  - VACUUM CHARACTERISTICS OF BEAM TUBES AND VACUUM EQUIPMENT DESIGNED TO PROVIDE ULTRA-HIGH VACUUM OPERATING CONDITIONS.

• OPERATIONAL CONSIDERATIONS

- ASTROPHYSICAL RESEARCH
  - HIGH ON-LINE AVAILABILITY
  - MULTIPLE MODES OF OPERATION:
    - 3X ; $T_{online} > 75\%$
    - 2X: (WA-LA); $T_{online} > 85\%$
    - 1X: $T_{online} > 90\%$
- ALLOCATION OF OBSERVING TIME BY PI/PAC/NSF
- TIME FOR DEVELOPMENT OF IMPROVED DETECTORS

LIGO DESIGN (cont.)

- DATA FORMATS
  - COMPATIBILITY WITH OTHER GRAVITATIONAL WAVE DETECTORS & PARTICLE DETECTORS
  - SAMPLE RATE AND PRECISION COMMENSURATE WITH SCIENTIFIC MISSIONS
- ENABLING RESEARCH & FACILITIES
  - LONG-TERM DEVELOPMENT OF ADVANCED DETECTORS
  - UNIVERSITY-BASED INTERFEROMETER FACILITIES
  - LIGO RESEARCH COMMUNITY

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MAJOR LIGO SYSTEMS

- CIVIL CONSTRUCTION
- VACUUM EQUIPMENT & BEAM TUBES
- DETECTOR / R&D

LIGO SCHEDULE

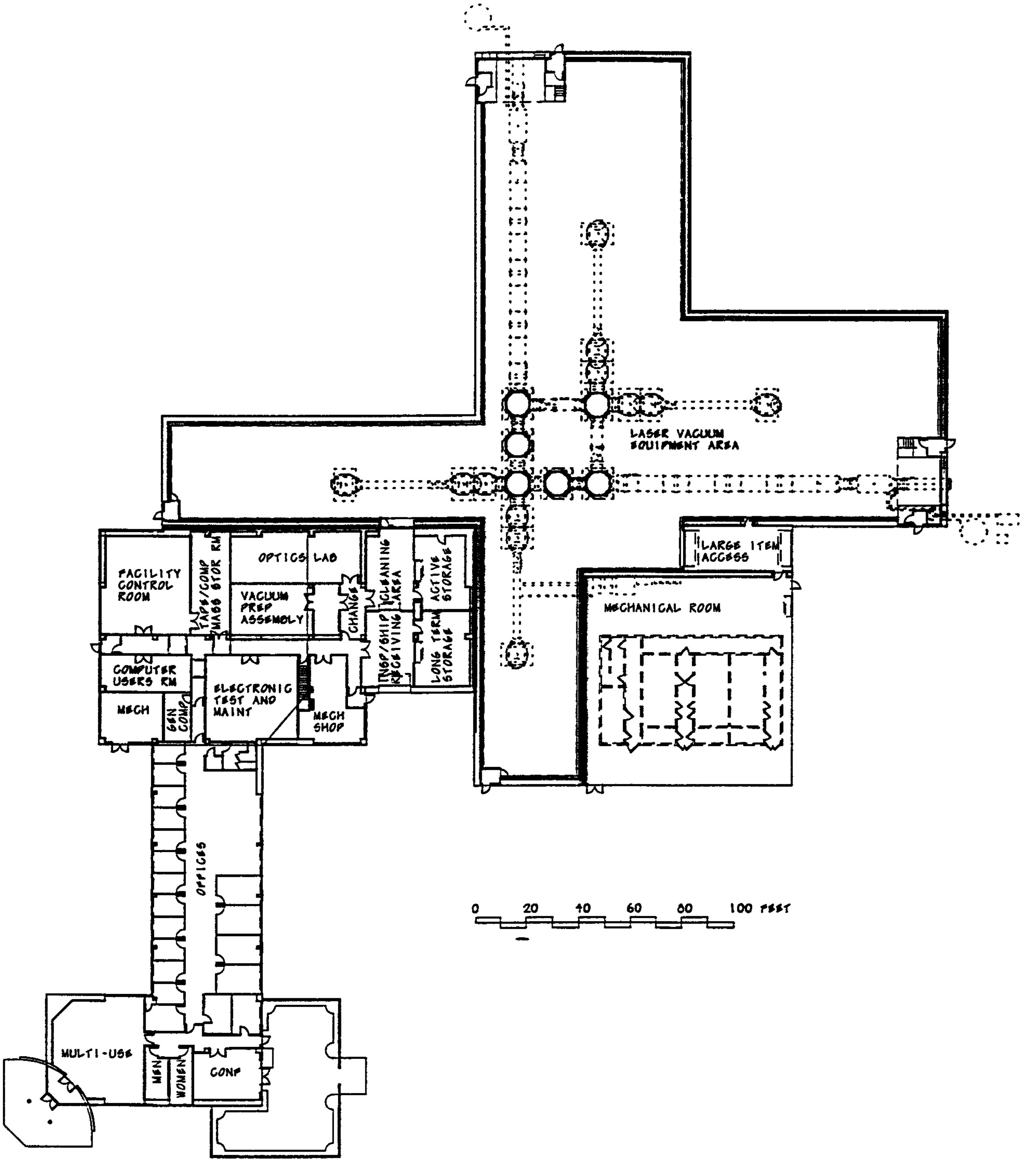
- 1996 - 1998
  - CONSTRUCTION OF FACILITIES
    - CIVIL CONSTRUCTION/ 7/96 START
    - VACUUM EQUIPMENT 5/96 START
    - BEAM TUBES 4/96 START
  - DETECTOR DESIGN & FABRICATION; R&D
- 1998 - 2000
  - DETECTOR INSTALLATION
  - SHAKEDOWN
- 2001
  - "FIRST LIGHT" AT INITIAL DESIGN SENSITIVITY $h_{RMS} = 10^{-21}$ (Δf = 100 Hz @ 100 Hz).

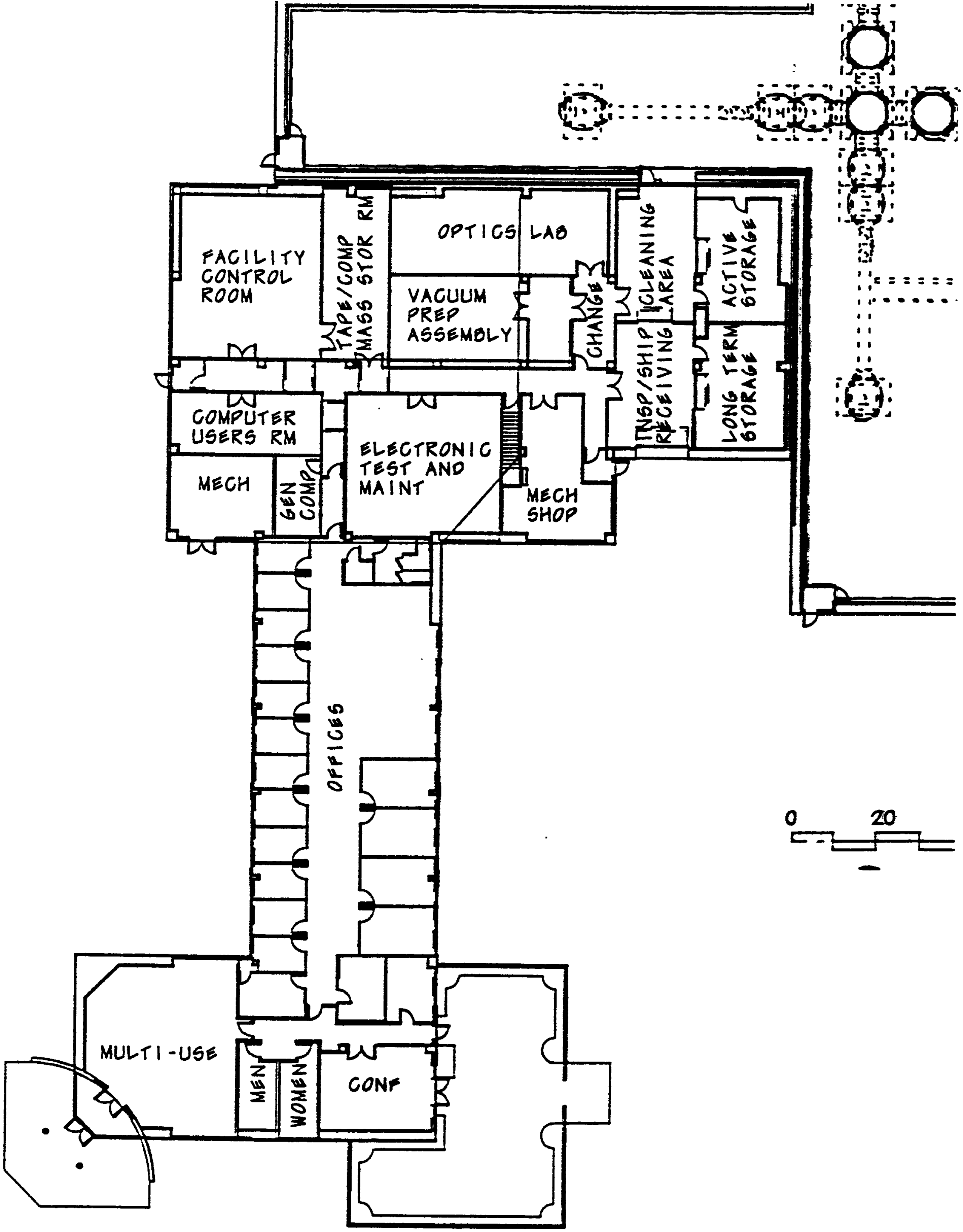
CIVIL CONSTRUCTION

• CHARACTERISTICS

- INFRASTRUCTURE
  - LARGE AND CLEAN LABORATORY (CLEAN CONSTRUCTION PRACTICES; HIGH BAY: 9 M HOOK HEIGHT)
  - BEAM TUBE ENCLOSURES TO PROTECT THIN-WALLED TUBE
  - OFFICE SPACE/LABORATORY SPACE TO ACCOMMODATE STAFF AND VISITORS
  - ROADS, FOUNDATIONS, STRUCTURES, ETC.

- REQUIREMENTS
  - REMOTE SITES WITH SEISMIC STABILITY -- THICK SLAB; ISOLATED FOUNDATIONS; SEPARATED BUILDINGS
  - FEW INTERNAL NOISE SOURCES, EMI/EMF BACKGROUNDS, ETC.
  - REMOTELY OPERABLE FACILITIES: ENVIRONMENTAL CONTROL AND STATE VECTOR LOGGING
  - CLEANLINESS


LASER VACUUM EQUIPMENT AREA
FACILITY CONTROL ROOM
TAPE/COMP MASS STOR RM
OPTICS LAB
VACUUM PREP ASSEMBLY
CHANGE
CLEANING AREA
ACTIVE STORAGE
INSP/SHIP RECEIVING
LONG TERM STORAGE
LARGE ITEM ACCESS
MECHANICAL ROOM
COMPUTER USERS RM
MECH
GEN COMP
ELECTRONIC TEST AND MAINT
MECH SHOP
OFFICES
MULTI-USE
MEN
WOMEN
CONF
0
20
40
60
80
100 FEET


FACILITY CONTROL ROOM
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ELECTRONIC TEST AND MAINT
MECH
GEN COMP
MECH SHOP
OFFICES
MULTI-USE
MEN
WOMEN
CONF
0
20

Support Facilities in Operations Support Building

Area	Purpose
Control Room / Analysis Area	All equipment control functions, machine diagnostics, data analysis and archiving
Optics Laboratory	Cleaning, maintenance, test and calibration of lasers and optics
Vacuum Preparation	Vacuum preparation and certification, mechanical-Q testing
Electronics Test/Maintenance	Control/Data systems staging, test, and maintenance
Mechanical / Technical	Mechanical staging, assembly and testing; vacuum-pump maintenance
Equipment Rooms	Telecommunications, computer networking, etc.
Shipping / Receiving	Outdoors<-->Clean-Room interfaces; cleaning; storage
Changing / Cleaning	Clean-room transition space for people, small equipment entering LVEA
Office / Library Space	Resident staff, detached-duty staff, visiting scientists/students
Conference room	Smaller group meetings, drawing layout space
Multi-Use Space	Seminars, “all-hands meetings”, and public entry/reception
Kitchen/shower/restrooms	

CIVIL CONSTRUCTION

• STATUS

- BOTH SITES UNDER CONSTRUCTION
- WASHINGTON SITE
  - GRADED TO FINAL TOPOGRAPHY; SOIL SETTLEMENT COMPLETED
  - BEAM TUBE SLAB/ROADS/ENCLOSURES UNDER CONSTRUCTION (2/96)
- LOUISIANA SITE
  - LOGGED
  - GROUND BREAKING TOOK PLACE 7/95
  - SITE CLEARED AND GRUBBED
  - BEING GRADED TO INTERFEROMETER PLANE (8/96)
- FINAL DESIGN OF THE LIGO FACILITIES (BUILDINGS) COMPLETED 4/96
  - LASER & VACCUM EQUIPMENT AREAS (LVEA/VEA)
  - OPERATIONS & SUPPORT BUILDING (OSB)
  - MECHANICAL EQUIPMENT ROOM
  - CHILLED WATER PLANT
- PROCUREMENT FOR FACILITY CONSTRUCTION UNDER WAY:
  - BIDS IN FOR 3 INTERFEROMETER FACILITY AT HANFORD 6/96
  - PREPARING BID PACKAGE FOR 2 INTERFEROMETER FACILITY FOR LA

VACUUM EQUIPMENT & BEAM TUBE

- WILL BE THE LARGEST ULTRA-HIGH VACUUM ($<10^{-9}$ torr) SYSTEM IN THE WORLD (~ 20,000 m^3)
  - VERY LOW ALLOWED AIR LEAKAGE:
    $\mathcal{F} < 10^{-9}$ ATM CC/S, He
  - VERY LOW OUTGASSING:
    - $P_{Advanced} < 10^{-9}$ TORR (ALL RESIDUALS);
    - $J[H_2]: < 10^{-13}$ torr-liter/cm^2/s
      $J[H_2O]: < 10^{-15}$ torr-liter/cm^2/s
    - PARTIAL PRESSURES FOR $CO + CO_2 + H_{2N}C_N + \ldots$ MUST BE EVEN LOWER
  - QUALITY CONTROL AND CLEANLINESS MUST BE PURSUED DILIGENTLY THROUGHOUT FABRICATION AND INTEGRATION PROCESS
  - OVER 140 km OF WELDS
- MOSTLY STANDARD VACUUM PUMP & CONTROL HARDWARE
- VERY LARGE APERTURE GATE VALVES TO ISOLATE 1.24 m BEAM TUBES
- LARGE PUMPING SPEEDS AND VOLUMES -- BEAM TUBE PUMPING SOLELY FROM 4km ENDS

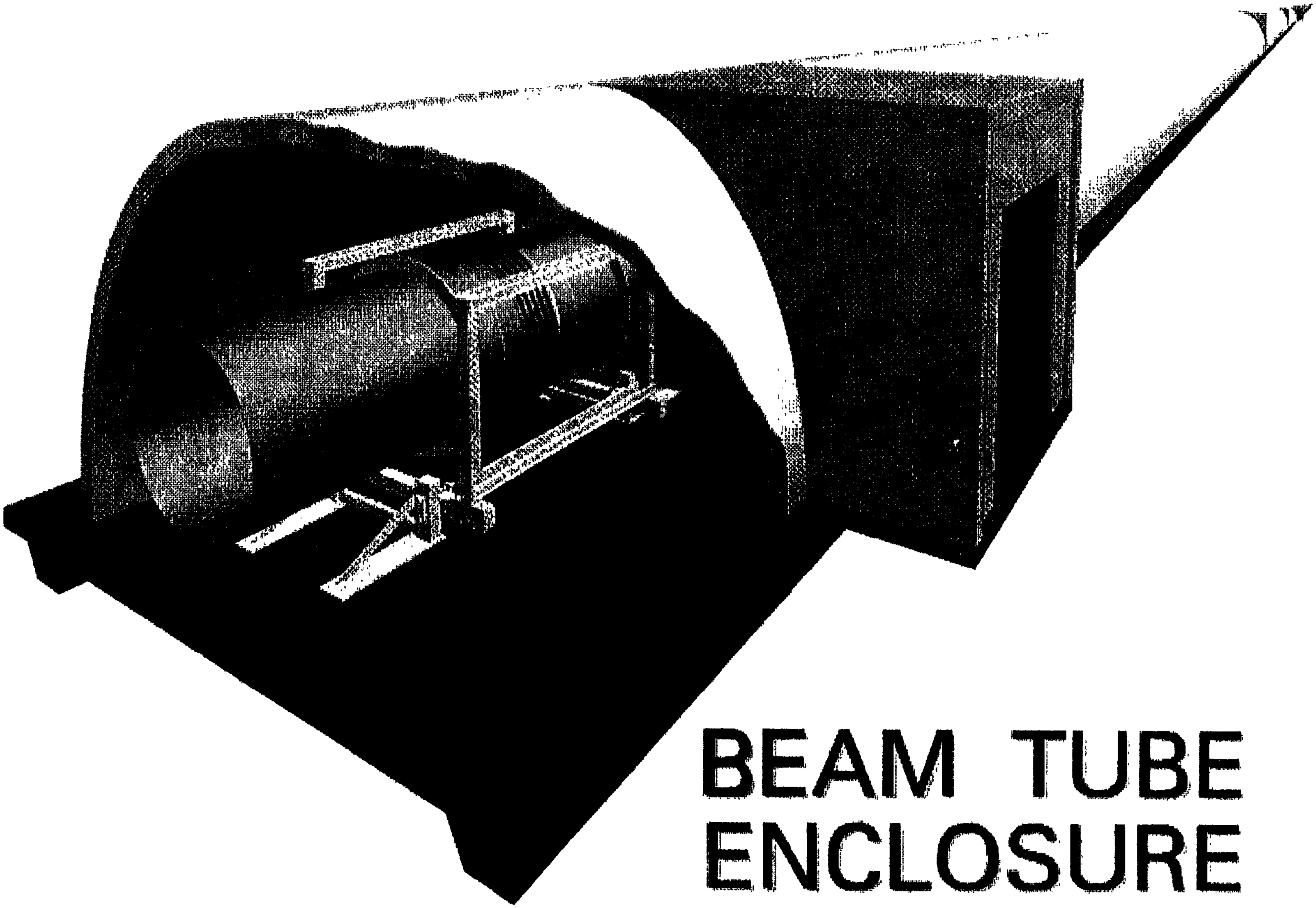
VACUUM EQUIPMENT

- **STATUS**
  - SPECIFICATIONS DEFINED -- SCIENCE REQUIREMENTS REVIEW 8/94
  - DESIGN PHASE COMPLETED 10/95
  - PROCCESS SYSTEMS INTERNATIONAL (PSI) SELECTED FOR HARDWARE CONTRACT
  - FINAL DESIGN REVIEW HELD 5/96
  - FIRST ARTICLE CHAMBER (BEAMSPLITTER CHAMBER) UNDER CONSTRUCTION - 8-9/96
  - PROTOTYPE LARGE APERTURE (1.22 M) VALVE FOR BEAM TUBE INTERFACE UNDER CONSTRUCTION
    - FIRST TWO ARTICLES DUE AT HANFORD 8/96

BEAM TUBES

- **PRODUCTION OF 16 KM TUBES FOR LIGO**
  - QUALIFICATION TEST REVIEW HELD 4/95
  - FABRICATION CONTRACT OF BEAM TUBES INITIATED 12/95
  - FINAL DESIGN REVIEW 4/96
  - INFRASTRUCTURE CONSTRUCTION NEAR SITE 4/96 - 7/96
  - INSTALLATION AT WASHINGTON STARTS 10/96
- **BEAM TUBE BAFFLE DESIGN COMPLETE**
  - BAFFLE SURFACE TREATMENT IDENTIFIED
    - OPTICAL BLACK GLASS ENAMELED GLAZE (1 mm; $\tau \sim 400 \mathrm{cm}^{-1}$)
    - R < .1 (Averaged over S & P polarizations)
    - $P[\mathrm{Backscatter}] \approx 10^{-3} \mathrm{sr}^{-1}$
  - BAFFLE MECHANICAL DESIGN COMPLETE
    - SERRATED WITH 8 mm P-P SERRATIONS @ 6 mm PITCH
    - SERRATION PATTERN PSEUDORANDOM (25% VARIATION IN P-P) TO MINIMIZE COHERENCE EFFECTS
    - 1 mm THICK 304 L SS MATERIAL, H_2 DEPLETED

L-16

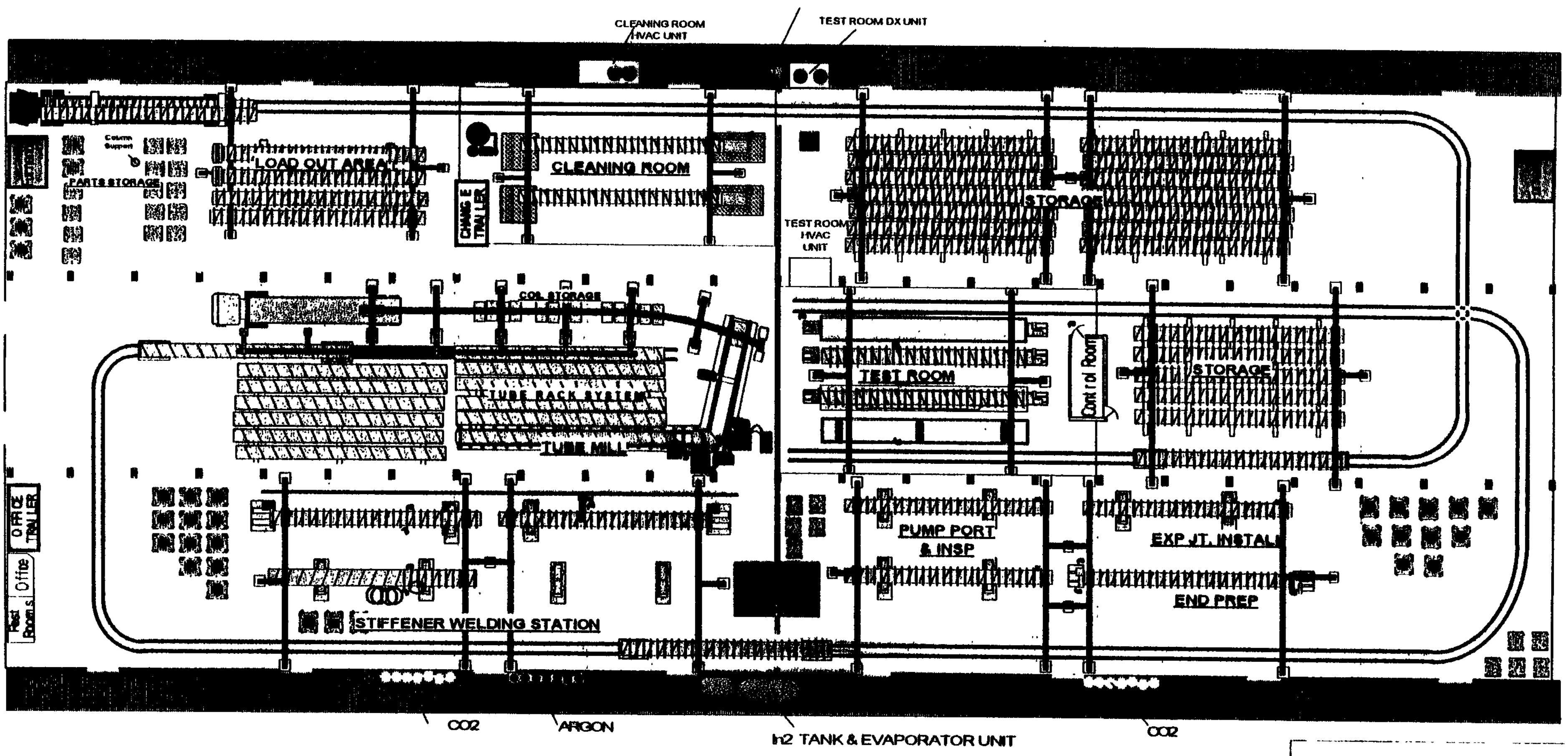


BEAM TUBE ENCLOSURE

41-7

BIG PASCO

WAREHOUSE #5, BAYS #1 & #2



Supplier/Purchaser's No.

CBI

LASER INTERFEROMETER GRAVATATIONAL WAVE OBSERVATORY

HANFORD LOCATION

FABRICATION FACILITY

BIG PASCO WHSE #5, BAYS 1 & 2

Customer's No. PC101526

By_____ Chkd_____ Date 6Feb96

Engineering Supervisor

95-9671

Dwg.

Sheet

Rev

BIGPASO1.CVS

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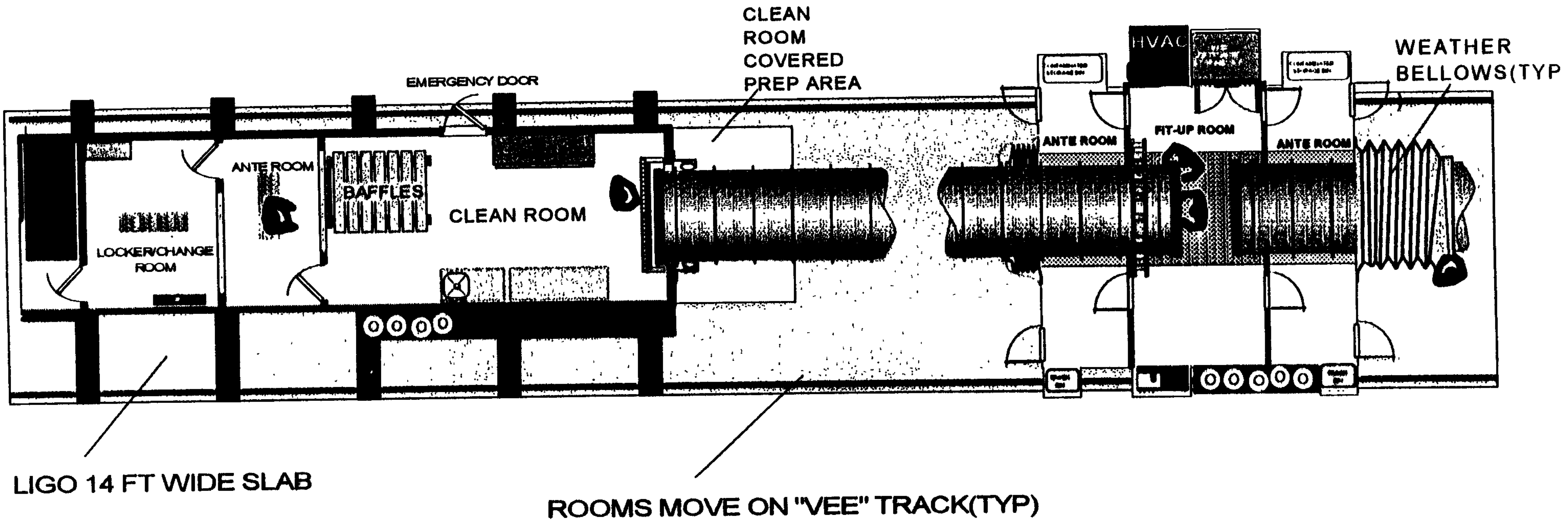
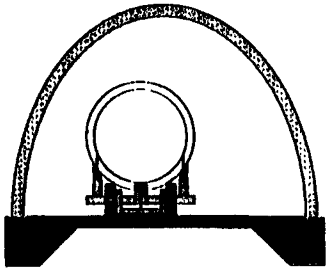
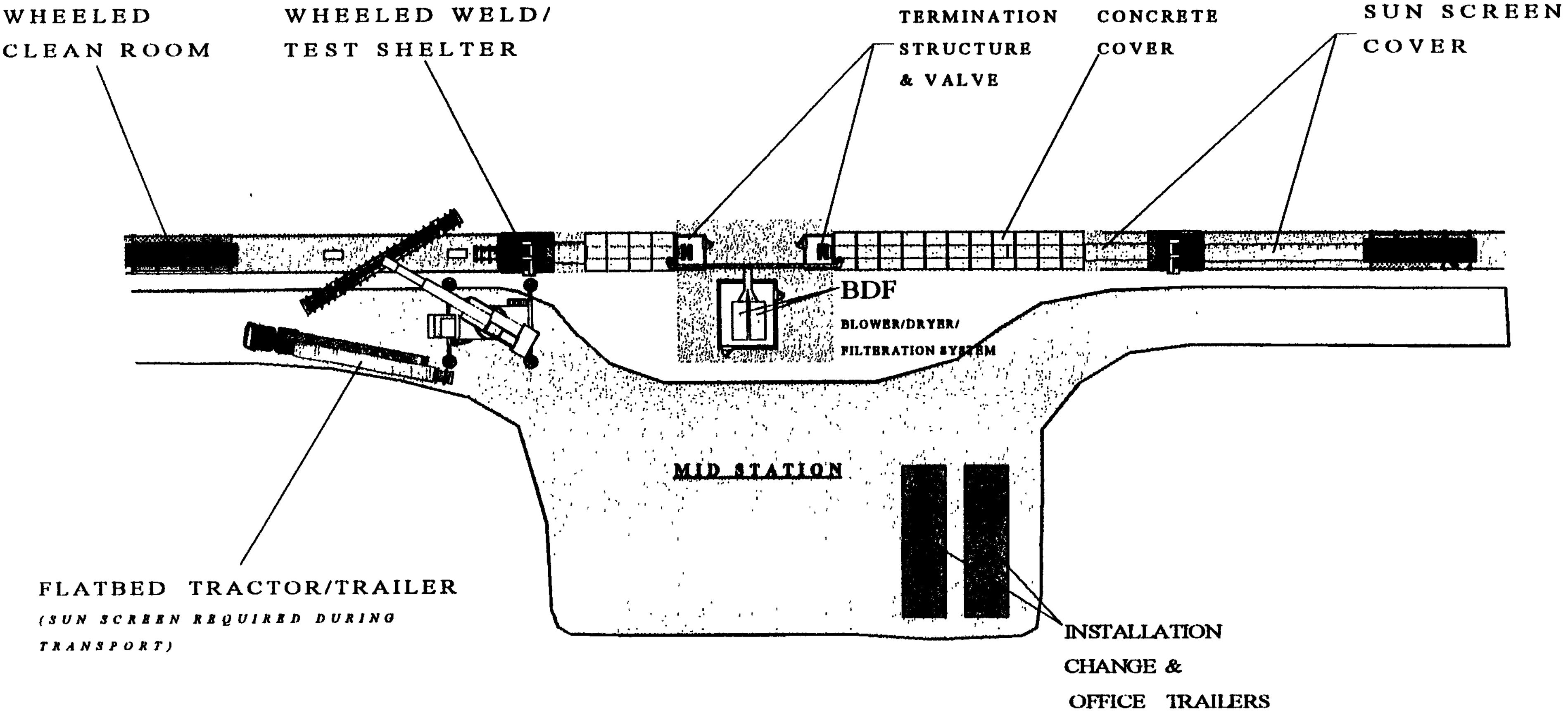
INSTALLATION PLAN



LIGO INSTALLATION PLAN





DETECTOR / R&D

• CHARACTERISTICS

- BASELINE CONFIGURATION EMPLOYS PROVEN TECHNIQUES
  - -40M AND 5M SCALE SYSTEMS (AT CIT & MIT)
  - -OPTICS EXPERIMENTS ON RECOMBINATION AND RECYCLING BEING PERFORMED IN R&D
  - -PRECISION ENGINEERING
  - -BASELINE CONFIGURATION CHANGED 8/95 FROM AR+ (0.5145 μm) LASER TO ND^{3+}: YAG LASER (1.064 μm)
- COLLABORATIVE STUDIES WITH INDUSTRY TO DEVELOP MIRROR COATING AND POLISHING TECHNOLOGIES
- BUILT-IN DESIGN FLEXIBILITY FOR LATER IMPROVEMENTS AS R&D RESULTS BECOME AVAILABLE
  - -PASSIVE & ACTIVE SEISMIC ISOLATION
  - -SENSING AND CONTROL
  - -ADVANCED CONTROL & DATA SYSTEM USING STATE-OF-THE-ART LAN/WAN ARCHITECTURES

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DETECTOR / R&D

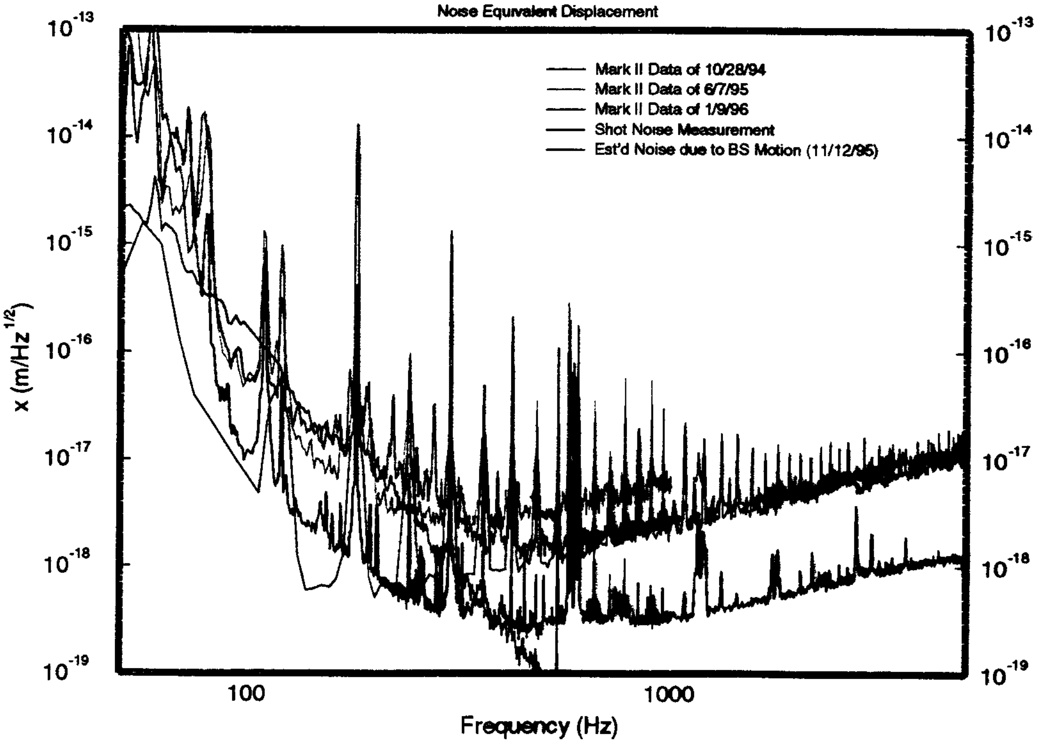
• STATUS

- **DESIGN UNDER WAY:**
  - PRESTABILIZED LASER SUBSYSTEM (PSL)
    - PRELIMINARY DESIGN READINESS REVIEW 6/95
    - PROTOTYPE SYSTEM BEING OPERATED ON 40 m INTERFEROMETER
    - CHANGE TO Nd:YAG LASER REQUIRES NEW PROTOTYPE FABRICATION IN 1996/1997
  - LENGTH SENSING & ALIGNMENT SYSTEM DESIGN READINESS REVIEWS HELD 5/95, 4/96
    - MODELING/SIMULATION WORK BEING PERFORMED FOR SERVO DESIGN
    - JPL SUPPORT - TIME DOMAIN LARGE-SCALE AXIAL DISPLACEMENTS
    - CYGNUS LASER CORP SUPPORT - ANGULAR D.O.F. MODEL
  - SUSPENSION SUBSYSTEM PRELIMINARY DESIGN REVIEW HELD 6/96 - PROTOTYPE SUSPENSION TO BE INTSALLED INTO 40 m
  - CORE OPTICS COMPONENTS DESIGN READINESS REVIEW HELD 2/96
    - SUBSTRATE PROCUREMENT BEING READIED
    - PATHFINDER PROGRAM WITH INDUSTRY HAS DEMONSTRATED CAPABILITY OF MEETING LIGO REQUIREMENTS
    - FINAL METROLOGY BEING PERFORMED IN CONCERT WITH NIST
  - MODE-CLEANER PROTOTYPE COMPLETED TO BE USED WITH NEW ND:YAG PRESTABILIZED LASER PROTOTYPE
  - ACTIVE SEISMIC ISOLATION (STACIS SYSTEM FROM BARRY CONTROLS, INC.) SUCCESSFULLY DEMONSTRATED AT MIT - MAY BE USED IN INITIAL LIGO
  - SEISMIC ISOLATION SYSTEM (PASSIVE) BEING OPTIMIZED AND DESIGNED BY HYTEC, INC. (LOS ALAMOS, N.M.)
    - IMPROVED DESIGN PROVIDES SIGNIFICANT LIGHTWEIGHTING - ACTIVE ISOLATION FEASIBLE
    - IMPROVED CONSTRAINED LAYER SPRINGS MAY INCREASE ISOLATION/REDUCE OUTGASSING LOADS

40m Interferometer Research

Program to test optical/sensing configuration on 40m

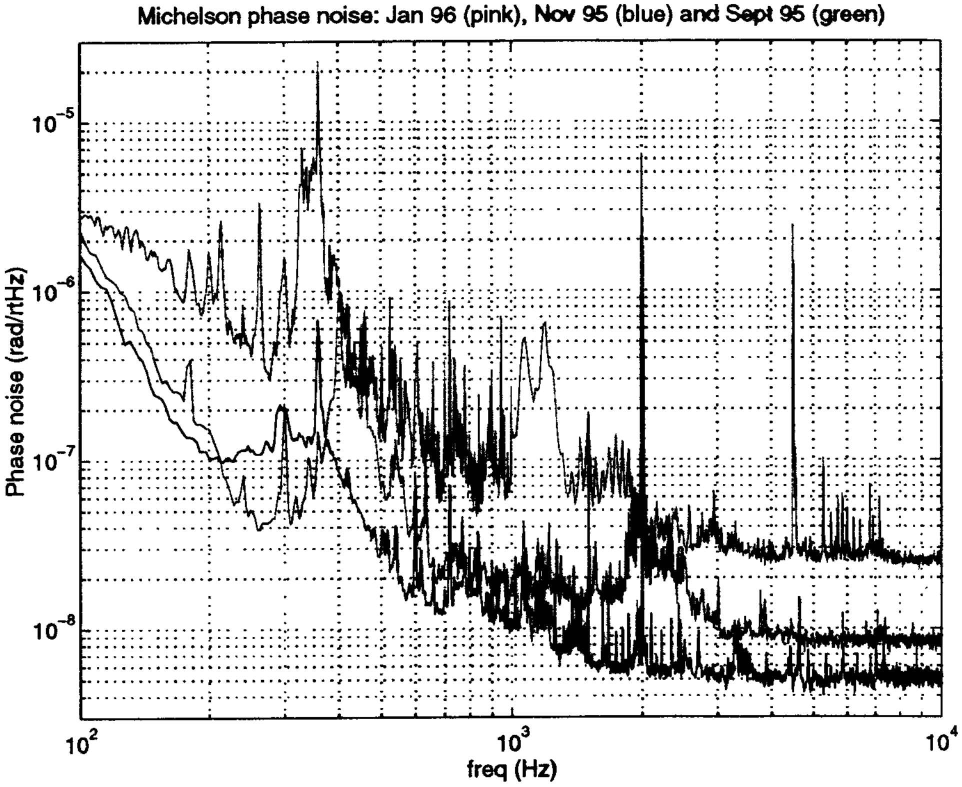
- Non-recycled Fabry-Perot Michelson interferometer
  - › extensive effort to understand noise at high frequencies
  - › incremental improvements in noise floor
  - › much more known about noise propagation in system
- Preparations for recycling in parallel
  - › optics specified, ordered
  - › servos/sensors specified, in design
- plan to start conversion to recycling in July


Preliminary Data from Optically Recombined 40-Meter Interferometer

Noise Equivalent Displacement

Phase Noise Interferometer Research

- Commissioning and first stage of measurements completed
- Non-recycled Michelson, Argon laser
  - › noise sources explained at present sensitivity level



- Recycling mirror installed, servo systems being tested
- Measurements during next month
- Conversion to 1.06 μm in mid-summer

R&D OBJECTIVES

- **Support initial detector technology**
    - CLOSE COORDINATION WITH DETECTOR
    - TASKS AND SCHEDULES PLANNED TO DELIVER INFORMATION WHEN NEEDED
    - DOMINATES PRESENT ACTIVITY
- **Develop new approaches for later interferometers**
    - ENHANCEMENTS TO THE INITIAL DETECTORS
    - NEW TERRITORY FOR ADVANCED DETECTORS
- **Form liaisons with other interested research groups**
    - FORUM FOR SHARING IDEAS, EFFORT

L-25

SUMMARY

- **LIGO IS BEING BUILT AS AN *OBSERVATORY* FOR GW ASTROPHYSICS**
- **LIGO FACILITIES HAVE PROCEEDED FROM FINAL DESIGN INTO FABRICATION & CONSTRUCTION PHASES**
  - CIVIL CONSTRUCTION TO START 8/96
  - ARM SLABS COMPLETED AT HANFORD
  - BEAM TUBE FABRICATION/INSTALLATION START 10/96
  - VACUUM EQUIPMENT FIRST ARTICLES UNDER FABRICATION
    - BEAM TUBE-VACUUM EQUIPMENT INTERFACE VALVES (1.2 M) UDE AT HANFORD 8/96
    - FIRST ARTICLE BEAMSPLITTER CHAMBER COMPLETE 9/96
- **LIGO DETECTOR SYSTEM DESIGN PROCEEDING**
  - BASELINE EXPECTED TO BE DESIGN GOALS
    - 10^{-18} METERS RMS @ 100 HZ
    - 10^{-9} RADIANS RMS OPTICAL PHASE
    - DETECTOR INSTALLATION AT HANFORD STARTS 7/98

R&D FOR LARGE BASELINE DETECTOR SYSTEMS

- INTEGRATED AND COLLABORATIVE R&D PROGRAM

- Current LIGO research and development program

- Example enhancements to the initial LIGO detector

- Longer range program: key issues and opportunities

Current LIGO R&D Program

›› Primary function to support initial detector design, fabrication, installation, diagnostics and operation

— Achieve sensitivity requirements for initial detector: sensing, random force and technical noise.

- displacement x_{rms} (100 Hz) $< 4 \times 10^{-18}$ m
- optical phase Φ_{rms}(100 Hz) $< 5 \times 10^{-10}$ radians

— Test the initial LIGO interferometer configuration in a suspended system

- servo control and acquisition
- scale to LIGO by modeling
- noise propagation through system

— Test initial LIGO interferometer subsystems

- characterization of triangular mode cleaner
- full size (25 cm) test mass suspension
- characterize and test initial full size optics
- technical design of active and passive seismic isolation
- development of 10 watt Nd:YAG laser source
- test of length control and fringe splitting system
- test of wavefront sensing interferometer alignment system

›› Tools and facilities

- 40 meter and 5 meter prototypes
- special facilities: optics test, seismic isolation test, fixed mass interferometers

The Initial LIGO Detector

›› Program

- Scheduled for installation beginning 7/98
- Triple coincidence operation $h_{rms} = 10^{-20}$ 12/00
- Design sensitivity $h_{rms} = 10^{-21}$ 11/01

Table 1: Initial detector parameters

Parameter	Nominal Initial Interferometer
Arm length	4000 m
Laser type @wavelength	Nd:YAG $\lambda = 1.064\mu$
Input power at recycling cavity	6 W
Contrast defect 1-c	$< 3 \times 10^{-3}$
Mirror loss	$< 1 \times 10^{-4}$
Power recyling gain	30
Arm cavity storage time	880 μ sec
Cavity input mirror transmission	3×10^{-2}
Total optical loss	4×10^{-2}
Mirror mass	10.7 kg
Mirror diameter	25 cm
Mirror internal Q	1×10^{6}
Pendulum Q (structure damping)	1×10^{5}
Pendulum period (single)	1 sec
Seismic isolation system	T(100Hz) = -110dB

Enhancements to the initial detector

- Initial detector balances risk and performance
  - "best is the enemy of possible"
  - deferral of less mature but promising techniques
- Initial observations followed by detector improvements
  - decisions involve PAC and community through LRC
- Possible scenarios:
  - detections have been made and statistics is needed
  - detections have been made and optimizations are required
  - no detections have been made but new posited sources
  - compact binary coalescences still most likely sources
  - a tested new technical concept is promising
  - ??
- Assume for the following
- enhancements broadly defined as incremental changes to the initial detector requiring R&D but not major configurational changes

Example incremental enhancements

step 1

- Double pendulum suspension

  Reduction in contribution of thermal noise from final isolation stage

  Electrostatic controller for final stage:

  Improved test mass Q

  Reduced sensitivity to fluctuating magnetic fields

  Mechanical filter for control noise

  Improved seismic isolation

step 2

- Reduced pendulum losses

  Alternate mounting techniques

  New flexure design and materials

- Reduced internal test mass losses

  Higher Q test mass: basic materials research and new designs

step 3

- Improved seismic isolation

  Lower spring constant springs

  External active isolation (if not incorporated in the initial detector)

step 4

- Higher circulating power in arms

  Higher input laser power

  Lower loss coatings on test mass mirrors

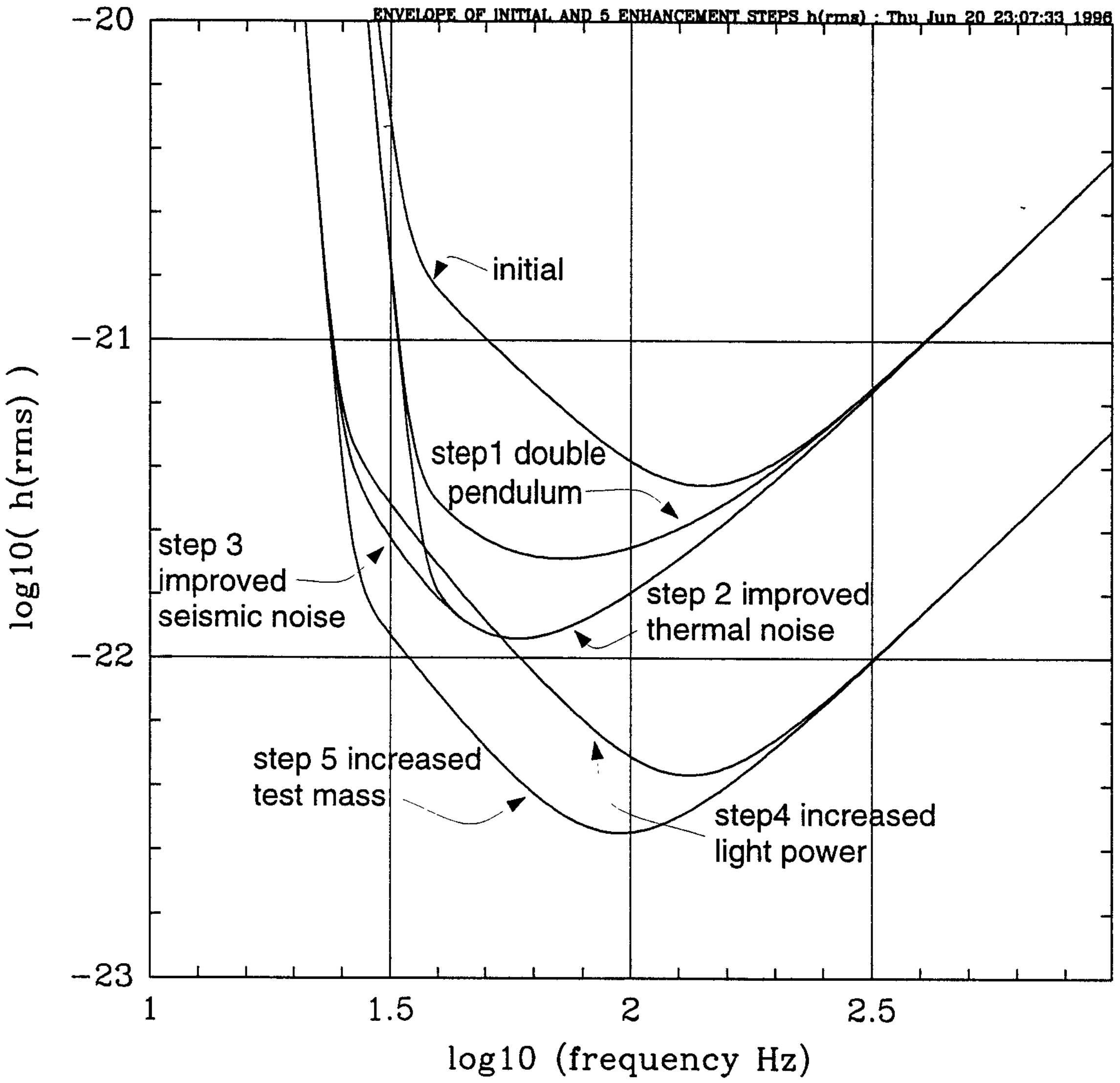
step 5

- Increased test mass

  Needed to reduce radiation pressure noise

  Reduction in pendulum thermal noise

Example incremental enhancements



Example incremental enhancements

- After final step:

Table 2: Sample enhanced detector parameters

parameter	sample enhanced value
Laser power (0.3 input efficiency)	100 W
contrast defect	$< 1 \times 10^{-3}$
mirror loss	2×10^{-5}
arm cavity storage time	880 μ sec
mirror mass	30 kg
mirror internal Q	3×10^{8}
Pendulum Q (double pendulum)	1×10^{8}
seismic isolation	T(100Hz) = -120 dB

Longer range program

›› Principal issues:

- reduction in thermal noise --- issue for low frequency detection
- increase in power handling of the optics -- issue for high frequency detection
- new interferometer configurations will be needed
- optimization of the power handling and response for specific searches

›› Interferometer response: trade bandwidth for sensitivity

— spectral response tailored to sources

- improvement in periodic searches where limited by phase noise
- stochastic background searches improve as $(\Delta B)^{0.25}$ favors increased sensitivity
- adaptive filters that follow the coalescences

— technical development

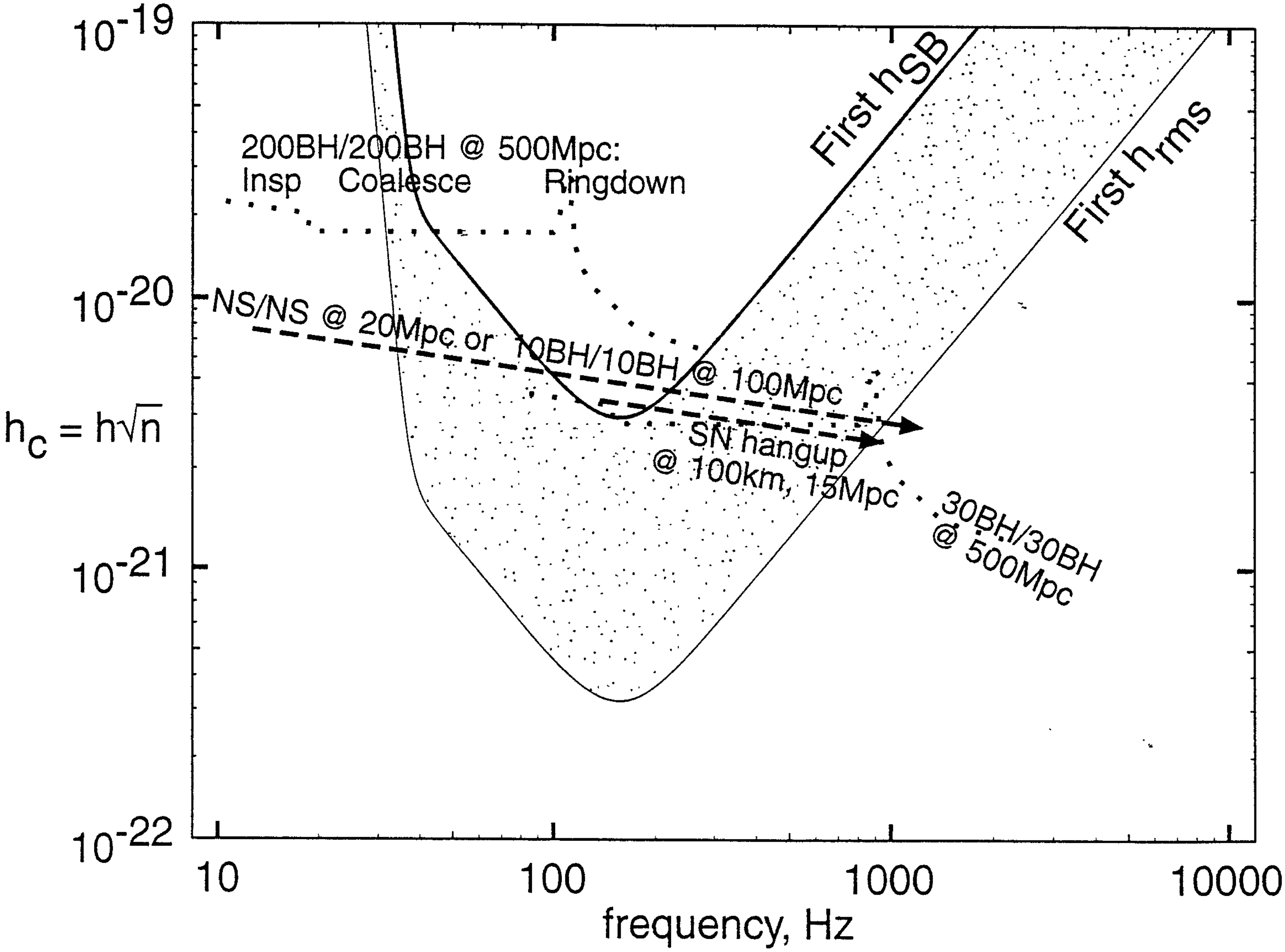
- interferometer configurations using opaque test masses
  - -- extends choice of materials with low optical and mechanical loss
  - -- reductions in thermal wavefront distortion
- interferometer configurations less sensitive to wavefront perturbations
- techniques to hold interferometers at operating points

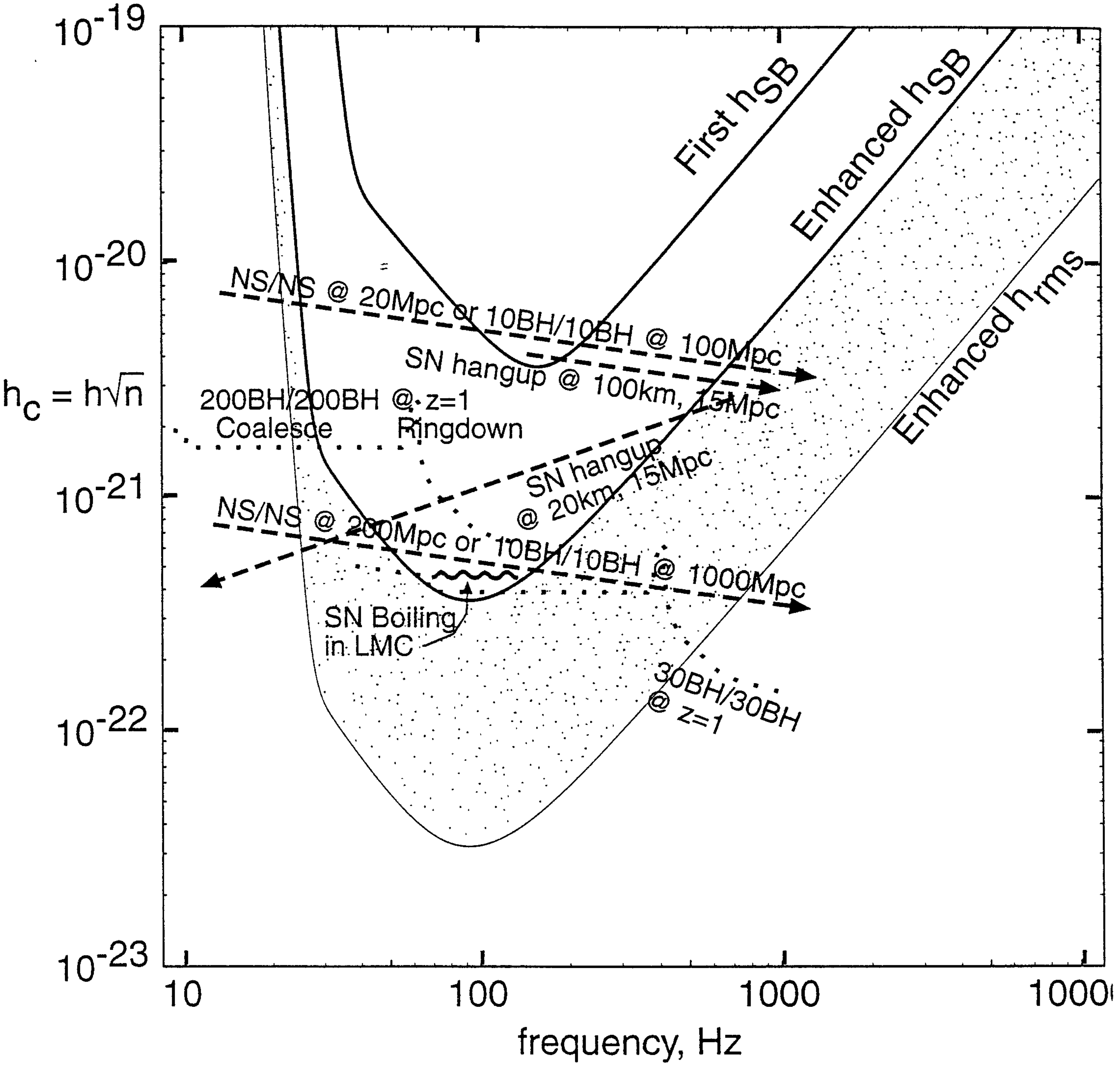
››Thermal noise

- fundamental materials research is needed
- direct measurement of test mass internal thermal noise

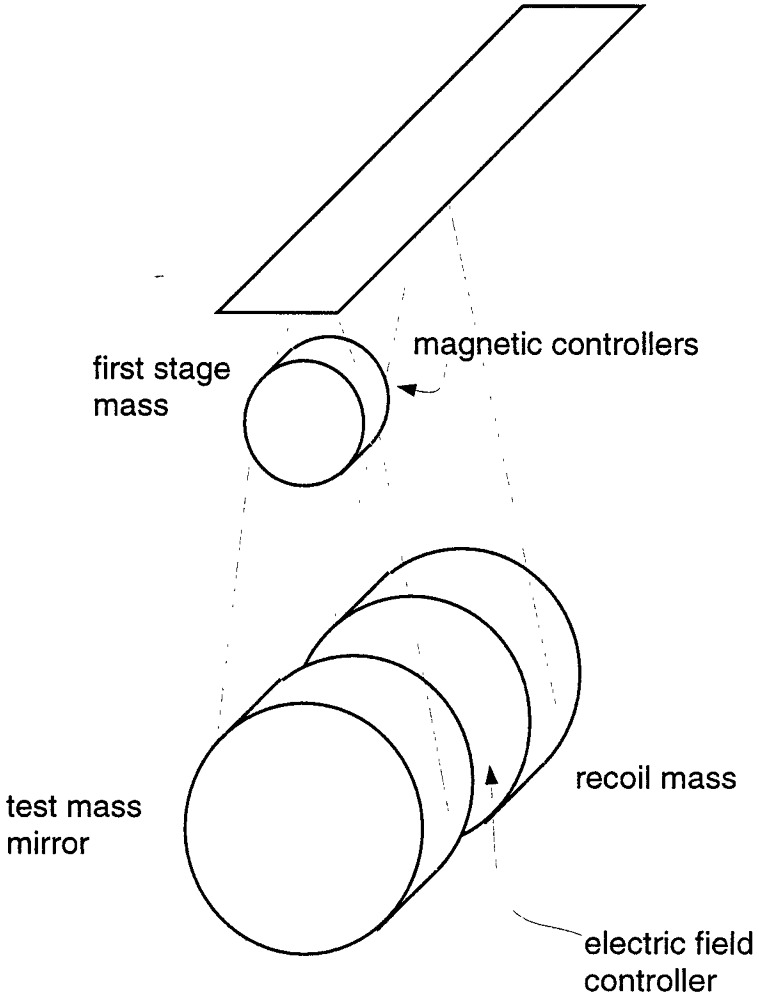
›› Seismic noise

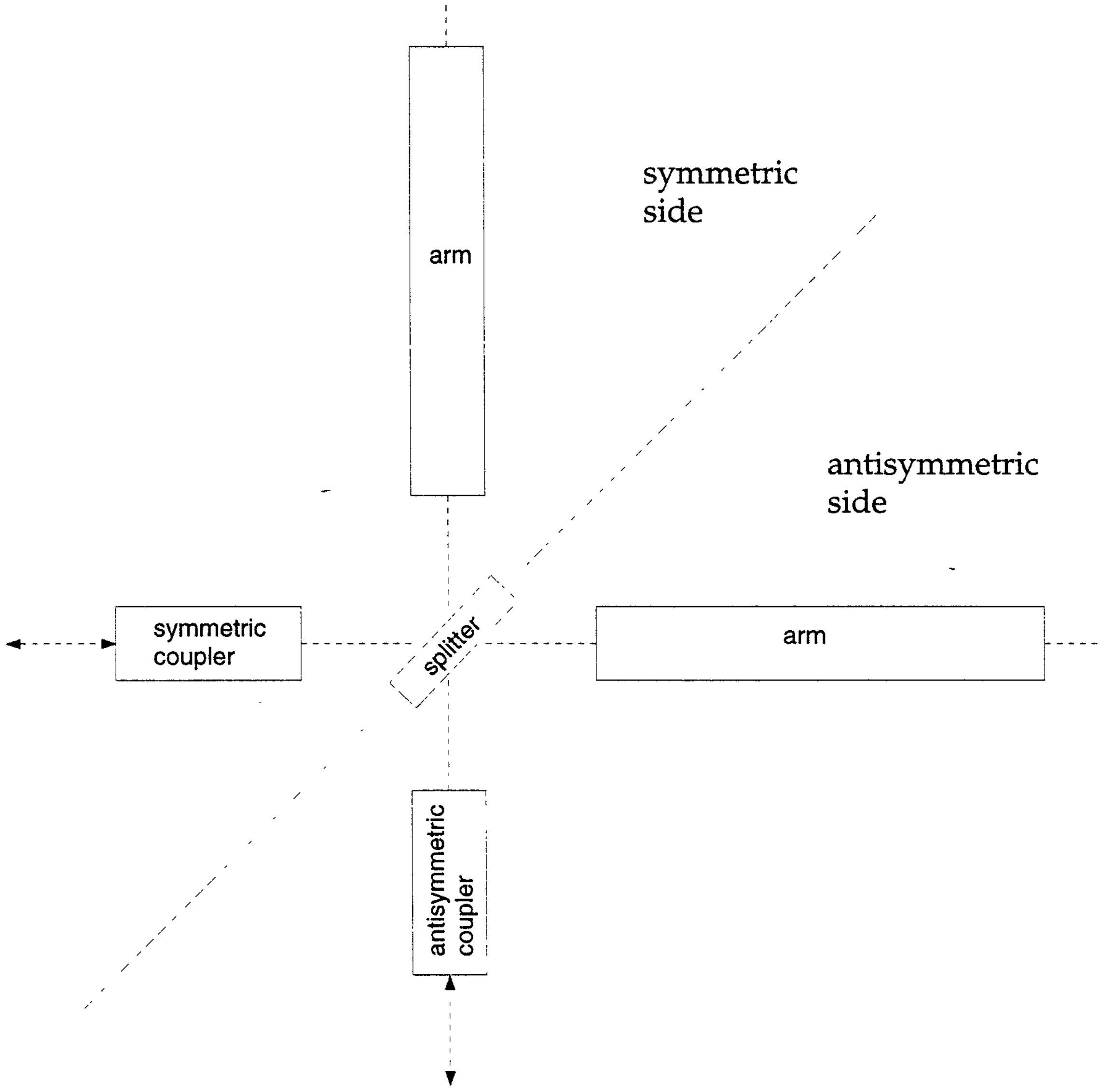
- passive and active seismic isolation to the level of the natural g gradients

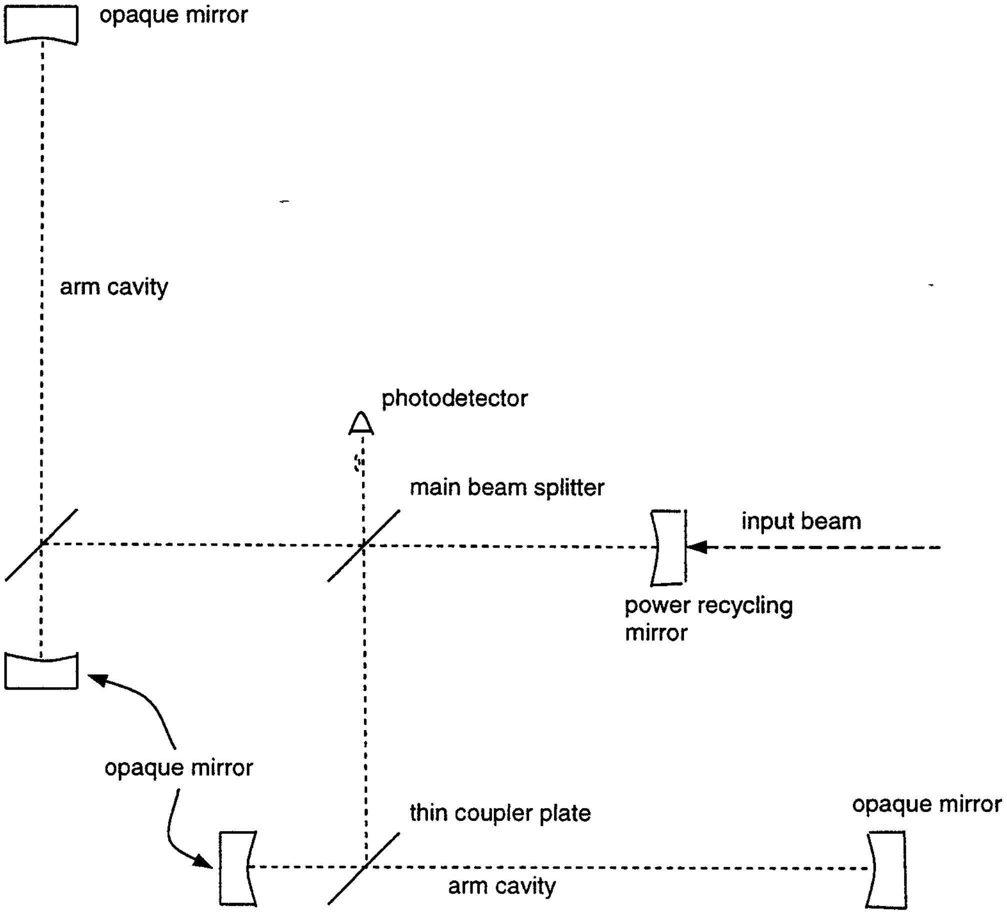

10^{-19}
10^{-20}
10^{-21}
10^{-22}
$h_c = h\sqrt{n}$
10
100
1000
10000
frequency, Hz
200BH/200BH @ 500Mpc:
Insp
Coalesce
Ringdown
First hSB
First h_{rms}
NS/NS @ 20Mpc or 10BH/10BH @ 100Mpc
SN hangup
@ 100km, 15Mpc
30BH/30BH
@ 500Mpc

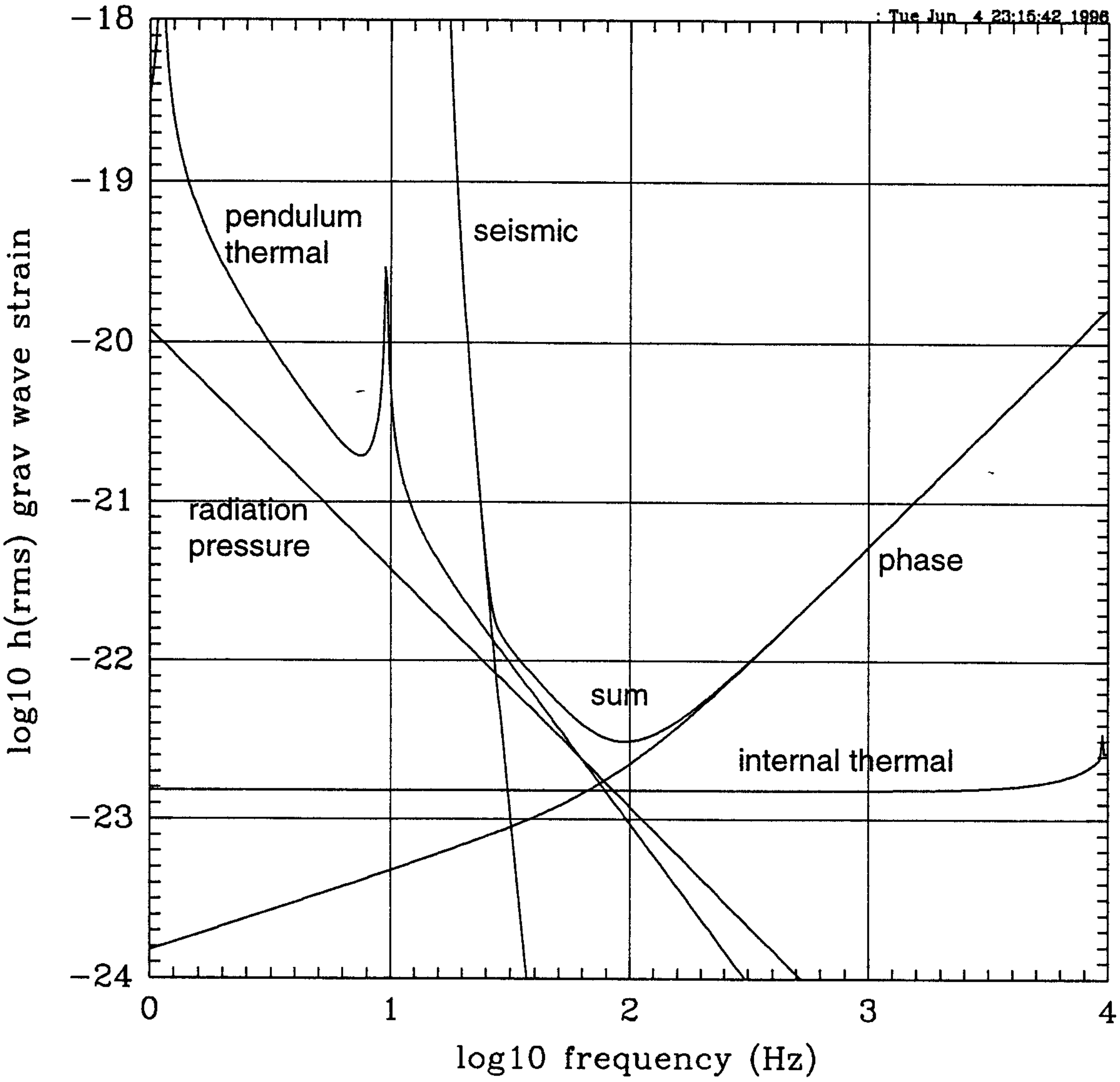


First hSB
Enhanced hSB
Enhanced h_rms
NS/NS @ 20Mpc or 10BH/10BH @ 100Mpc
SN hangup @ 100km, 15Mpc
200BH/200BH @ z=1
Coalesce
Ringdown
SN hangup @ 20km, 15Mpc
NS/NS @ 200Mpc or 10BH/10BH @ 1000Mpc
SN Boiling in LMC
30BH/30BH @ z=1
h_c = h√n
10^-19
10^-20
10^-21
10^-22
10^-23
10
100
1000
1000
frequency, Hz


first stage
mass
magnetic controllers
test mass
mirror
recoil mass
electric field
controller


symmetric
side
arm
antisymmetric
side
symmetric
coupler
splitter
arm
antisymmetric
coupler


opaque mirror
arm cavity
photodetector
main beam splitter
input beam
power recycling mirror
opaque mirror
thin coupler plate
opaque mirror
arm cavity

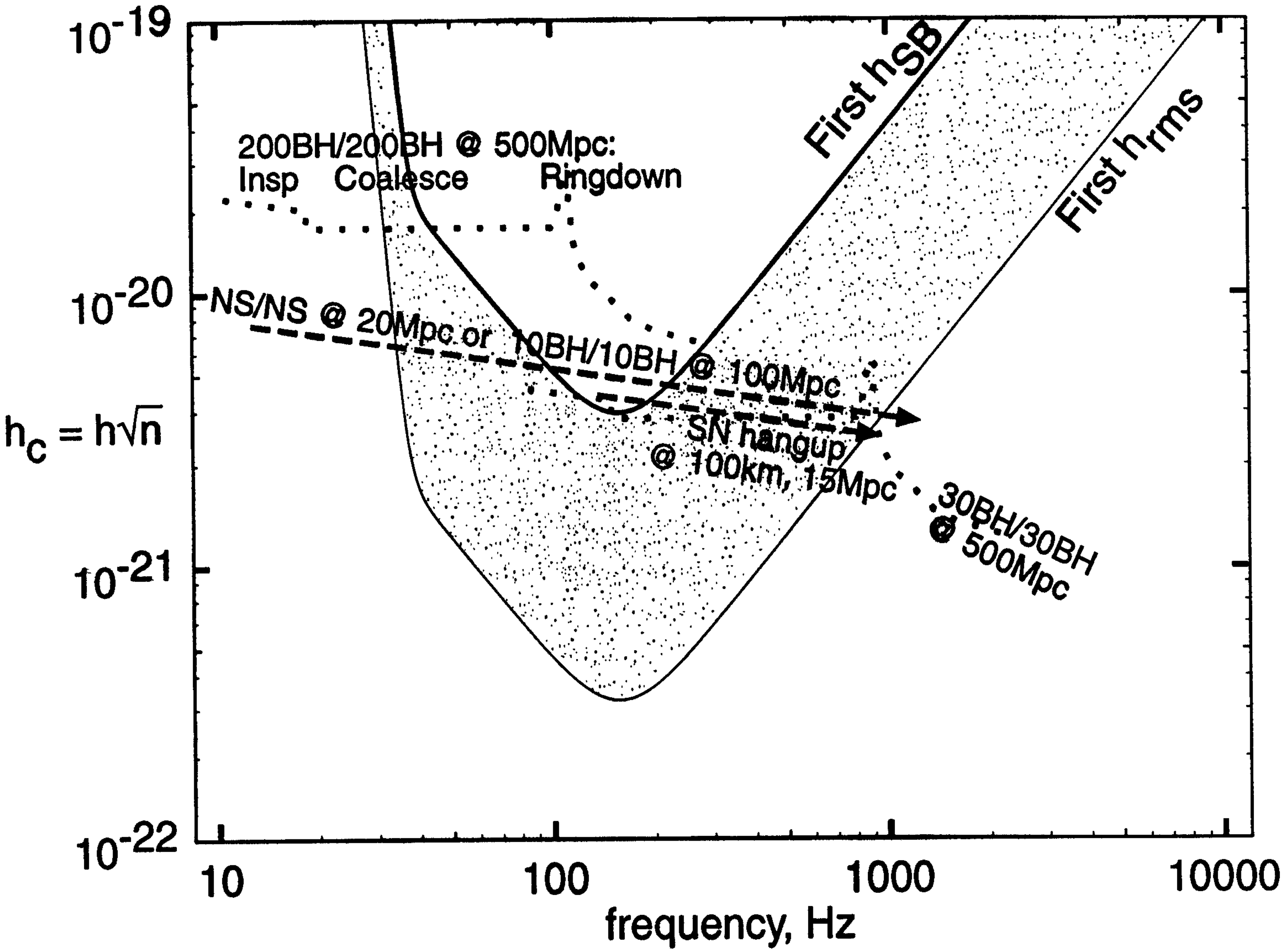

: Tue Jun 4 23:15:42 1996
log10 h(rms) grav wave strain
−18
−19
−20
−21
−22
−23
−24
pendulum
thermal
seismic
radiation
pressure
phase
sum
internal thermal
0
1
2
3
4
log10 frequency (Hz)

The Uses of LIGO

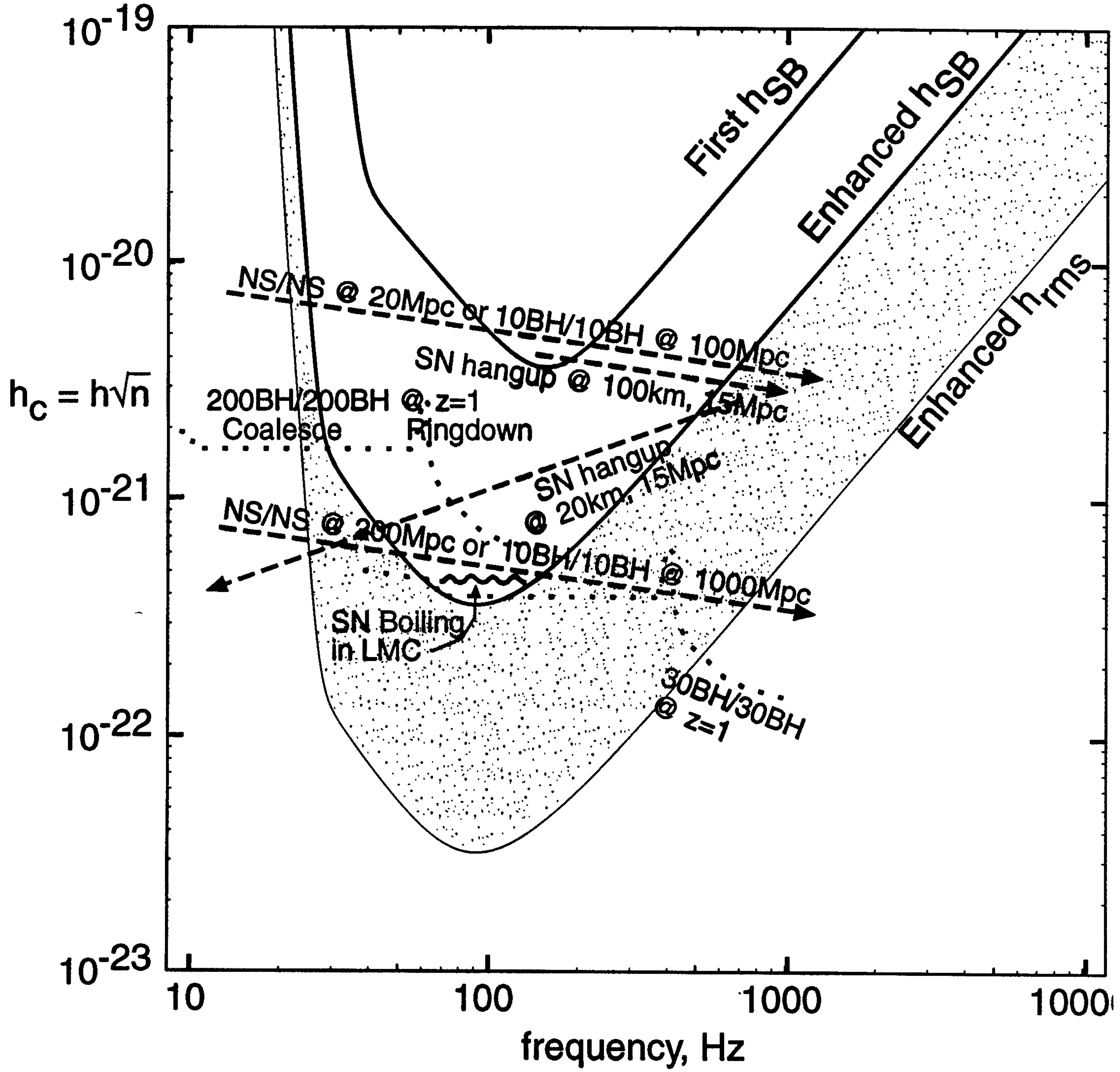
- Physics Capability
- The Schedule
- Data Analysis
- Plans of the LIGO Group
- Modes of Collaboration

Barry Barish

CAPABILITIES OF THE INITIAL LIGO INTERFEROMETERS



CAPABILITIES OF ENHANCED LIGO INTERFEROMETERS



LIGO

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)

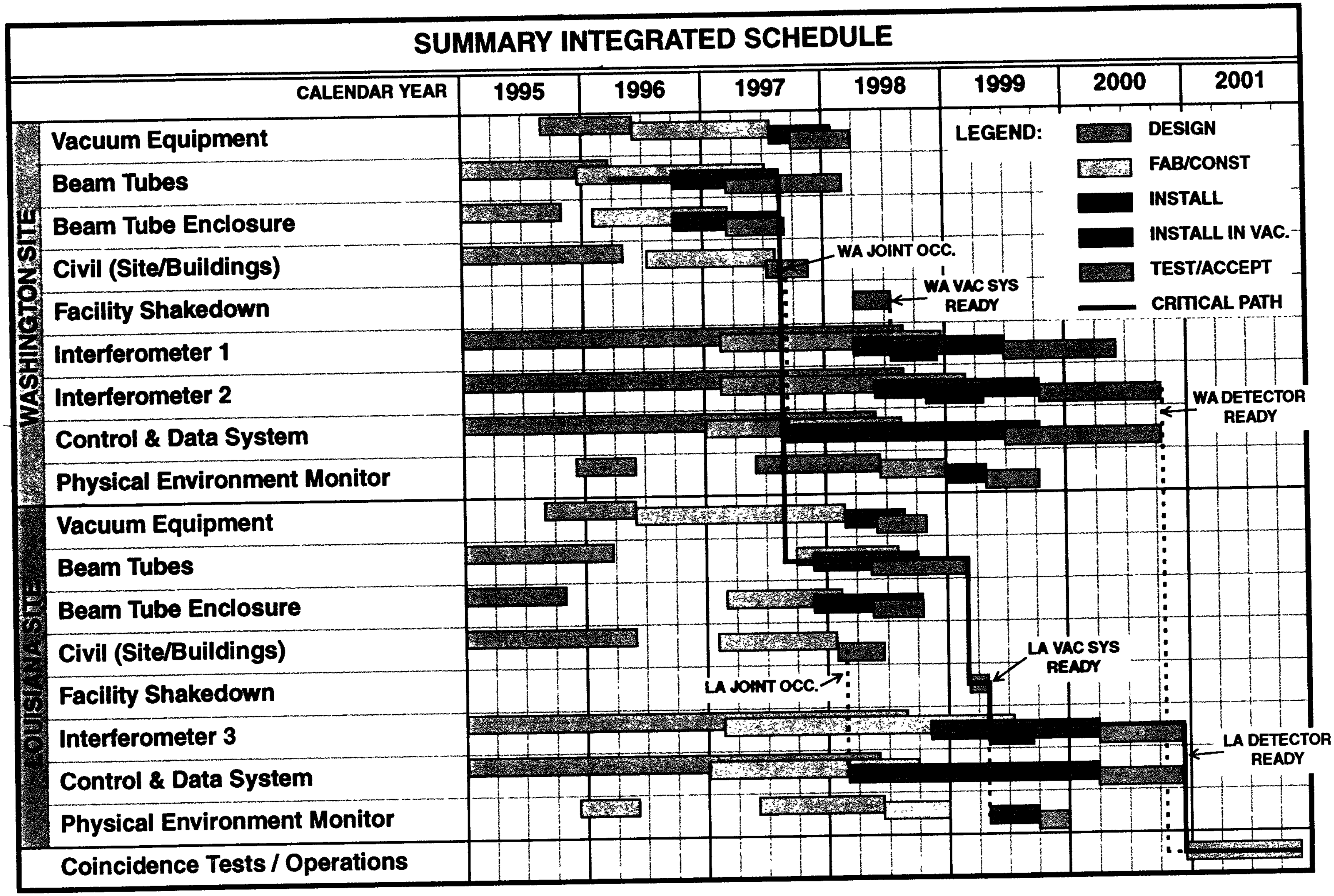
- Coincidences with other Detectors
  - VIRGO, Geo-600, etc
  - Resonant Bars or Spheres

- Coincidence Data
  - LIGO - ring on the sky <1 degree
  - LIGO - no polarization information
  - LIGO + VIRGO - polarization decomposition; position in sky < 1 degree
  - Stochastic Background

LIGO

The Project

- Construction Project (1995-1999)
  - » facilities and initial detector
  - » simulation and analysis systems
- Commission Facility (1998-2001)
  - » implement initial detectors
    - – $h \sim 10^{-20}$ - coincidence
      - initial search (end of 2000)
    - – $h \sim 10^{-21}$ - initial design sensitivity (end 2001)
  - » data analysis/software development
  - » R&D towards enhancements/future detectors
    - – developments and demonstrations; collaborative
- Full Operations (2002 + ...)
  - » running and data analysis
    - – coincidences with other detectors
    - – data availability
  - » enhance initial detector
    - – advanced R&D; highly collaborative
  - » advanced detectors
    - – flexibility and infrastructure



SUMMARY INTEGRATED SCHEDULE

LIGO

Approved Funding

Fiscal Yr	Construction	R&D	Operation	Total
1992	$15.9M	$3.2M		$19.1M
1993	$20.0M	$4.0M		$24.0M
1994	0	$4.0M		$4.0M
1995	$85.0M	$4.0M		$89.0M
1996	$55.0M	$4.0M		$59.0M
1997	$55.0M	$0.8M+?	$0.3M	$56.1M
1998	$41.2M	$2.5M?	$7.3M	$48.5M
1999		$2.5M?	$20.9M	$20.9M
2000		$2.5M?	$21.1M	$21.1M
2001		$2.5M?	$19.1M	$19.1M
Total	**$272.1M**	**$20.0M+?**	**$68.7M**	**$360.8M**

LIGO

R&D Program

- 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)
- Advanced R&D by LIGO Groups
  - » scope ~ $2.5M/year (Caltech/MIT)
  - » highly collaborative
  - » demonstration of techniques on 40m, 5m
  - » typicical enhancement ~$5M equipment funds
- Community Program

LIGO

Data Analysis

- Data Controls
  - EPICS system
- Software Environment
  - AVS -- C++ ; Object Oriented
- Simulations
  - subsystem modeling
  - end to end model under development
- Data Acquisition
  - ~600 Gbytes/day raw rate
  - pre-processing; filtering
  - calibrations (length sensing, environmental, etc)
- Data Analysis
  - on-line (supernovae, etc)
  - off-line (storage and access)
  - data formats; coincidences with VIRGO, etc
  - User programs, documentation, etc

Computing
Requirements

- Large amount of data(600 Gbytes/day)
  - data storage
  - pre-processing
  - filtering and compressing

- Binary Neutron Inspiral
  - 1.5 Tbytes of templates - random access

- Periodic Sources
  - all sky search with 2000 samples/sec
  - ~300 Tflops

- Coincidences and Communications
  - Louisiana/Livingston --> Caltech/MIT
  - T1 lines; satellites

LIGO

Commissioning/Operations

- Management for Hanford: (staff ~ 20)
  - F. Raab (Head)
  - O. Matherny (Facilities Manager)
  - J. Worden (Vacuum Engineer)
  - R. Bork (Control and Data Systems)

- Management for Livingston: (staff~ 20)
  - M. Coles (Head)
  - G. Stapfer (Facilities Manager)
  - A. Sibley (Vacuum Engineer)

- MIT / Caltech
  - installation, commissioning, and running
  - support the operations of the facilities
  - data analysis and science

- Advanced Detector development <u>not</u> supported in Operations Plan

LIGO
Program Advisory Committee

- Pre Program Advisory Committee
  - Members - Saulson (ch), Prescott, Hamilton, Reudiger, Giazotto, Finn
  - Fall meeting: Formed charter and suggested members for the LIGO Research Community (LRC)
  - Spring Meeting: Formed charter and suggested members for the LIGO Program Advisory Committee
- Program Advisory Committee
  - being formed; first meeting in fall '96

LIGO
The Community

- Aspen Workshops (Jan 95,96)
- LIGO Research Community (LRC)
  - » Formed charter, membership of LRC (172 members; now 200+)
  - » Elected Executive Board; Chairman (S.Finn)
  - » Meeting @ Spring APS
- Collaborations
  - » VIRGO : Workshop in April on Data Formats
    - cooperate on technology, data analysis; MOU in process
  - » GEO 600:MOU - visitors program
  - » TAMA: MOU - visitors program
  - » MOUs :
    - Bender (JILA), Byer (Stanford), Saulson (Syracuse); Sandeman (Australian groups), K. Thorne (Caltech), etc.

LIGO
Modes of Use

- Individual
  - Visitor Program (~3 FTE / yr)
    - data analysis; 40 meter; R&D program, etc
  - R&D or Data Analysis Development leading to collaboration
    - P. Saulson; B. Allen, K. Thorne
- Institutional
  - Collaboration on Initial Detector
    - Florida Group (input optics +)
  - Collaboration on Advanced R&D for enhancements (enabling technology)
    - Australia on Saphire Test Masses
  - Collaboration on Data Analysis/Software Development
  - Independent effort toward advanced interferometer
  - Independent Data Users