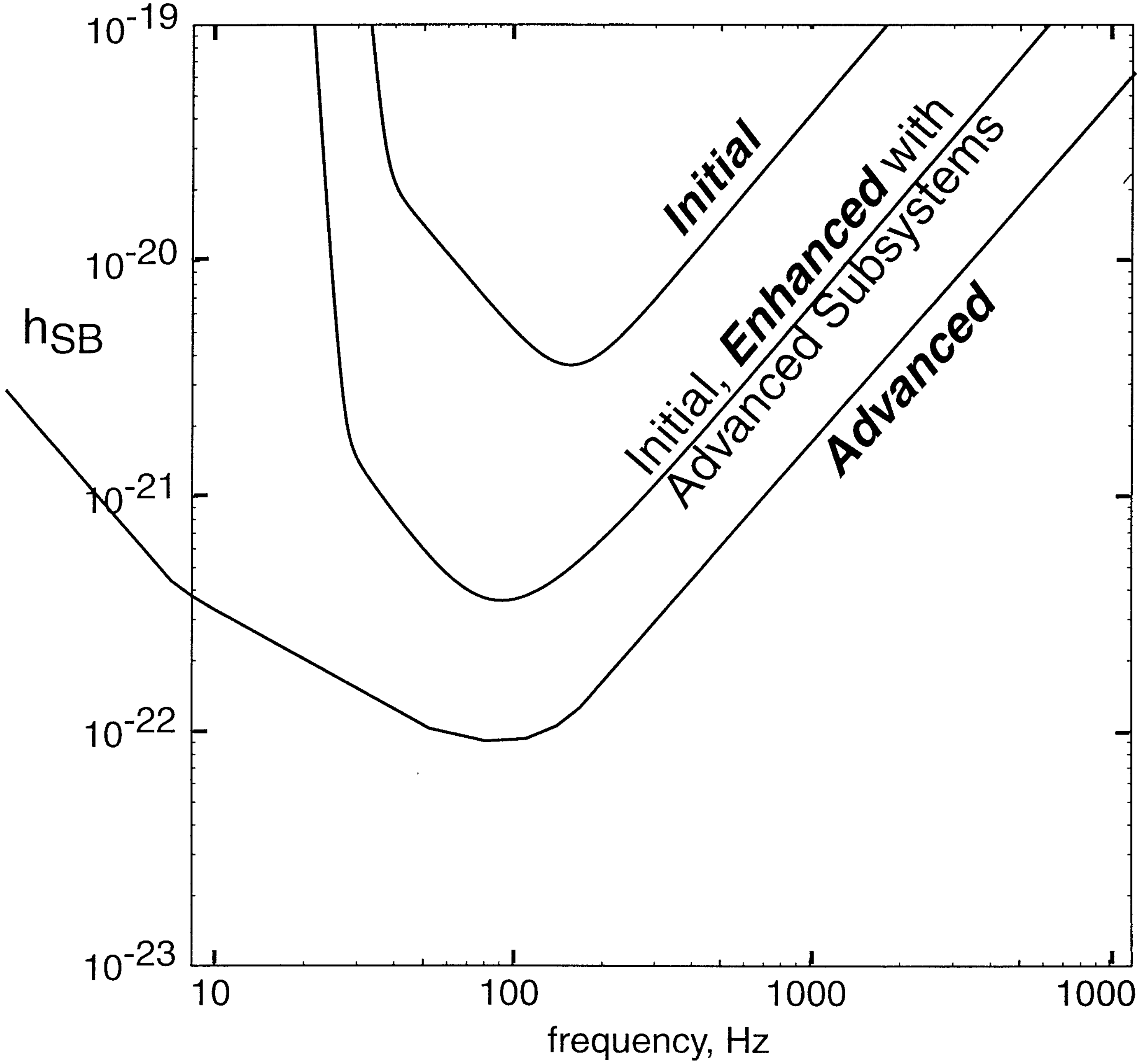
LIGO-G980125-00-R

ASTROPHYSICAL MOTIVATIONS FOR LIGO LABORATORY'S ADVANCED R&D

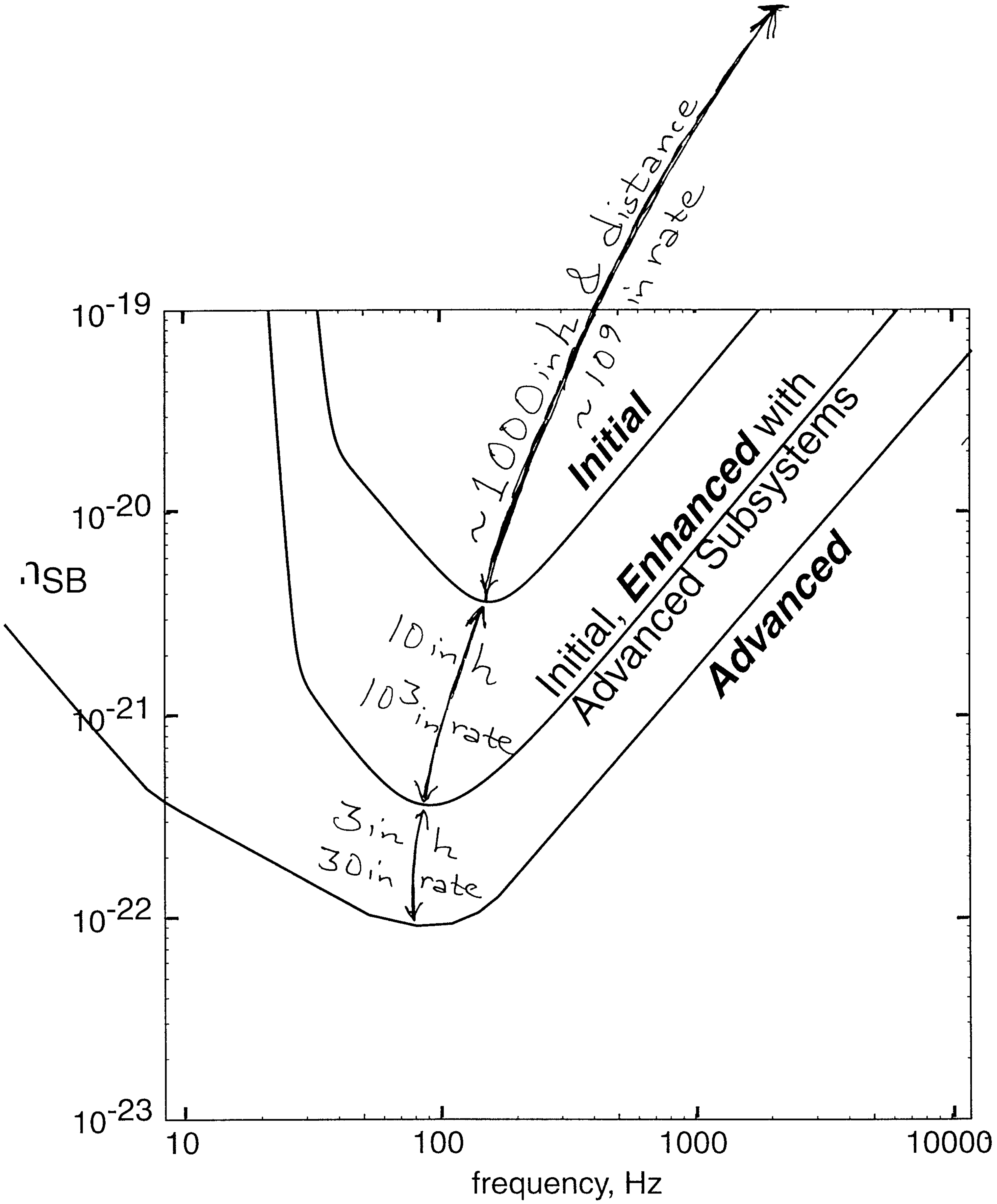
Kip S. Thorne, Caltech

Presentation to NSF panel to review the LIGO Advanced
R&D Proposal, at Arlington, VA, 22 January 1998

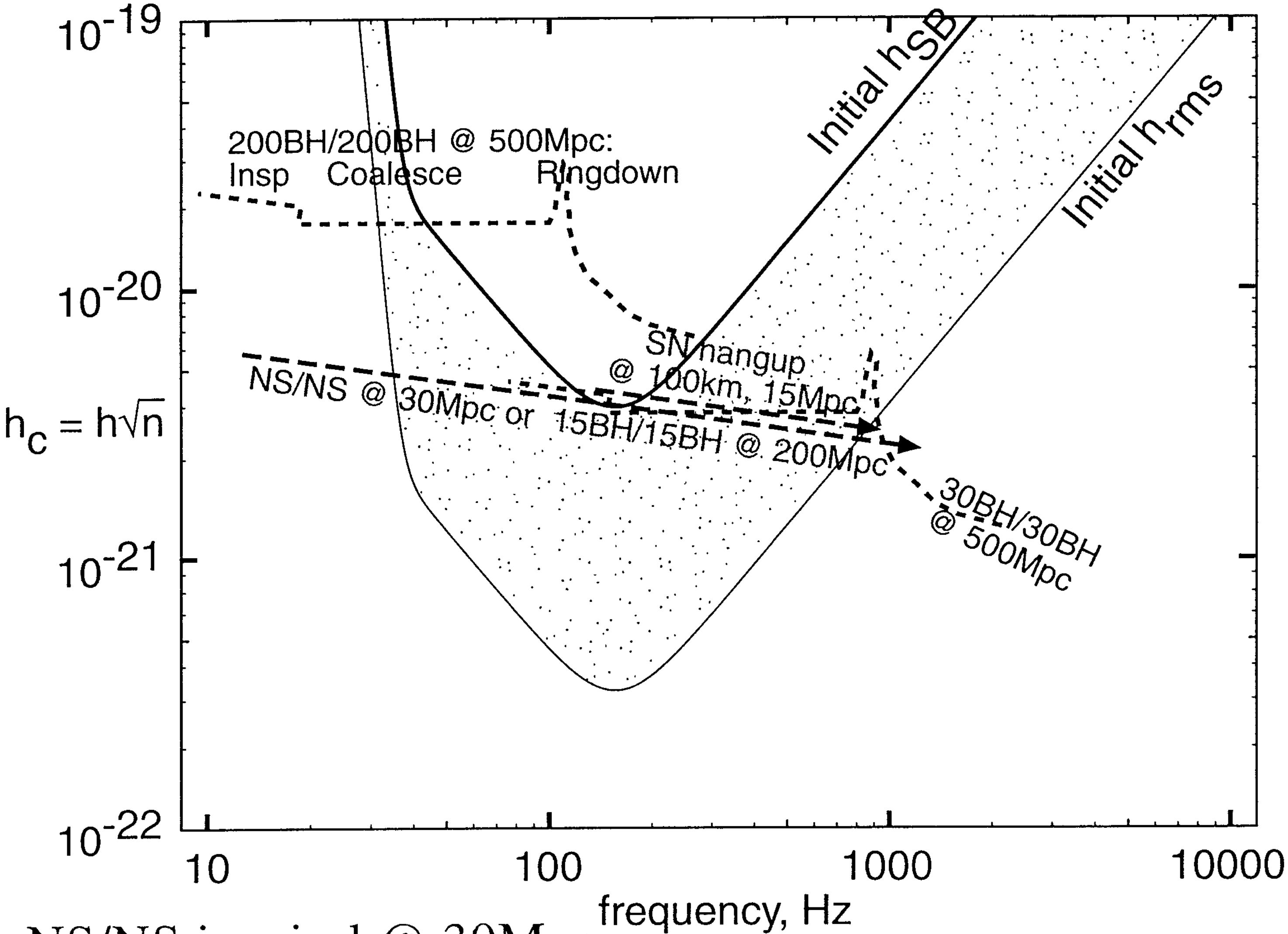
SENSITIVITY TO GW BURSTS (11 h_{rms})



SENSITIVITY TO GW BURSTS (11 h_{rms})



INITIAL SEARCH (2002-2003): Plausible Sources



NS/NS inspiral @ 30Mpc
(most optimistic: 16Mpc; best estimate: 150Mpc)

15BH/15BH inspiral @ 200Mpc
(= best published estimate for globular clusters)

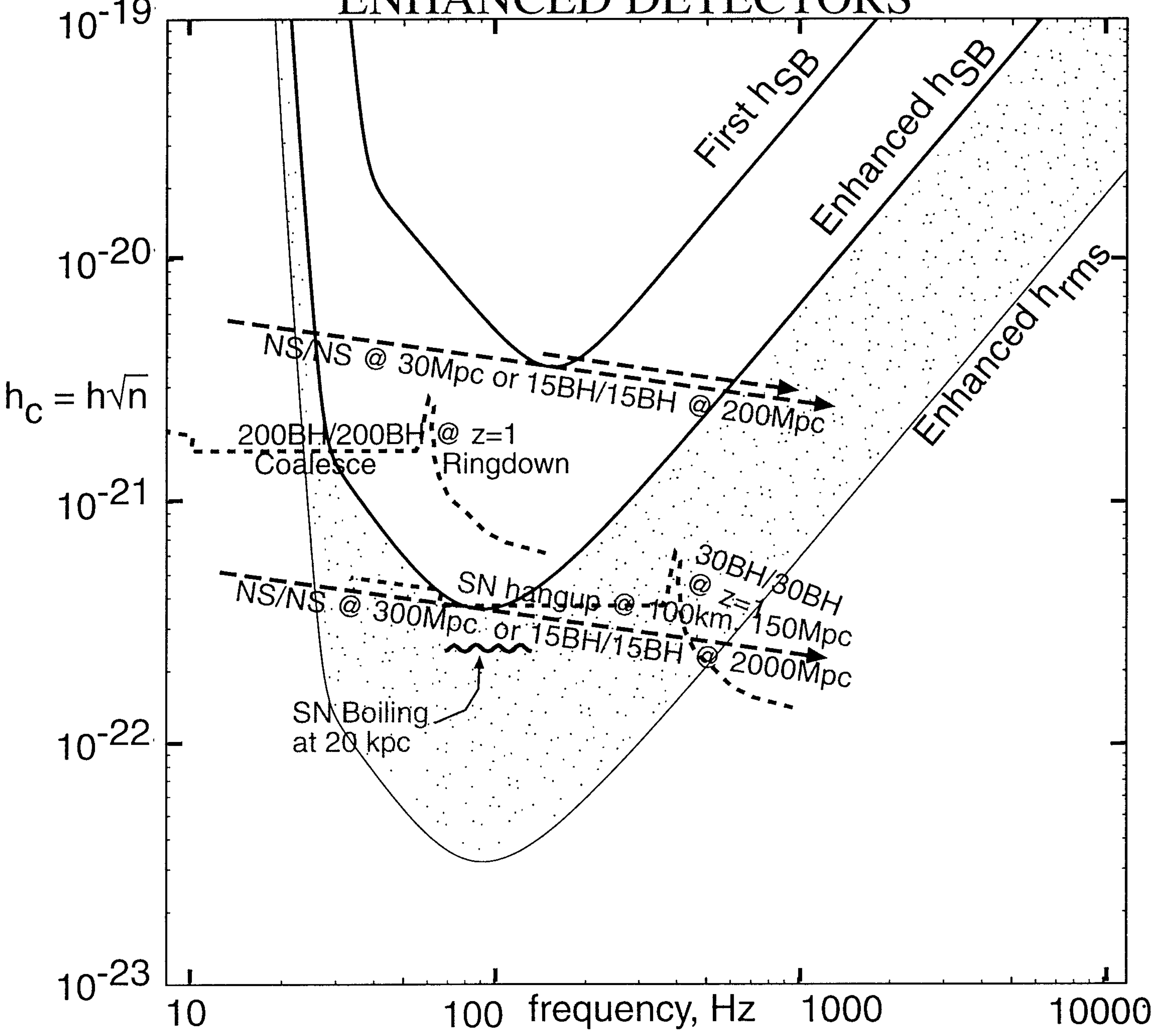
Merger of BH/BH Binary with masses 30 to 200, @ 500Mpc (highly uncertain)

Nonaxisymmetric supernova @ 15Mpc

1 msec pulsars in our Galaxy with ellipticity 10^{-6}

Stochastic background at $3x10^{-7}$ of closure energy

ENHANCED DETECTORS



NS/NS inspiral @ 300Mpc (best estimate: 150Mpc)

15BH/15BH inspiral @ 2000Mpc

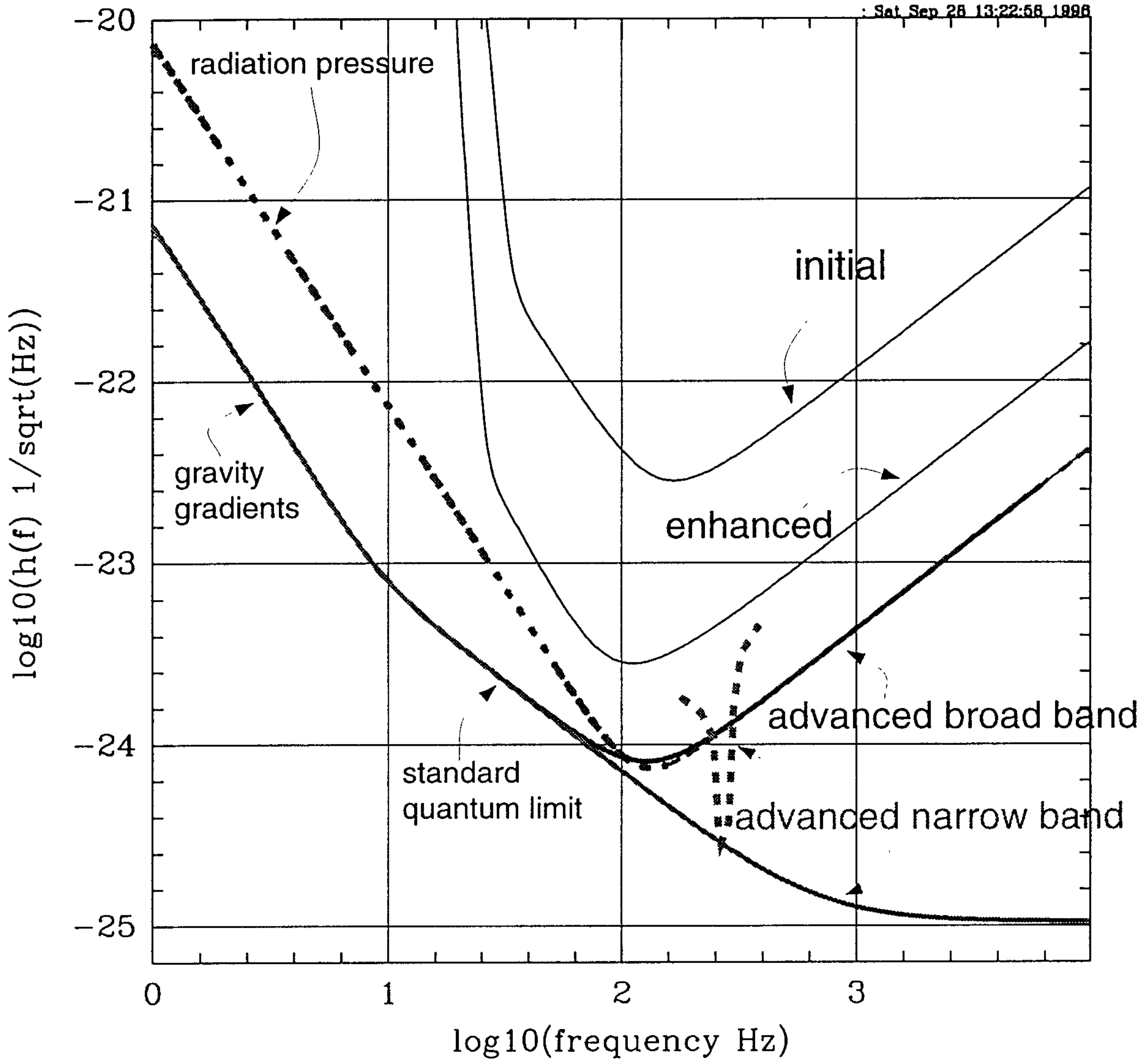
Merger of BH/BH Binary with masses 30 to 200, @ z=1

Nonaxisym supernova @ 150Mpc; NS boiling in our galaxy

1 msec pulsars in our Galaxy with ellipticity $2\text{x}10^{-7}$

Stochastic background at $3\text{x}10^{-9}$ of closure energy

ADVANCED DETECTORS



Comparison with Enhanced Detectors:

Broad-Band:

30-fold increase in event rates & stochastic energy
much greater accuracies of information extraction
study5x heavier black holes

Narrow-Band:

Pulsar Searches 100x farther, or 100x smaller ellipticity
Stochastic Background 100x lower energy
Studies of NS/NS merger (measure NS eqn of state)

LIGO Laboratory Advanced R&D Proposal

Gary Sanders
LIGO Laboratory

Presenters

- Astrophysical Motivations for LIGO Lab Advanced R&D - Thorne (20 min)
- Overview of Proposed Program - Sanders (15 min)
- Stochastic Research/Thermal Noise Interferometer - Shoemaker (40 min)
- Higher Laser Power, Core Optics for Higher Power, Sapphire for Core Optics- Whitcomb (30 min)
- Advanced Photodetectors, Adaptive Thermal Compensation - Zucker (20 min)
- Advanced Controls Research - Coyne (15 min)
- Resonant Sideband Extraction - Mason (15 min)
- Resource Overview - Lindquist (10 min)
- LIGO Scientific Collaboration Perspective - Weiss (15 minutes)

Resubmittal

- Same 5 year period of performance as proposed last year
- Same programmatic goal of advanced subsystems and detectors
  - » But LSC is more mature so LIGO II is the explicit goal
- Roughly same level of effort as proposed last year
- Several new tasks
  - » photodiode research
  - » active compensation
  - » advanced controls

FY1997

- Original FY1997 request was for $1.7 M
- Granted $800K
- Funds received in July
- To date, tasks initiated are:
  - sapphire
  - Thermal Noise Interferometer
  - Resonant Sideband Extraction experiment

LIGO Funding by NSF Task and by Year

Fiscal Year	*Construction*	*R&D*	*Operations*	*Advanced R&D*	*Total*
Thru 1994	**35.9**	**11.2**			**47.1**
1995	**85.0**	**4.0**			**89.0**
1996	**70.0**	**2.4**			**72.4**
1997	**55.0**	**1.6**	**0.3**	**0.8**	**57.7**
1998	**26.2**	**0.9**	**7.3**	**2.7**	**37.0**
1999			**20.9**	**2.8**	**23.7**
2000			**21.1**	**2.9**	**24.0**
2001			**19.1 (10 months)**	**2.9**	**22.0**
Total	**272.1**	**20.0**	**68.7**	**12.1**	**372.9**

All funds shown in 'then-year' $M

LIGO CO-INVESTIGATORS

Professor Barry Barish
Principal Investigator

Dr. Gary Sanders
Co-Principal Investigator
Advanced R&D Coordinator

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GariLynn Billingsley
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Dr. Eric Black
Dr. James Blackburn
Brett Bochner
Dr. Jordan Camp
Dr. Mark Coles
Dr. Dennis Coyne
Advanced Controls Task Leader (Section 10)
Peter Csatorday
Dr. Peter Fritschel
Dr. William Kells
Sapphire Optics Task Leader (Section 7)
Dr. Peter King
Dr. Albert Lazzarini
Professor Ken Libbrecht
Thermal Noise/Resonant Sideband Extraction Task Leader (Sections 4, 11)
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Dr. Mark Pratt
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Dr. Brent Ware
Professor Rainer Weiss
Dr. Stanley Whitcomb
High Power Laser Task Leader (Section 5)
Dr. Hiroaki Yamamoto
Dr. Michael Zucker
Photodetector and Thermal Compensation Task Leader (Sections 8, 9)

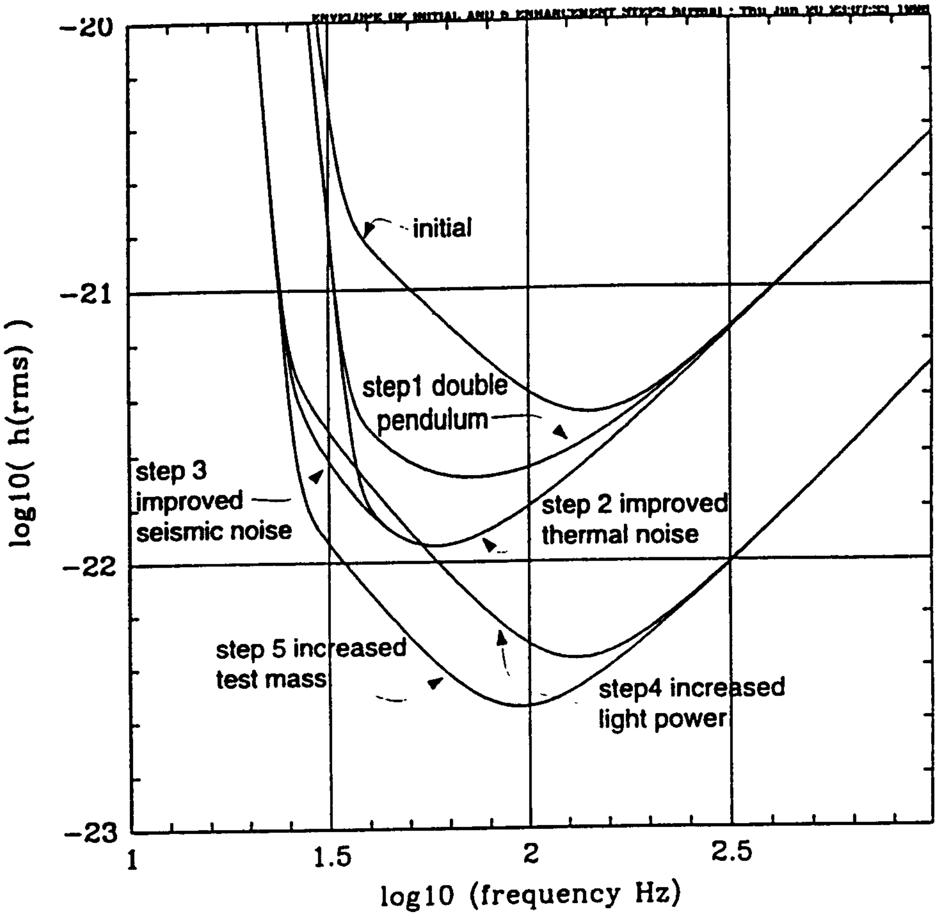


Figure 4: The improvements in h_{rms} associated with the steps outlined in the proposed program and resulting in the parameters given in Table 2. The logic of the steps is determined by the assumption that compact binary coalescences are the most likely source to be detected, hence the importance of improving the sensitivity near 100 Hz. The improvements associated with the double suspension, reduction in the thermal noise and increase in the test mass (steps 1, 2 and 5) are tightly coupled.

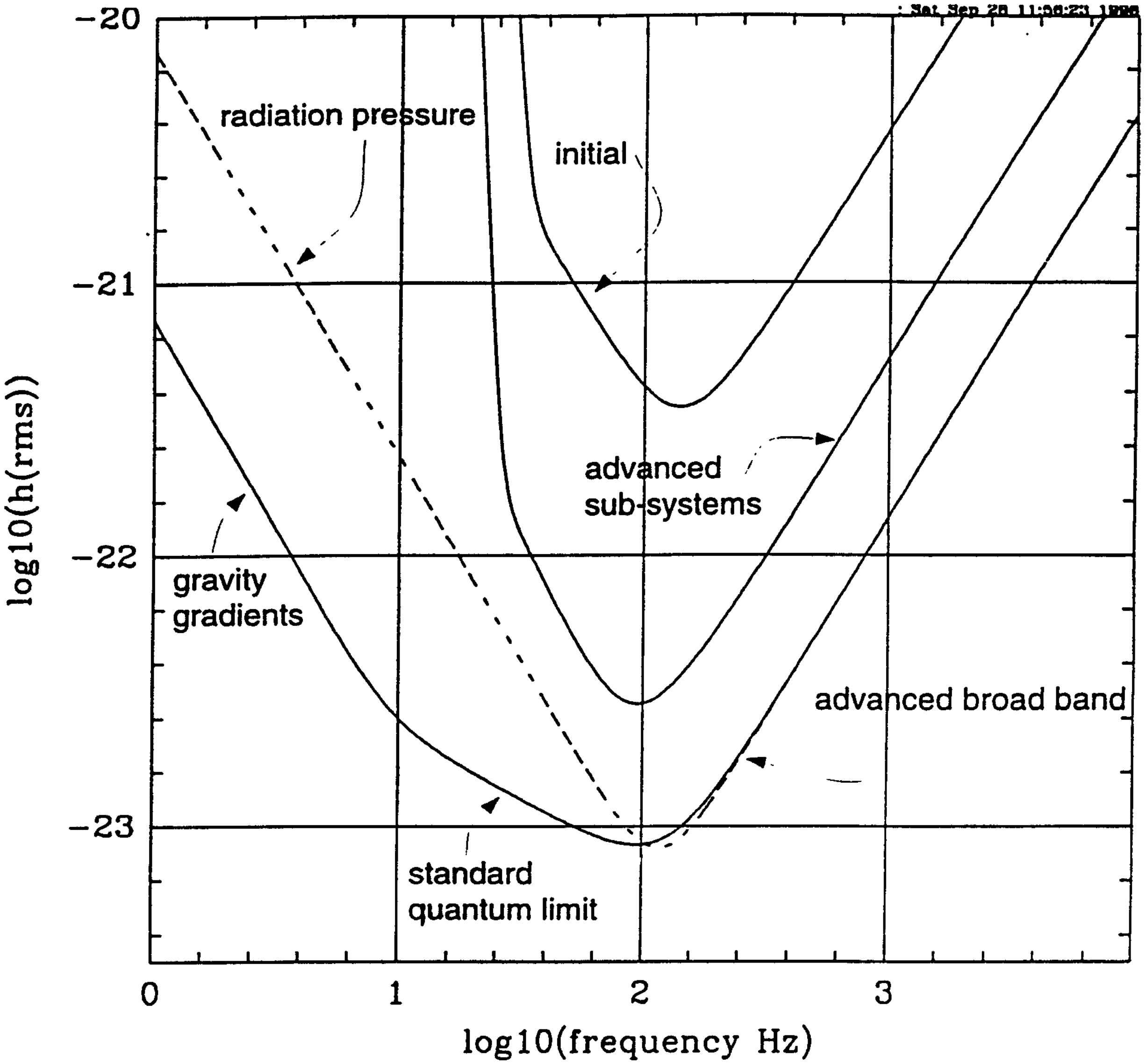
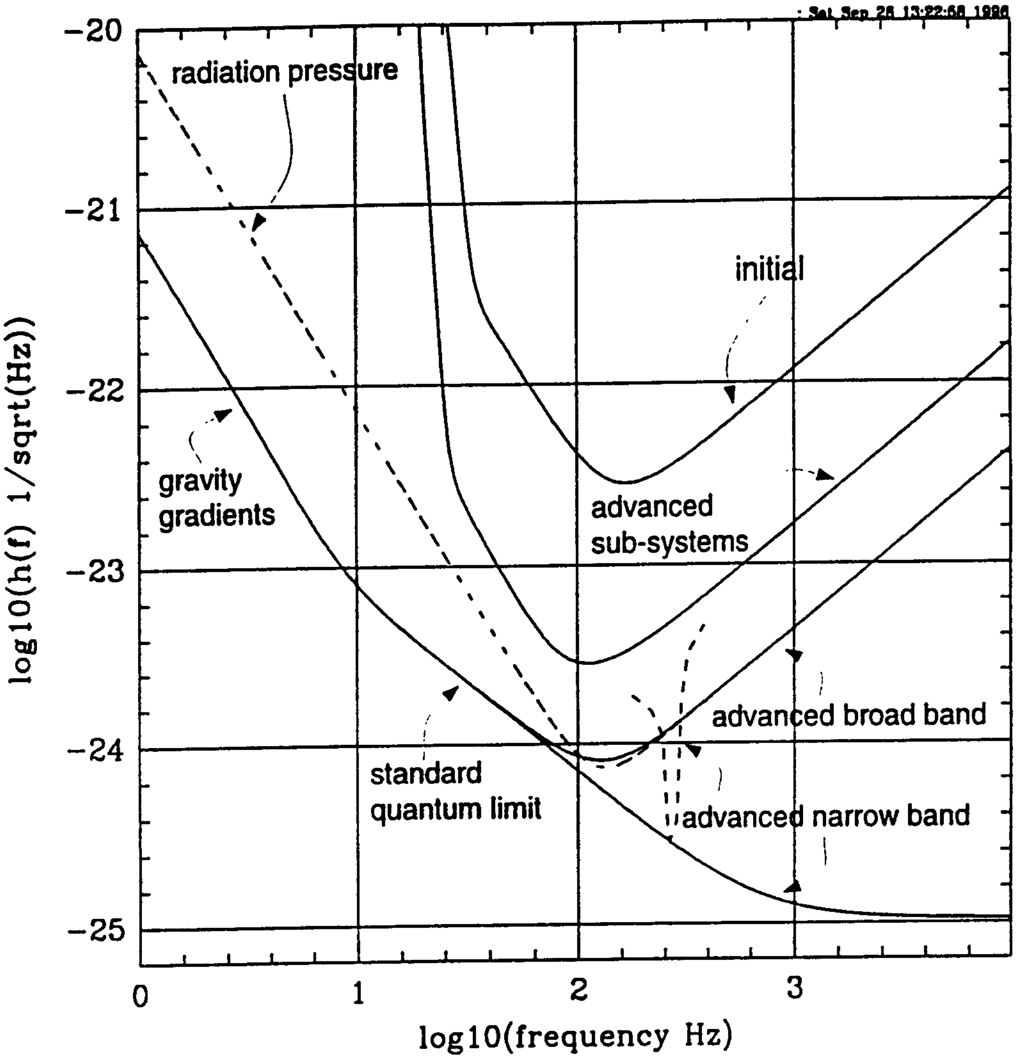


Figure 2: The h_{rms} noise envelopes for the initial LIGO (LIGO I) detector and a detector (LIGO II) that has been enhanced by the application of the advanced subsystems described in the text and Figure 4 on page 11. The strategy for this specific set of steps is to improve the sensitivity near 100 Hz and thereby the detection of NS/NS coalescences.The curve labeled advanced broad band is the noise in a future detector (beyond LIGO II) using 300kg test masses and 5 ppm loss mirrors illuminated by a 100 watt 1 micron laser. The line labeled radiation pressure is the limiting noise for this advanced detector at low frequencies. By reducing the circulating power in the interferometer the noise below 100 Hz can brought to the lower curve limited by gravity gradients and the standard quantum limit but with an increase in the sensing noise above 100 Hz. The assumption has been made that the research in advanced detectors has resulted in bringing the thermal and seismic noise below the other limiting terms.

Figure 3: The amplitude spectral strain noise expressed as an equivalent h(f) to characterize the detector. The detection "signal to noise" is determined from this quantity when the source spectrum is known. The noise power in the detection of a particular source is calculated by integrating $h(f)^2$ as a function of frequency through the optimal filter for the source. The curves represent the same detectors as those in Figure 2 except that a solid curve has been added to show the noise envelope for advanced narrow band detectors with a sensing bandwidth of 1 Hz associated with the assumption of 5 ppm mirrors used in a 4 km long interferometer arm.



The Advanced Detector R&D Program outlined below addresses the desire for higher sensitivity detectors in two ways: through upgrades to the initial interferometers (called *advanced sub-systems (LIGO II)*) that can be made without major redesign of the interferometer and through *advanced detectors (beyond LIGO II)* that require fundamental changes to the interferometer:

- *Advanced subsystems* are intended to address a single performance limitation in the initial interferometers by replacing a single subsystem in the LIGO interferometers with an improved design. Examples include higher power lasers, new test mass suspensions, or new test mass materials. These lead to the LIGO II detector.
- *Advanced detectors* are currently less mature in their development, but offer significant

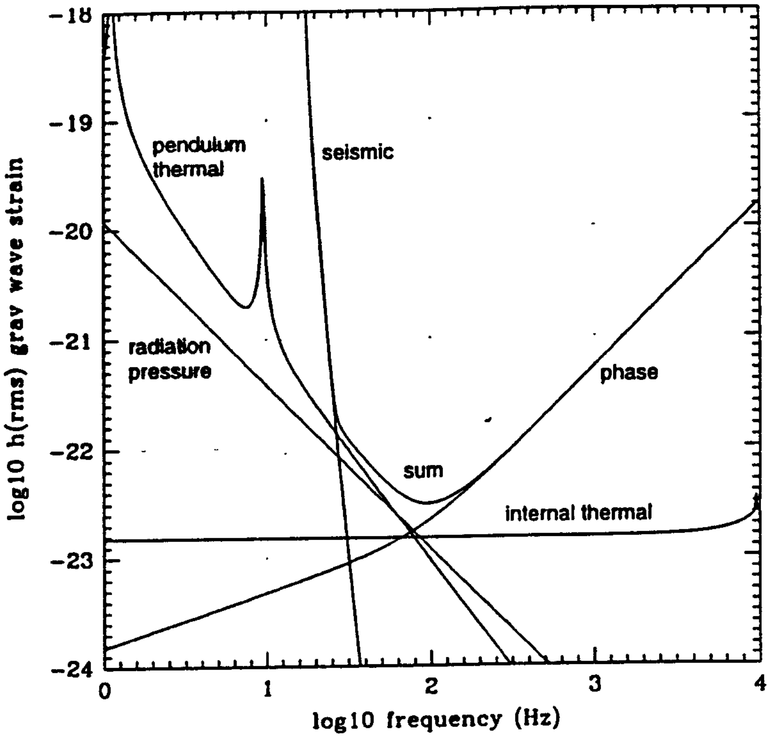


Figure 5: Components of the error budget for the enhanced LIGO interferometers. Refer to Table 2 for interferometer parameters

Table 2: Sample detector parameters with advanced sub-systems

parameter	*sample enhanced value*
Laser power	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

Research addressing Stochastic Forces

D. Shoemaker   22 January 98

Scope

- thermal noise
- excesses beyond thermal noise
- seismic noise
- control systems for the mechanical aspects of the interferometer

Strategy

2004: First opportunity for significant changes

- first science run finishing in ~2003
- allows a ~5 year cycle of research, development, engineering, test

Low-Frequency Performance goals dictated by thermal noise

- target materials (quartz, sapphire) loss characterized
- will do best effort but bare material Qs known
- isolation goal: let optimistic level for thermal noise dominate
- only moderate improvements in isolation required

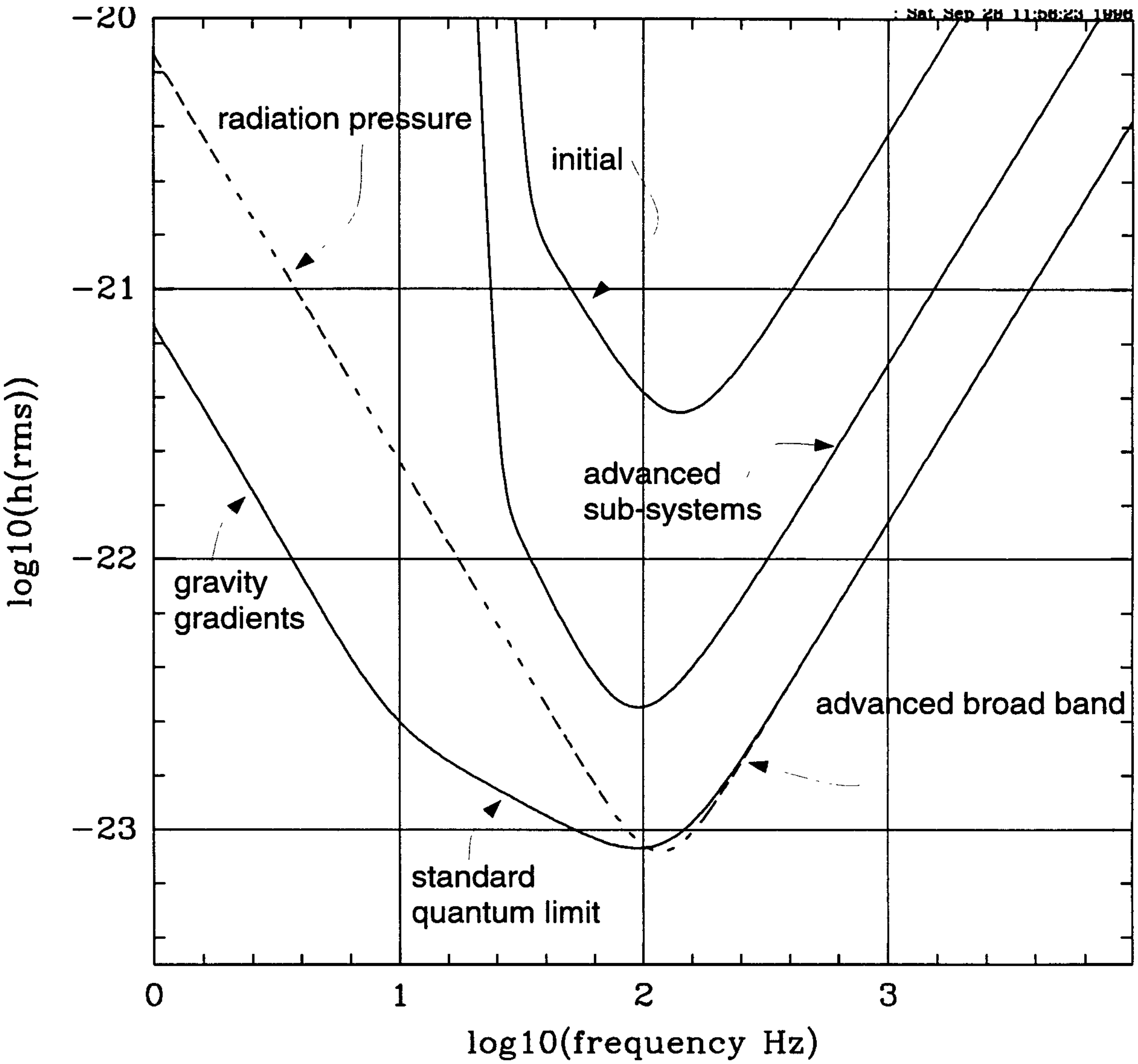
Leads to near-term plan for research:

- model and plan the system: requirements, trades
- research means to handle and assemble quartz/sapphire test masses, characterize the results in terms of noise performance
- leave LIGO I passive isolation in place, augmented by...
- double-pendulum suspension, and
- modest active isolation system

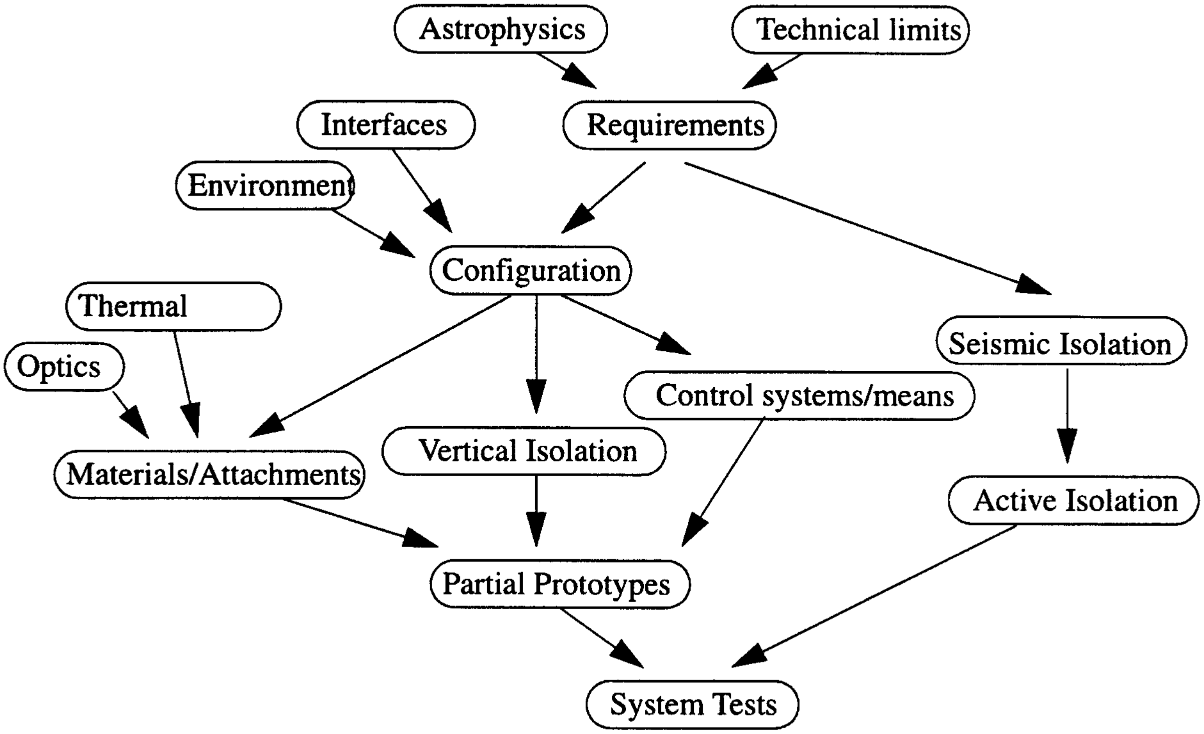
Long-term strategy: gravity gradient limited performance

- not a specific focus of this research proposal
- interest in LIGO and community for aggressive application of sensing/servo techniques, but all approaches to be considered

Performance goals and limits



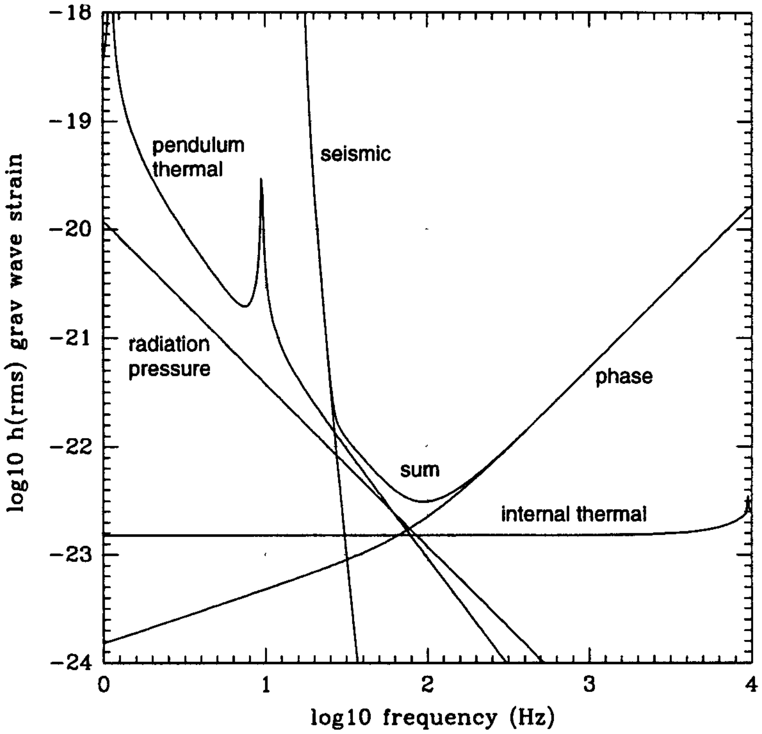
Roadmap



Long history of suspension/isolation/thermal noise

- significant effort at MIT, Caltech, other institutions
- plan to build on and collaborate with all in field
- in particular, close Ligo Science Collaboration (LSC) effort

Top-level design questions



Requirements

- point of departure: Advanced Subsystem LIGO sensitivity curve
- individual technical noise sources to be re-estimated

Environment

- site seismic noise: correlations, extrema, stationarity, drifts
- acoustic noise, other couplings found to be important

Interfaces and inter-subsystem trades

- present passive stack; coarse actuators; optics; acquisition

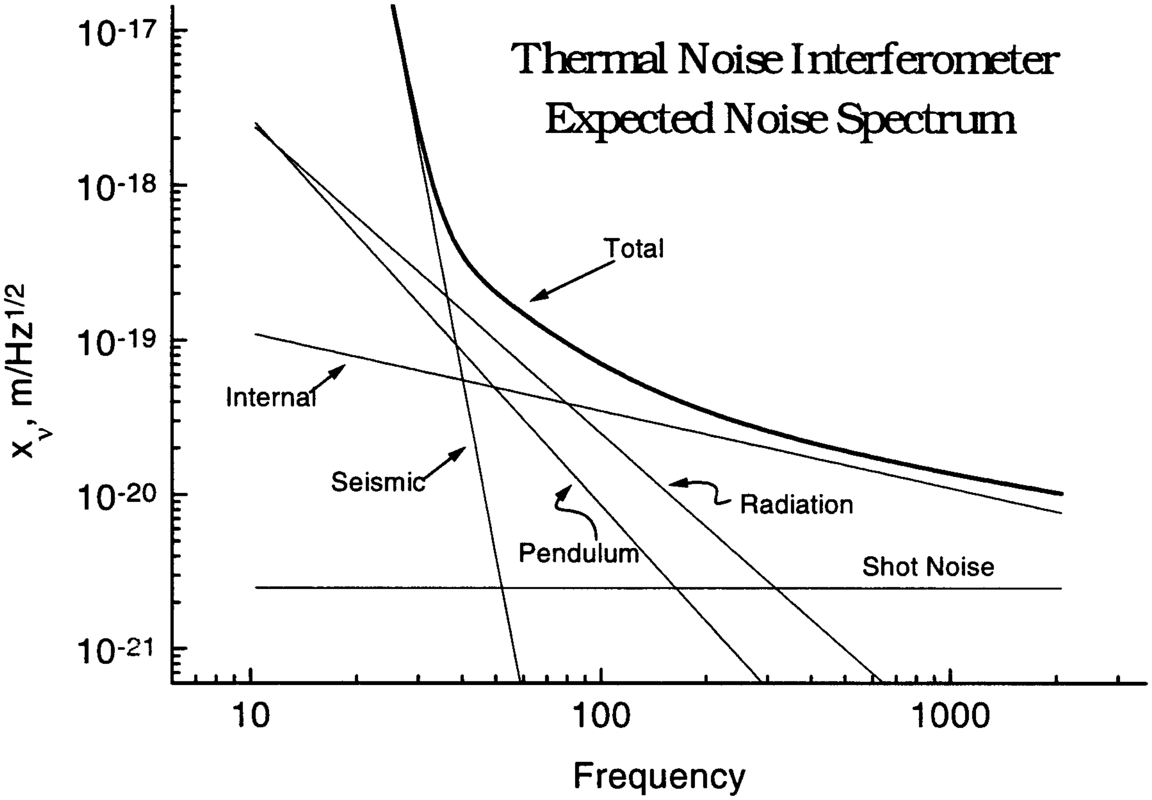
Thermal Noise research

Development of fused-silica-fiber pulling technology

- acquisition and 'tuning' of commercial system
- tests of Q and strength

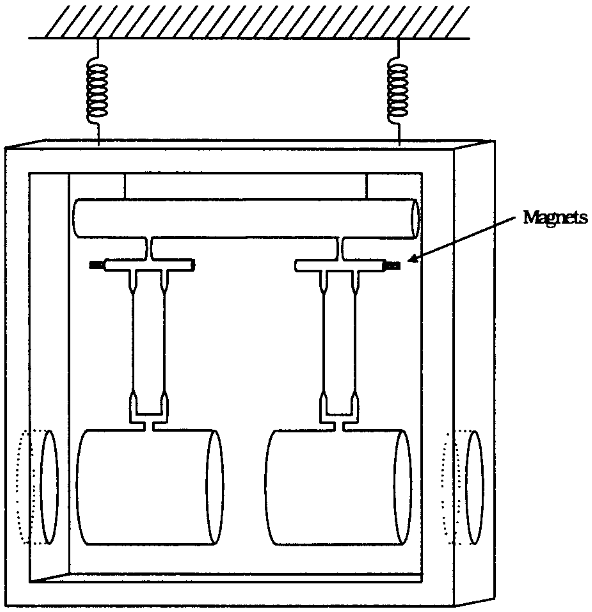
Direct measurement of thermal/excess noise

- special-purpose Thermal Noise Interferometer
- focussed on internal thermal/excess noise of substrates



- will allow tests of partial suspension prototypes
- materials and techniques to be explored

Thermal Noise Interferometer

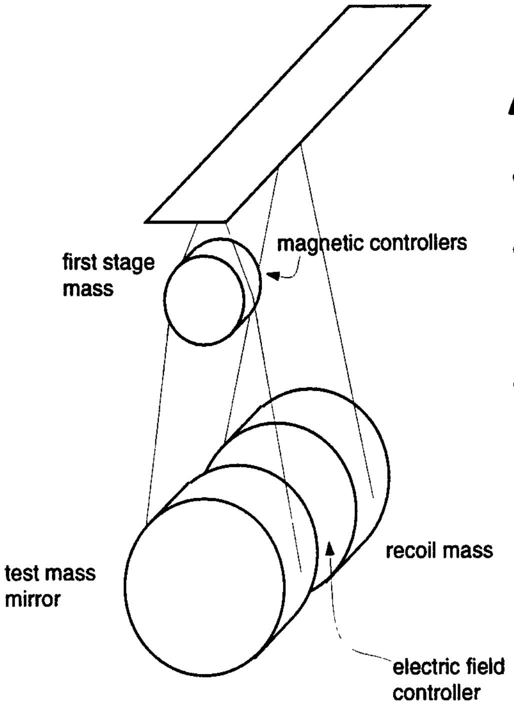


Configuration

- short measurement cavity, long reference cavity
- LIGO-like passive stack (from Phase Noise Ifo)
- common-mode mounting of test masses

Suspension

Change from initial LIGO single suspension



Advantages of double pendulum

- Distribution of control forces
- reduction in forces on test mass
  - smaller coupling to world
- changes in actuator technology
  - reduced loss, lower thermal noise
- improved seismic isolation

Critical design questions

- material for test mass (sapphire?)
- material for suspension fibers (quartz?)
- attachment means for fiber (silicate bonding? welding?)
- vertical compliance (Maraging steel? quartz coil springs?)
  - required, due to earth's curvature, to realize advantages

Prototypes for test in TNI, and MIT Test Ifo to be developed

- considerable interaction with collaborators

Active Seismic Isolation

Plan to re-use the bulk of LIGO I passive isolation system

- with double pendulum, allows thermal noise to dominate in GW band
- considerable cost/complexity savings if incorporated in new design
- will be well-understood and characterized system
- changes (e.g., damping of springs) if indicated by experience

Active isolation system

- Objective: to reduce further required dynamic range in suspension; goal: factor 30 reduction, 0.1-10 Hz
- target design is (principally) external to vacuum
  - may include sensors in vacuum to control stack dynamics
- MIT contributing commercial system for test
- Collaboration with JILA to exploit, improve, and integrate

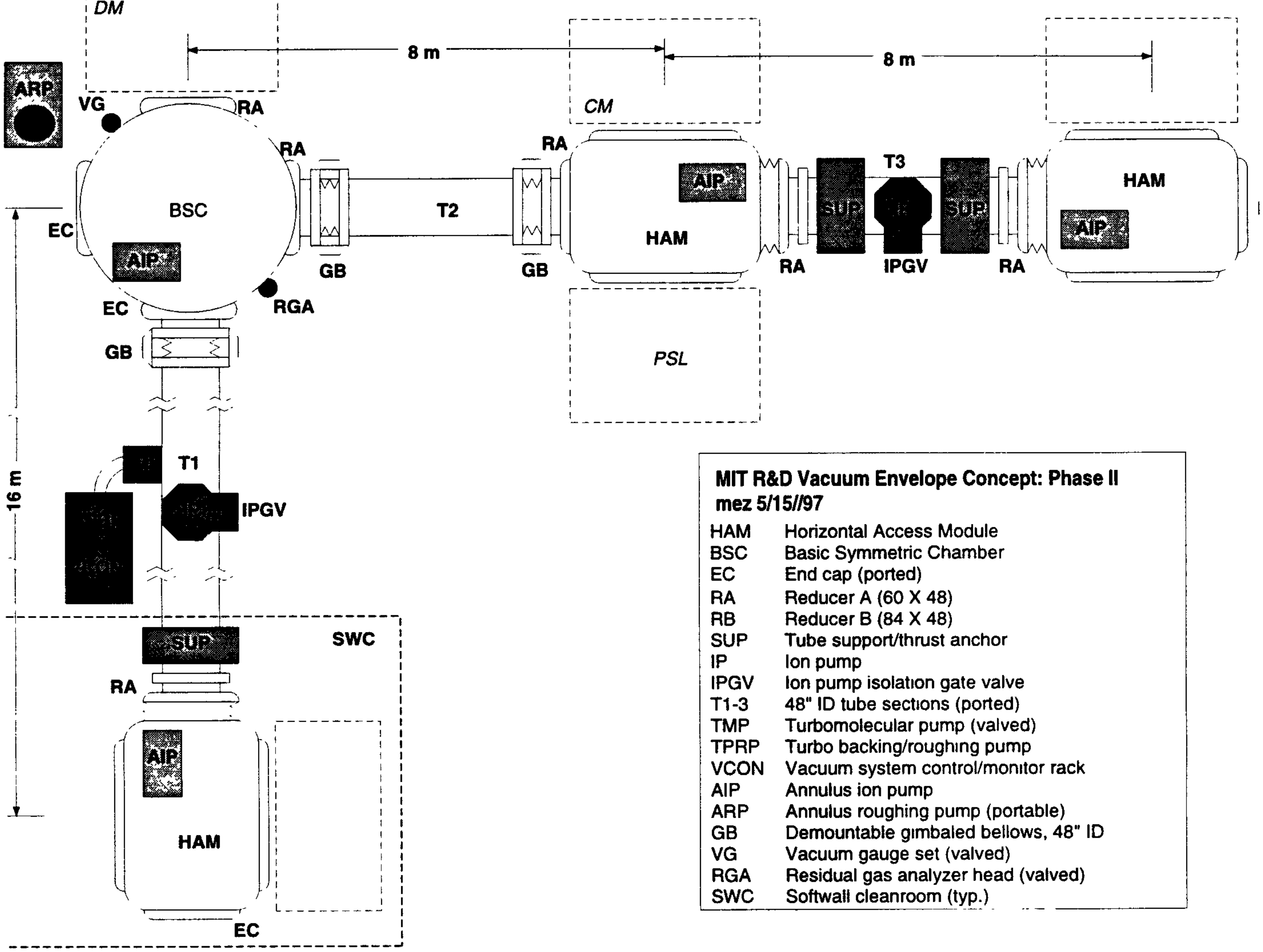
Control systems and actuators/sensors

- attempt to eliminate actuators on test mass through acquisition cleverness and trades between isolation/suspension system
- modeling to use LIGO I Length/Angle models as basis
- if needed, develop electrostatic actuators for test mass

Characterization of LIGO I suspensions

- understand what we wish to do differently; cross couplings

System tests



MIT R&D Vacuum Envelope Concept: Phase II
mez 5/15//97

HAM	Horizontal Access Module
BSC	Basic Symmetric Chamber
EC	End cap (ported)
RA	Reducer A (60 X 48)
RB	Reducer B (84 X 48)
SUP	Tube support/thrust anchor
IP	Ion pump
IPGV	Ion pump isolation gate valve
T1-3	48" ID tube sections (ported)
TMP	Turbomolecular pump (valved)
TPRP	Turbo backing/roughing pump
VCON	Vacuum system control/monitor rack
AIP	Annulus ion pump
ARP	Annulus roughing pump (portable)
GB	Demountable gimbaled bellows, 48" ID
VG	Vacuum gauge set (valved)
RGA	Residual gas analyzer head (valved)
SWC	Softwall cleanroom (typ.)

LIGO/Community facility for end-to-end full-scale testing

- tests of isolation/suspension systems, thermal noise strategies
- final qualification of such systems prior to LIGO site installation
- flexible envelope, also for optics studies
- fully operational in '99, for testing of double suspension system

Schedule

Principal activities in FY 98:

- modeling of the system and parts thereof: requirements, environment, interfaces, configuration (all LSC members)
- characterization of the LIGO I suspensions on-site (PSU)
- start of work on active isolation systems (as-is tests) (JILA)
- Thermal Noise Ifo construction, first operation (MSU)
- start of fabrication of passive isolation for MIT Test Ifo
- (moving of MIT Lab and installation of Test Ifo Vacuum System)

Principal activities in FY 99:

- improvements to active seismic isolation (JILA, Stanford)
- vertical compliance development and test (GEO)
- materials and attachment means (Syracuse, MSU)
- Thermal Noise Ifo results (MSU)
- completion of MIT Test Ifo isolation, some interferometry
- first prototypes: development and test (All LSC members)

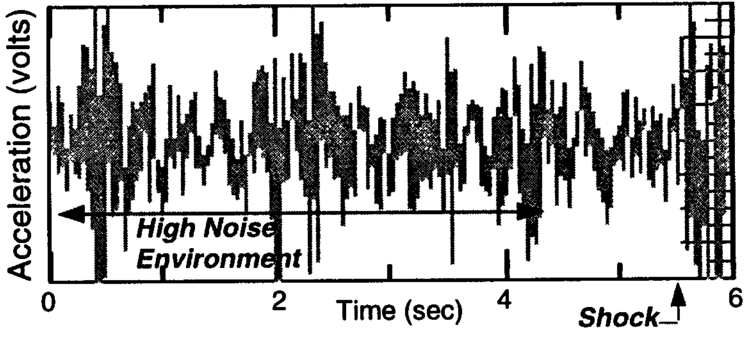
Principal activities in FY2000-2001:

- System tests of individual suspensions
- System tests of complete interferometer

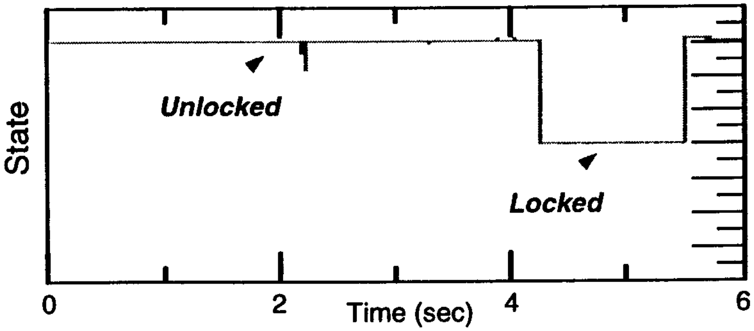
ADVANCED CONTROL TECHNIQUES: MOTIVATION

- Challenging detector availability goals have been established for the LIGO observatories:
  - ›› Single interferometer operations > 90% of the time with minimum of 40 hr. continuous lock periods
  - ››Double coincidences > 85% time and triple coincidences > 75% time with 100 hr. minimum continuous lock periods
- 40 m prototype experience:
  - ››Limited periods of continuous interferometer lock will be the main contributor to detector down-time (40m prototype lock durations vary from seconds to a few hours)
    - —Control system instabilities caused by drifts in the interferometer system parameters
    - —Displacement noise events which kick the interferometer out of lock

Ground Excitation vs Time



State of Interferometer vs Time



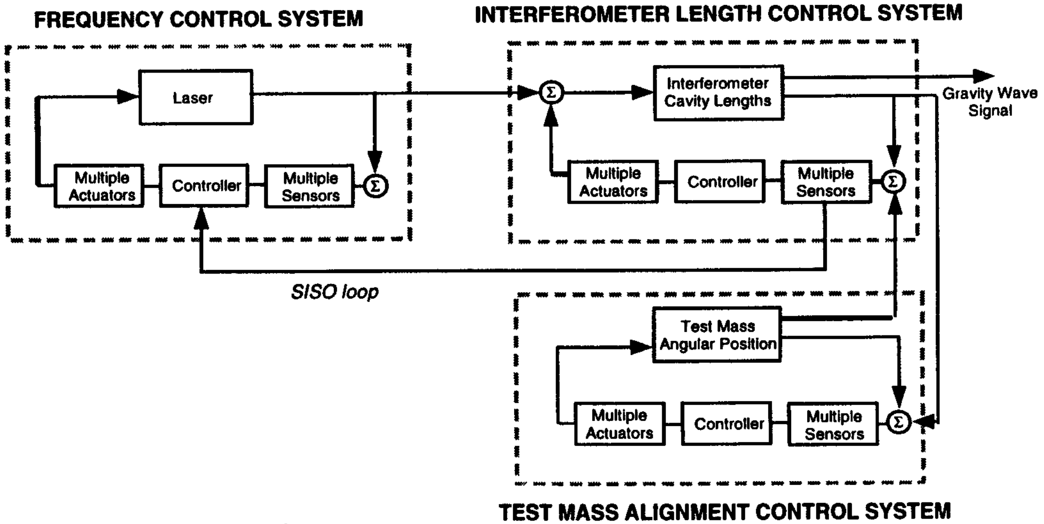
ADVANCED CONTROL TECHNIQUES: BACKGROUND

- LIGO has frequency, length and alignment servo-control loops
  - ››The optical model for the length control system is a 4x4 matrix of transfer functions:

$$H_{ij}(s) = G_{ij} \cdot \frac{\left(1 + \frac{s}{z_{ij}}\right)}{\left(1 + \frac{s}{p_{ij}}\right)}$$

The 4 degrees of freedom are the common mode arm cavity length *L+*, the differential arm cavity length *L-*, the Michelson difference *l-*, and the Michelson common mode length *l+*

  - ››The interferometer optical alignment model is a 10x10 matrix of transfer functions whose elements have a similar form

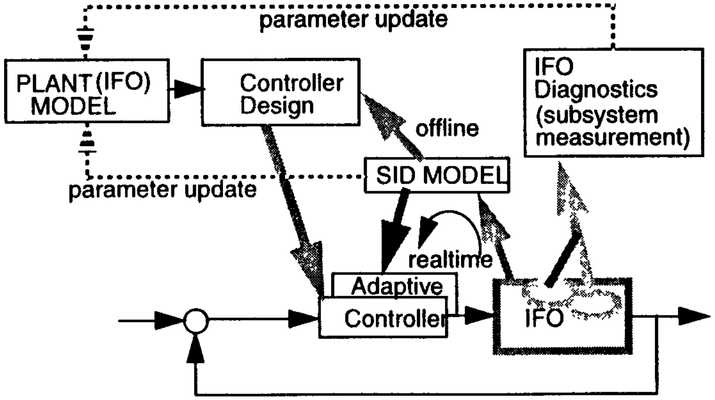


ADVANCED CONTROL TECHNIQUES: BACKGROUND (continued)

- Potential hardware imperfections, model errors, unknowns or parameters subject to drift which could effect control system robustness include:
  - Beamsplitter reflectivity ≠ 50%
  - Mixer phase error
  - Deviations from resonance
  - Visibility variation
  - Fabry-Perot cavity input and end test mass absorption (resulting in radius of curvature changes)
  - Sensor & actuator cross-talk (optical, mechanical & electrical)
  - Alignment/length Coupling
  - Modulation depth & phase variation

ADVANCED CONTROL TECHNIQUES: STRATEGY

- System identification will be used in conjunction with subsystem diagnostic and measurement techniques to update our understanding of the system and its control
- Once the system susceptibilities are understood, an adaptive controller can be formulated to compensate
- SID and Adaptive Control are mature technologies;
  The application to Interferometry is unique

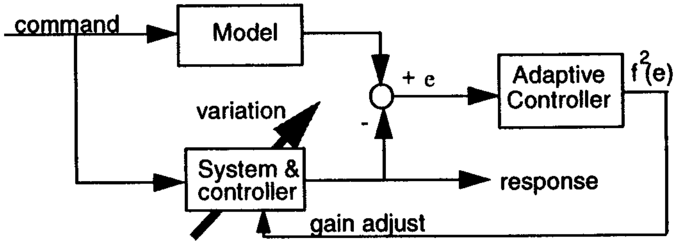


ADVANCED CONTROL TECHNIQUES: SYSTEM IDENTIFICATION

- System Identification (SID) is an empirical approach to modeling interferometer system dynamics
  - ››Non-parametric identification (i.e. frequency response estimation)
  - ››Parametric system models (e.g. state space representation)
- For LIGO we seek a recursive, real-time parameter identification of the multi-input/multi-output optical response of the interferometer in Detection Mode:
- Many techniques are available and will be explored; Potential candidates include:
  - ››Generalized Least Squares and Maximum Likelihood Estimators (e.g. the Prediction Error Method) are computationally simple
  - ››Observer/Kalman Filter Identification (OKID) -- time domain based, can be extended to identification of closed loop effective controller/observer combination (Observer Controller Identification, OCID)
  - ››State-Space Frequency Domain (SSFD) identification -- frequency domain based (can use spectrum analyzers)

ADVANCED CONTROL TECHNIQUES: ADAPTIVE CONTROL

- Adaptive Control can improve sensitivity while maintaining robustness to disturbances and plant variations
- Adaptive control time scales:
  - ››milliseconds for the ordinary feedback
  - ››many minutes for updating the control parameters and performing SID
- Possible adaptive control algorithm: Model Reference Adaptive Control



Advanced R&D Review:

Lasers and Optics

S. Whitcomb

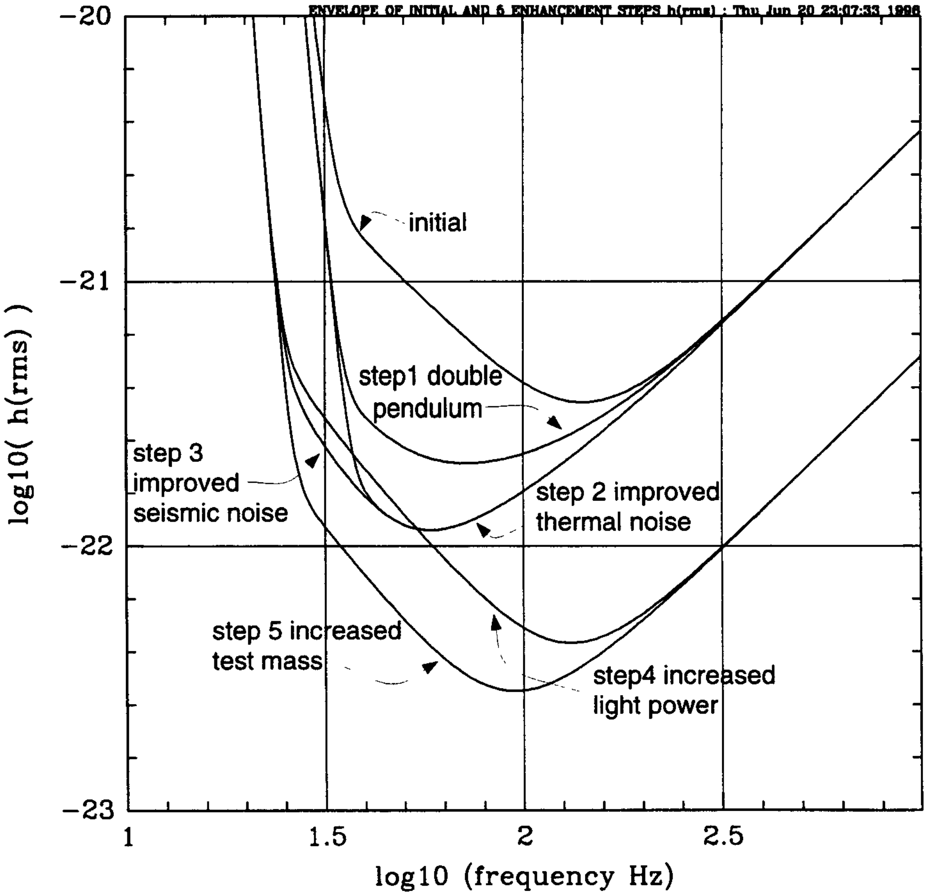
22 January 1998

Outline

- **Higher Power Lasers**
- **Improved Interferometer Optics**
- **Sapphire Optics**

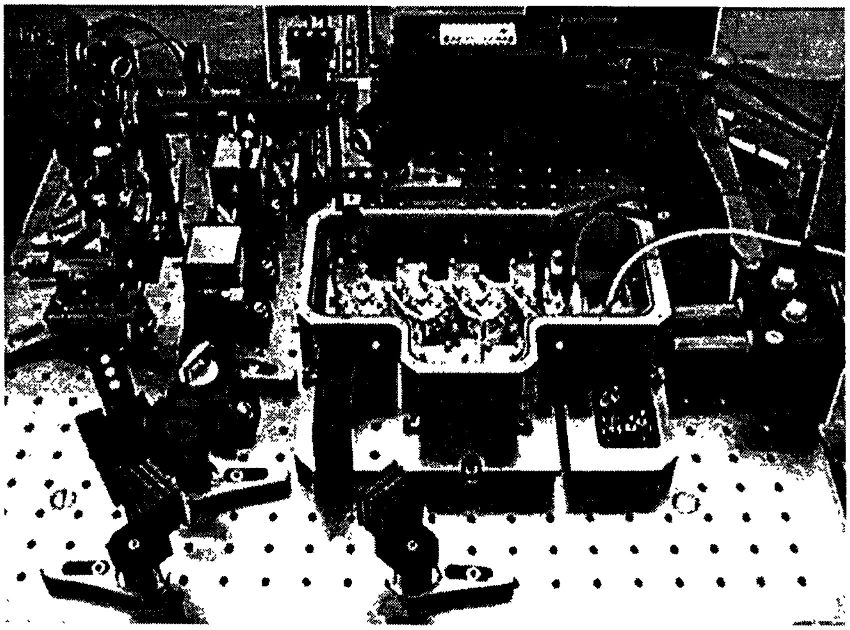
LASERS AND OPTICS
High Frequency Sensitivity

- **Improvements in shot noise due to:**
  - ››Higher laser power
  - ››Lower loss optics
  - ››Optics to handle higher power



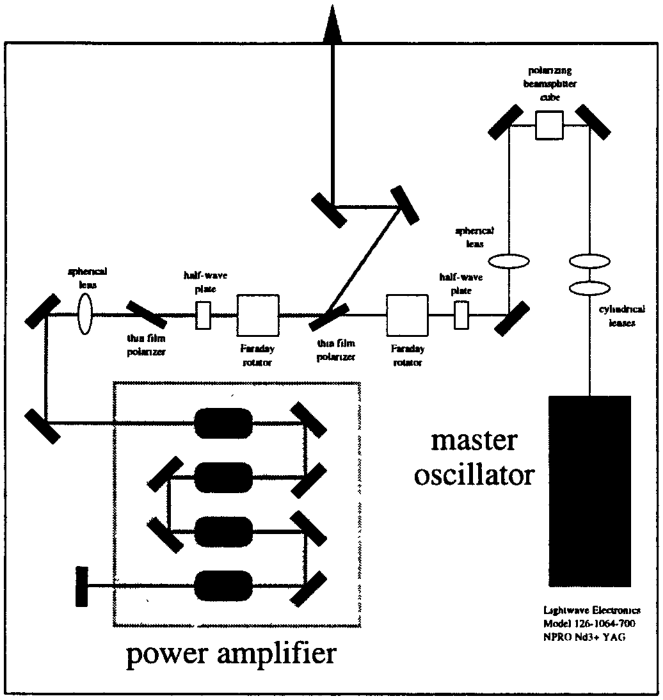
Initial LIGO Laser: 10 W Nd:YAG

- **Development contract with Lightwave Electronics**
- **Goal: Develop 10 W diode-pumped Nd:YAG laser suitable for Initial LIGO**
  - ››Single Frequency
  - ››Diffraction-Limited, Single Transverse Mode
  - ››Intensity and Frequency Stabilization
- **First unit delivered to LIGO at end of 1997**



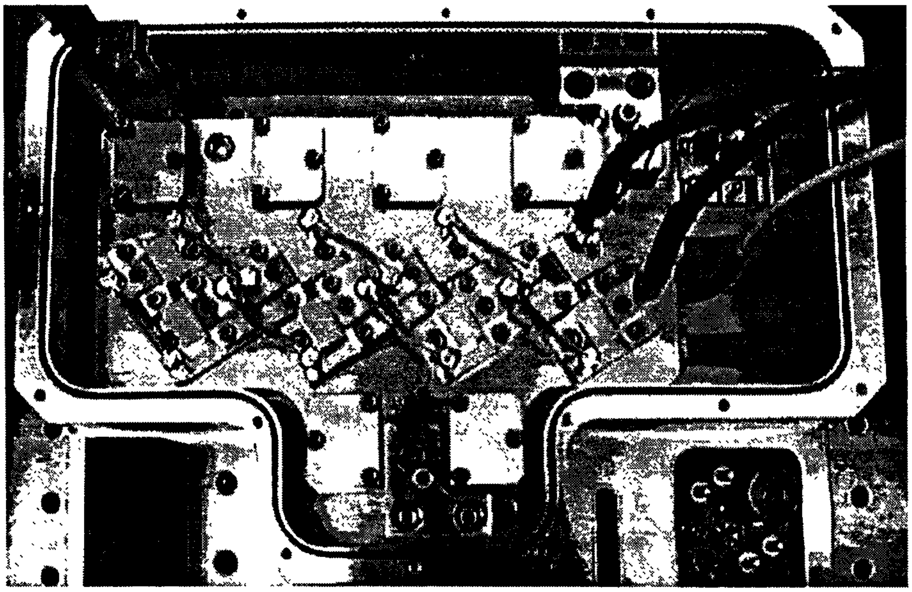
HIGHER POWER LASER

Initial LIGO Laser: 10 W Nd:YAG



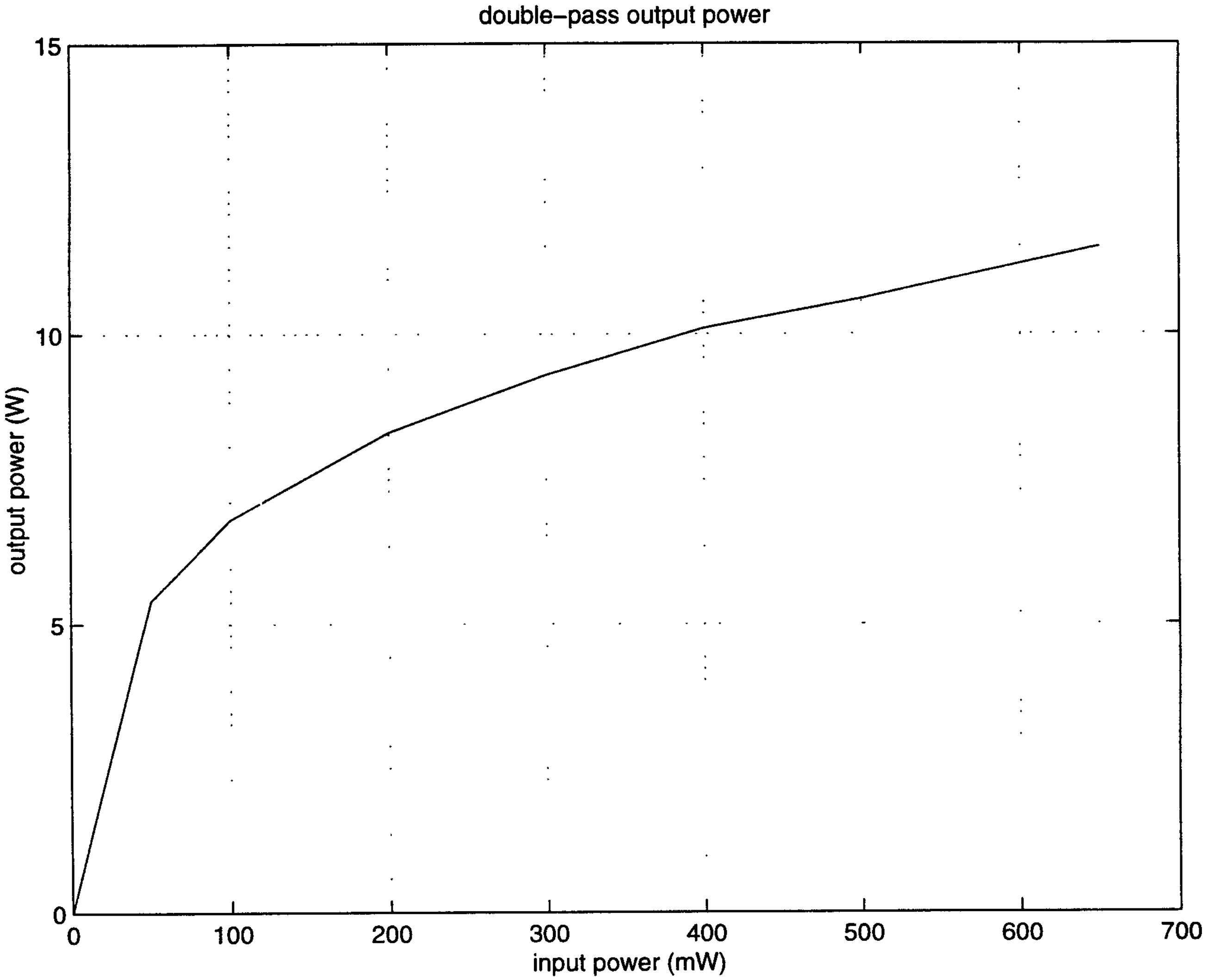
- **Double pass MOPA configuration adopted**
  - ››Commercial 700 mW NPRO used as master oscillator
  - ››Very good beam profile
  - ››Moderate efficiency and saturation

- **New geometry for pumping gain elements**



HIGHER POWER LASER

10 W MOPA Performance: Moderate Gain Saturation

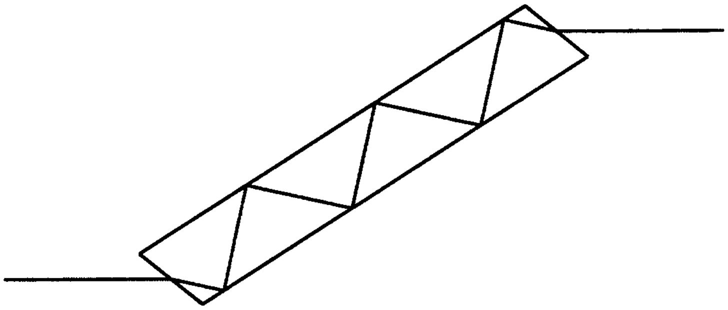


Advanced LIGO Laser: Performance Goals

- **Nd:YAG, or equivalent**
- **Diode-laser pumped**
- **Wavelength ~ 1 μm**
- **100 W output power**
  - ››Single frequency, single transverse mode
- **Frequency and intensity control actuators**

Advanced LIGO Laser: Zig-zag Slab Geometry

- **Rod geometries (used in LIGO 10 W laser) give high efficiency (good match to mode shape) but do not scale well to higher power**
    - ››Thermal stresses introduce polarization losses
- **Zig-zag slap geometry**



    - ››Thermal gradient gives stress-induced birefringence aligned with polarization direction >> no increased loss
    - ››Zig-zag path averages spatial variation in gain, etc. (at least over on dimension)
- **Major question is configuration for optical extraction**

Advanced LIGO Laser: MOPA

- **Proposed by Byer group (GALILEO/ Stanford)**
- **MOPA advantages, disadvantages**
  - \+ Easily scalable to higher power - mode volume not tied to resonator length
  - \+ Frequency control simple (applied to master oscillator)
  - \+ Can put electro-optic control elements in low power beam (prior to amplifier)
  - \- Extraction efficiency not as high as with oscillator (reduces efficiency, increases cost)
  - \- Possibility of parasitic oscillations or noise due to amplified spontaneous emission (ASE)
  - ? Beam quality
  - ? High frequency noise

HIGHER POWER LASER

Advanced LIGO Laser: Injection-Locked Oscillator

- **Injection-locked oscillator using stable-unstable resonator**
  - \+ High efficiency
  - \+ Gain saturation suppresses ASE
  - \- Scaling to higher power (larger mode volume) requires "unconventional" resonator configuration
  - \- Requires additional (simple) servo to lock power oscillator to master oscillator
  - ? Beam quality
  - ? High frequency noise
- **Stable-unstable resonator**
  - ››Proposed by Munch group (ACIGA/Adelaide)
  - ››Resonator is stable in direction, unstable in the perpendicular direction
  - ››Uses variable transmission output coupler to control beam profile

HIGHER POWER LASER
Work Plan

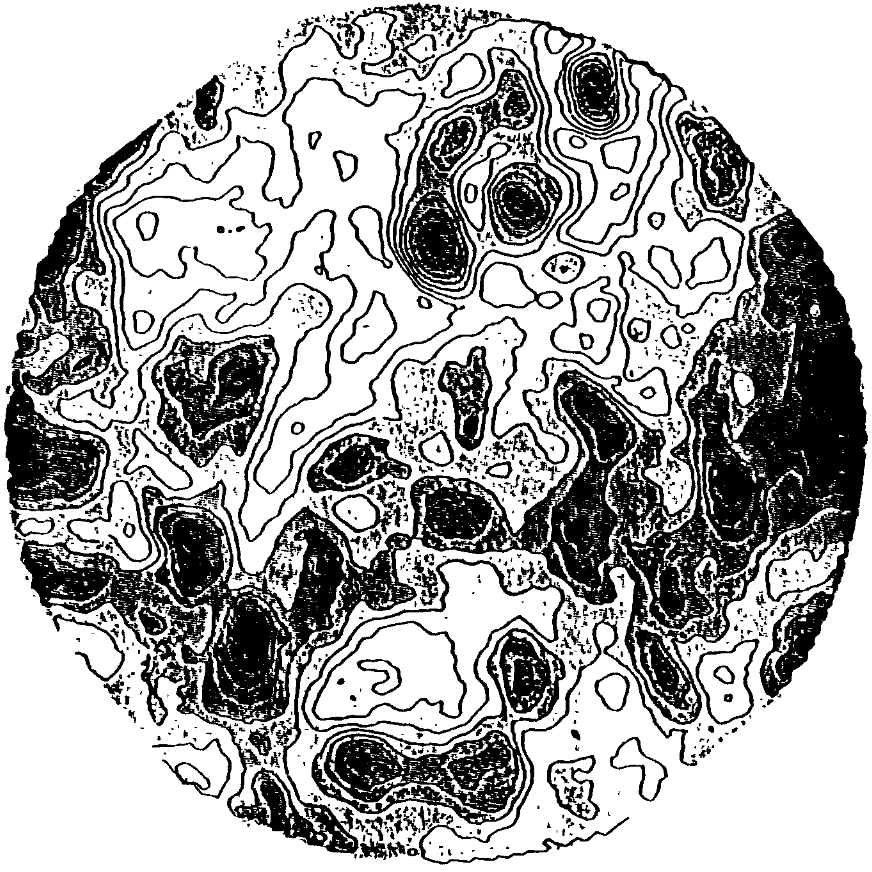
- **Collaborate with GALILEO (Stanford) and ACIGA (Adelaide) in two step development**
- **LIGO responsibilities: requirements, testing**

Milestones	*Responsible*	*Date*
Evaluate performance of 10 W LIGO laser	LIGO, GALILEO	3/98
Develop laser requirements for LIGO II interferometer	LIGO, ACIGA, GALILEO	7/98
Build 40 W stable-unstable resonator laser	ACIGA	12/98
Characterize 40 W stable-unstable resonator laser	ACIGA, LIGO	5/99
Build 40 W MOPA laser	GALILEO	12/98
Characterize 40 W MOPA laser	GALILEO, LIGO	5/99
Upgrade to 100 W stable-unstable resonator laser	ACIGA	12/00
Characterize 100 W stable-unstable resonator laser	ACIGA, LIGO	5/01
Build 100 W MOPA laser	GALILEO	6/00
Characterize 100 W MOPA laser	GALILEO, LIGO	12/00
Decision on LIGO II high power laser configuration	All	9/01

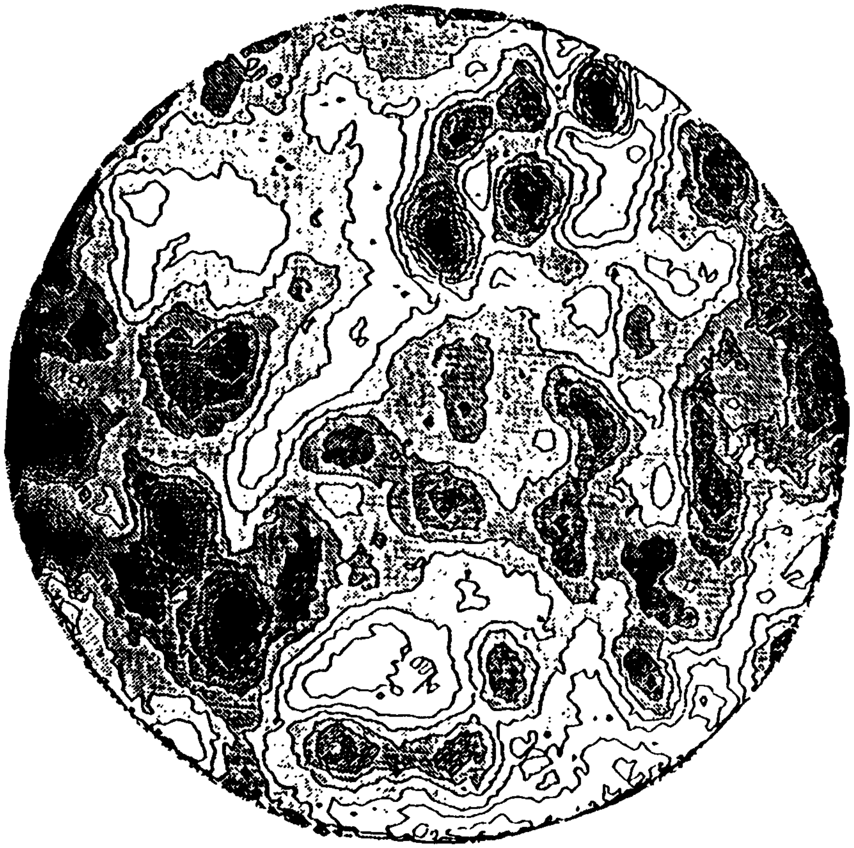
Optics for Initial LIGO: Results of Pathfinder Devel.

- **Polishing**
  - ››Surface figure < 0.5 nm rms
  - ››Microroughness < 0.1 nm
  - ››Radius matching < 2%
- **Coating**
  - ››Surface figure < 1 nm rms
  - ››Microroughness - presumed negligible
  - ››Radius change < 1% (!?)
- **Metrology**
  - ››Just barely adequate!
  - ››Needs extension to 1 μm

CONTOUR INTERVAL ~ 1 NANOMETER
SERIAL NUMBER 001



HDOS MEASUREMENT
(1.58 nm RMS)



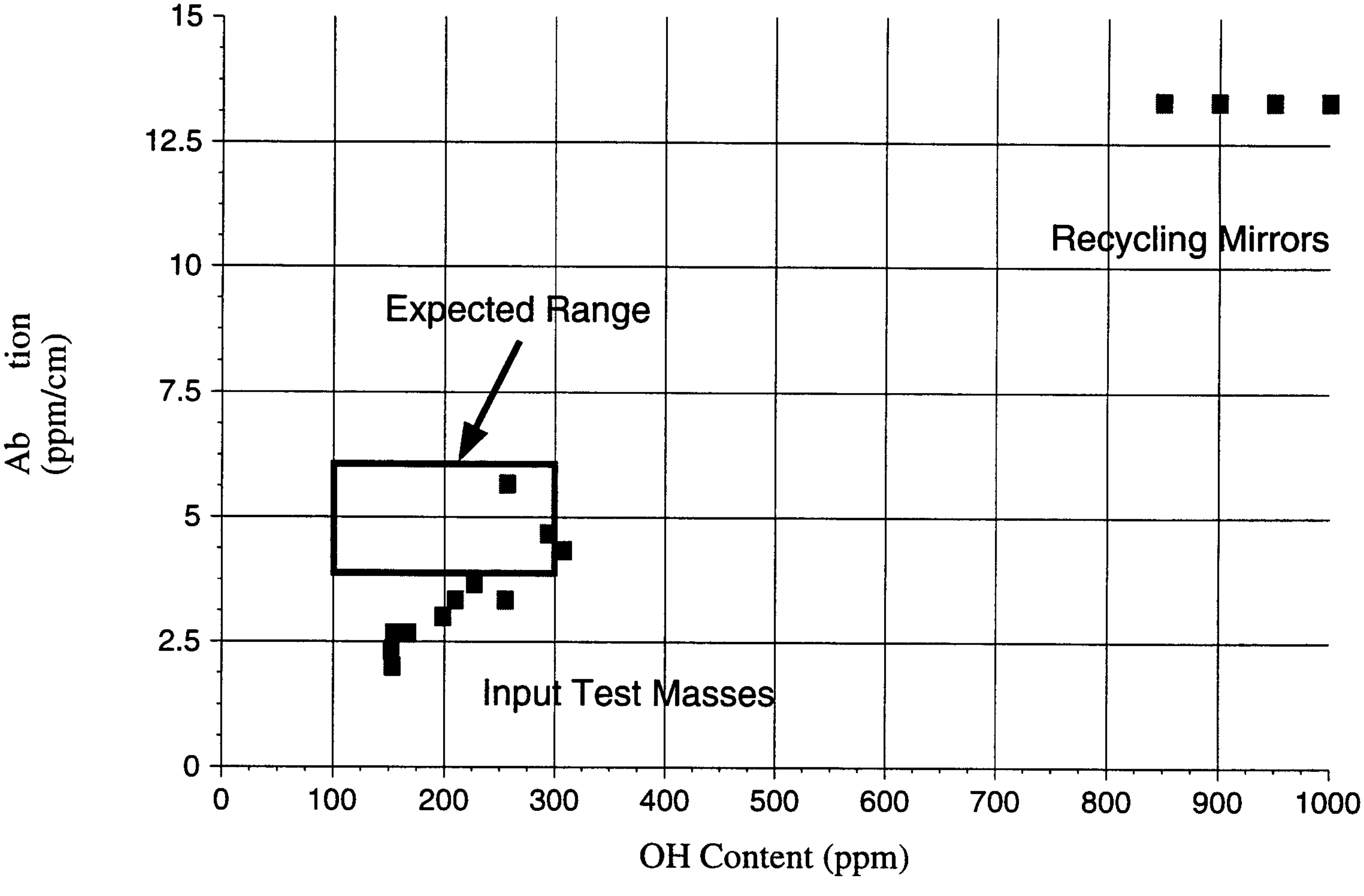
NIST MEASUREMENT
(1.75 nm RMS)

IMPROVED OPTICS

Optics for Advanced LIGO: Development Goals

- **Coating Uniformity**
  - ››Pathfinder results meet initial LIGO requirements
  - ››Improvement of (2-3) x seems possible; reduces (dominant) small angle scatter losses by (4-9) x
- **Substrate and coating absorption**
  - ››Coordinate substrate/coating absorption measurements with analysis and vendor improvements
- **Metrology**
  - ››Maintain and improve optical metrology capability at 1 μm
- **Other Issues**
  - ››High power damage?
  - ››Contamination?
  - ››Thermal lensing compensation
  - ››In situ cleaning of optics

Optics Development: Substrate Absorption



IMPROVED OPTICS

Work Plan

- **Most efforts scheduled to begin in1999 because of competing LIGO construction demands on equipment, contracts and staff**

Milestones	*Responsible*	*Date*
Surface figure metrology < 0.1 nm rms	LIGO	6/00
Polishing Process: figure < 0.1 nm rms	LIGO/Industry	12/01
Coating uniformity metrology	LIGO	6/02
Coating Process: uniformity < 0.1 nm rms	LIGO/Industry	12/02
Coating Absorption metrology	LIGO	6/02
Coating Process: loss < 0.1 ppm	LIGO/Industry	12/02
Bulk absorption metrology	LIGO	1/00
Qualification of a full size piece of lensing compensation material	LIGO	1/01
Damage test capability	LIGO	1/00
In situ cleaning method identified	LIGO	12/01

Why Sapphire for LIGO Interferometer Optics?

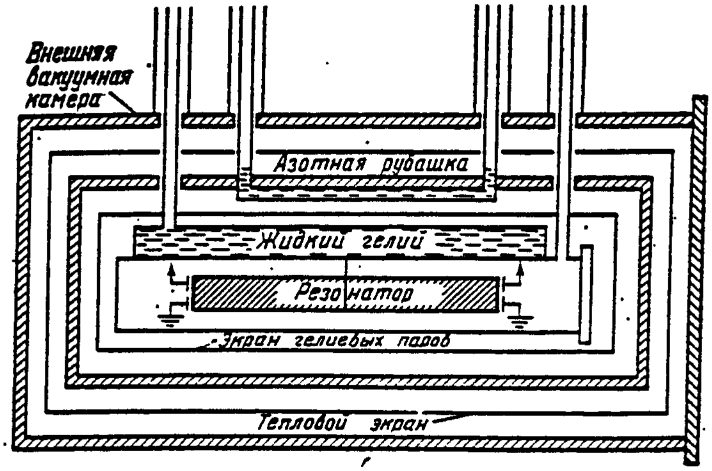


Рис. 8. Схема криостата для исследования механических резонаторов при низких температурах.

Измерение добротности резонатора осуществлялось по времени затухания его свободных колебаний. Возбуждение и регистрация упругих колебаний в резонаторе производились емкостными преобразователями. Температура резонатора определялась по значению собственной частоты его колебаний, предварительно проградуированной по термопаре медь — константан и термометру на основе угольного сопротивления. При этом термопара и термометр присоединялись непосредственно к кристаллу только во время предварительной градуировки, так что исключался механический контакт резонатора с ними при проведении измерений добротности.

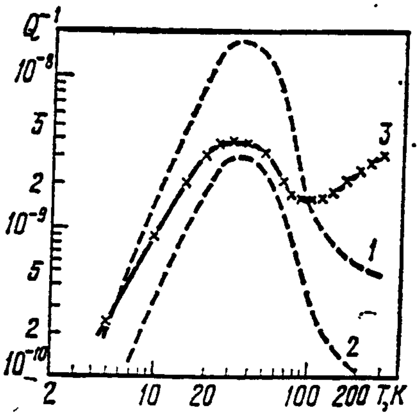
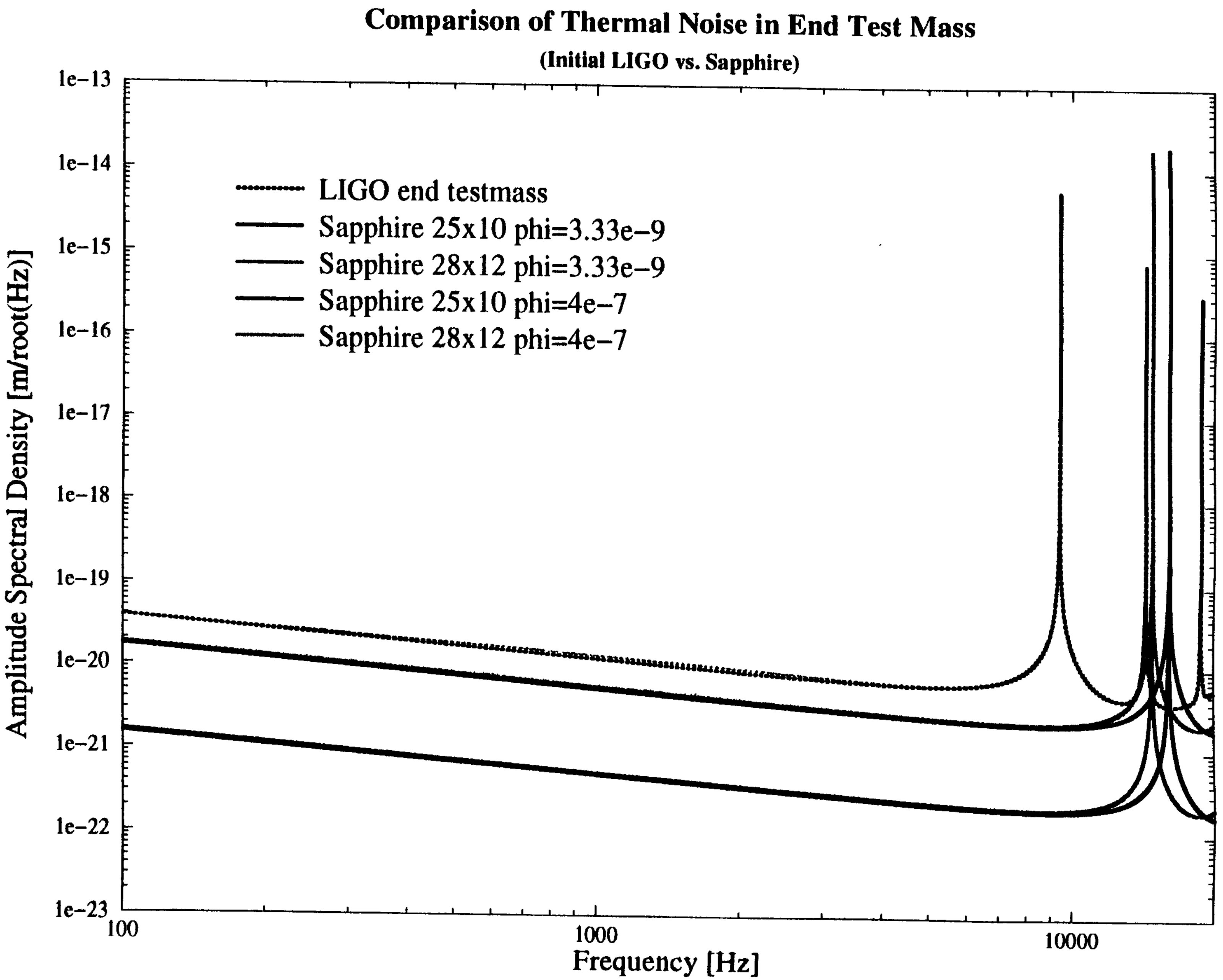


Рис. 9. Рассчитанные (кривые 1 и 2) и измеренная (кривая 3) температурные зависимости Q^{-1} резонатора из сапфира с собственной частотой 38 кГц.


Comparison of Thermal Noise in End Test Mass
(Initial LIGO vs. Sapphire)
LIGO end testmass
Sapphire 25x10 phi=3.33e-9
Sapphire 28x12 phi=3.33e-9
Sapphire 25x10 phi=4e-7
Sapphire 28x12 phi=4e-7
Amplitude Spectral Density [m/root(Hz)]
1e-13
1e-14
1e-15
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
100
1000
10000
Frequency [Hz]

SAPPHIRE OPTICS

Demonstrated Capabilities for LIGO Optics

- **Single crystals grown up to 65 kg**
  - ››Crystal orientation not most desirable for LIGO
  - ››Largest pieces have typically shown poorer optical quality
- **Optical Homogeneity ~3 x 10^{-7} rms**
  - ››~5x worse than best SiO_2
  - ››Limited measurements on 5 cm pieces
  - ››May be measurement limited, may be good enough
- **Can be "super-polished" (<1 Å microroughness)**
  - ››No tests of large scale surface figure at 1 nm level
- **Low absorption at 1.06 μm (~3 ppm/cm)**
  - ››Comparable to best SiO_2, but higher thermal conductivity reduces thermal lensing in transmission

SAPPHIRE OPTICS
Absorption Testing/Development

- **Pioneering survey at 1.06 μm by Blair, Cleva, and Man (UWA and Virgo)**

Supplier	Absorption (ppm/cm)
Union Carbide	16 – 22 ± 2
Crystal Systems (CSI Standard)	55 ± 4
Research Institute of Synthetic Crystals	200 ± 20
Melles-Griot	11 – 16 ± 2
Crystal Systems (CSI White)	3.3 ± 0.2

- **No obvious correlation with growth method or known impurities**
- **Have already obtained additional CSI White samples obtained to test consistency**
- **Glow Discharge Mass Spectroscopy initiated to characterize impurities**

SAPPHIRE OPTICS
Growth of Suitable Blanks: Approach

- **Difficulty is that preferred orientation ("0°" = C axis perpendicular to optic surface) is a poor growth direction**
- **Two potential suppliers/growth techniques identified**
  - ››Crystal Systems Inc. - Heat Exchanger Method (HEM)
  - ››Shanghai Institute of Fine Mechanics (SIOM) - Directional Thermal Gradient Technique (TGT)
- **Working with both suppliers to grow and evaluate test pieces of 0° material**
  - ››Early CSI 32 cm diameter growth runs gave poor optical quality
  - ››First SIOM test piece (10 cm diameter) to be delivered in early 1998

SAPPHIRE OPTICS
Optical Fabrication Development

- **Polishing trials by CSIRO and General Optics on 15 cm x 6 cm 0° sapphire blanks**
  - ››Two blanks purchased by LIGO
  - ››General Optics has started initial polishing steps
  - ››CSIRO waiting for break in current workload
  - ››LIGO, CSIRO to test for surface errors
  - ››Issues include scratches and point defects due to hardness of sapphire
- **Coating to be done at REO after completion of polishing**
  - ››REO has experience coating sapphire in smaller sizes
  - ››Issues include nonisotropic (and large) thermal expansion coefficient
  - ››Testing of coating suitability to be done by LIGO

SAPPHIRE OPTICS

Attachments and Suspensions for Maximum Q

- **Primary interest and expertise of University of Western Australia**
- **UWA group to develop apparatus for measuring internal mode Q's by excitation/ ringdown**
  - Test Catherine wheel support for maximum Q test
  - Investigate Nb flexures and brazed attachments

SAPPHIRE OPTICS
Work Plan

Milestone	*Responsible*	*Date*
Fully develop Pathfinder quality material	LIGO, SIOM, C-S,	mid 98
		late 99
Select adequate material source(s). Produce additional samples if needed	LIGO, VIRGO	early 00
Demonstrate polish to Pathfinder specs. (half size blanks)	CSIRO,LIGO,VIRGO	early 98
		early 99
Select adequate polishers	LIGO, VIRGO	mid 99
Demonstrate HR coating to Pathfinder specs	REO, LIGO, VIRGO	late 98
		early 99
Characterize Q test bed @ > 4 x108 level	UWA	mid 98
Set upper limit Q to candidate source material	UWA, LIGO	early 99
Select candidate low Q attachment technique	UWA, LIGO, VIRGO	mid 00
Produce (2) full size blanks of Phase I selected material	selected source, LIGO	early 01
Preliminary test full size blanks	UWA, LIGO, VIRGO	mid 01
Integrate suspension attachments with Adv. SUS	UWA, LIGO	early 02
Polish and coat (4 sides)	REO, vendor, LIGO	late 02
Final measurements (as suspended Q)	LIGO, VIRGO, UWA	mid 03

High-Power Photodetectors
Adaptive Thermal Compensation of Core Optics

LIGO Advanced R&D Proposal Review

January 22, 1998

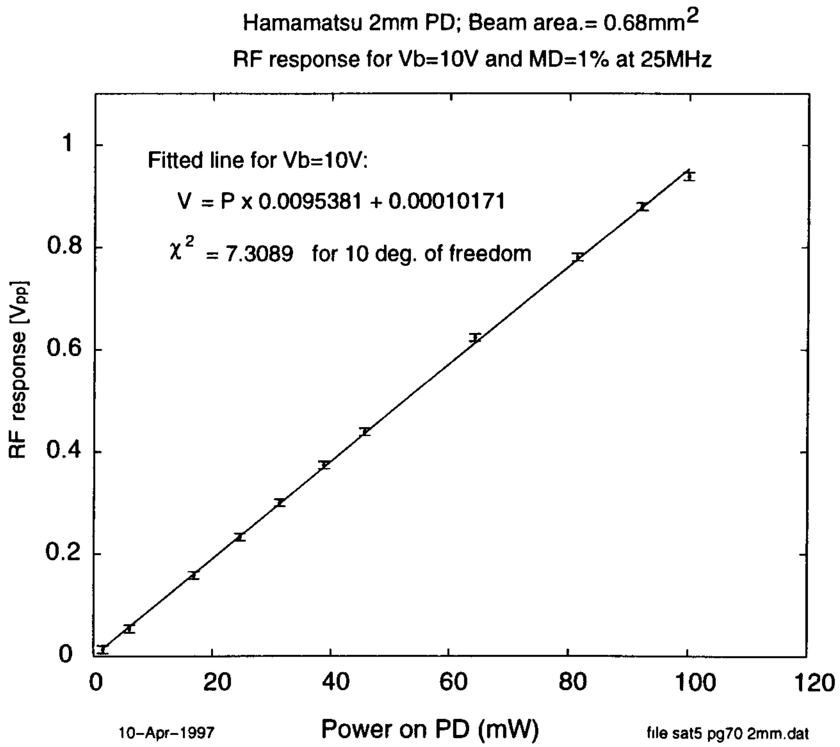
M. E. Zucker

LIGO M.I.T. Advanced R&D Team

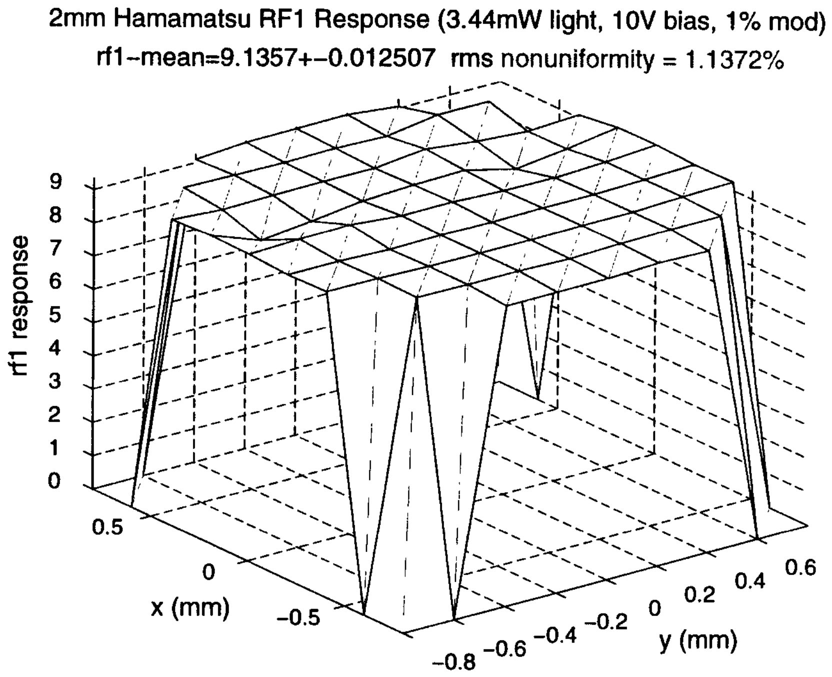
High-Power Photodetectors for Advanced LIGO

- LIGO I Photodetector program has tested and identified InGaAs devices which meet initial detector needs:
  - 4 in parallel can handle ~ 0.6W CW at “dark port”
  - Can handle $\Delta U \sim 3$ J transient on loss of lock (using lossy EO shutter)
  - Quantum efficiency $\varepsilon \sim 83\%$ is acceptable
  - backscatter BRDF ~ 10^{-4}/sr is below LIGO I phase noise limit
  - SNR ($\sim 1/R_d C_j$) is adequate (0.1 * shot noise)
- BUT: Just barely!

LIGO I Photodetector Performance



RF response vs. incident power, beam area 0.68 mm^2, diode dia. 2.0 mm



RF response vs. beam position, 2.0 mm dia. diode

PD Specs Scaled to LIGO II Power and Sensitivity

Parameter	*LIGO I*	*LIGO II*	*Current design*
Steady-state power	0.6 W	3.0 W[a]	0.75 W
Transient damage	3 J / 10 ms	30 J / 10 ms	3 J / 10 ms
Signal/Noise	1.4×10^{10} $Hz^{1/2}$	3.1×10^{10} $Hz^{1/2}$	1.5×10^{10} $Hz^{1/2}$
Quantum efficiency	80%	90%	83%
Spatial uniformity	1% RMS	0.1% RMS	1% RMS
Surface backscatter	10^{-4} /sr	10^{-5} /sr[b]	$< 10^{-4}$/sr

a. Assuming a factor of two improvement in contrast defect
b. Assuming comparable active detector area.

- Fortunately, current device limits are not intrinsic:
  - packaging & lead bonding impose artificial thermal limit
  - much better surface qualities readily achieved with InGaAs
  - R_d, C_j and thermal properties limited by design of ohmic contact

High-power photodetector research program

- Device physics & engineering research (Stanford)
- Enhanced overload protection (U. Fla.)
- Device testing, integration and interferometer trial (LIGO)
  - backscatter, thermal impedance, uniformity measurements
  - suppressed-carrier modulation testing
  - pulsed power damage threshold characterization
  - optical/mechanical/electronics integration & prototype trials
- Device technology transfer to industrial partners (All)

Photodetector Development Timetable

Milestone	*Responsibility*	*Target*
LIGO II detector requirements adopted	LIGO	12/98
Initial custom device fab & characterization	Stanford	3/99
CW suppressed-carrier interferometer on-line	LIGO	3/99
Second stage custom devices fab/char	Stanford	10/99
Pulsed damage test facility on-line	LIGO	3/00
Transient protection prototype test	U. Florida	3/00
Initial industrial prototype device production	Stanford	8/00
Characterize industrial prototype devices	LIGO/Stanford	11/00
Engineering design of prototype assembly	LIGO	3/01
Final industrial production run	Stanford	8/01
Characterize final industrial devices	LIGO/Stanford	11/01
Assembly/bench test of engineering prototype	LIGO/Stanford/U. Fla.	12/01
Integration test on suspended interferometer	LIGO. Stanford/U. Fla.	3/02

Adaptive Core Optics for Advanced LIGO

- Problem: LIGO I sees thermal effects at 10 W laser power.[1] > 100 W required for “Advanced” shot noise sensitivity.
- Several thermal effects foreseen:
  - cavity mode distortion --> poor coupling
  - differential cavity mode mismatch --> contrast defect
  - recycling cavity sideband loss for power-recycled Schnupp scheme
- Several strategies proposed:
  - Insensitive configuration (RSE), readout (DRSB, NRSB)
  - lower bulk- and surface-loss, CTE, dN/dT and higher κ_{th} optics
  - Adaptive Core Optics

---

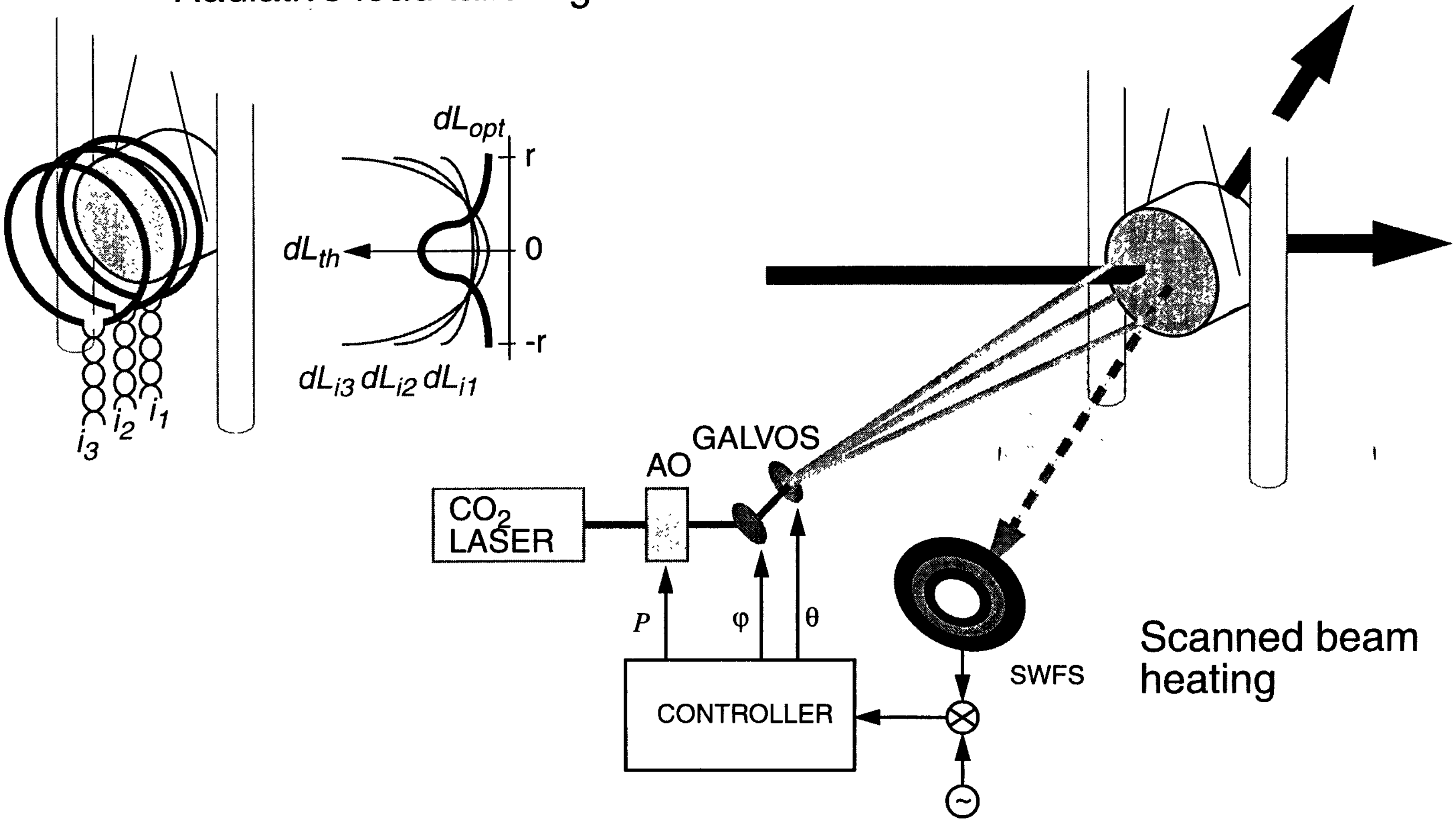
[1] Recycling mirror curvature specifications must counteract calculated ITM thermal lens to avoid significant performance penalty.

Research Program

- Modeling
  - Couple quasi-static thermal FEA with optical mode propagation
- Sensing research
  - Modified Schack-Hartmann sensors
  - “Super Wavefront Sensor” (SWFS)
    - > “bull’s eye” RF detectors (prototype under development at UF)
  - Dithering & synchronous image processing
  - Dead reckoning (!) -- thermal inputs are stable, time constants very long
- Actuation research
  - scanned auxiliary (‘heater’) laser (e.g., CO_2; highly general, “brute force”)
  - radiative coupling control (e.g., filaments & low-ε shields; “finesse”)

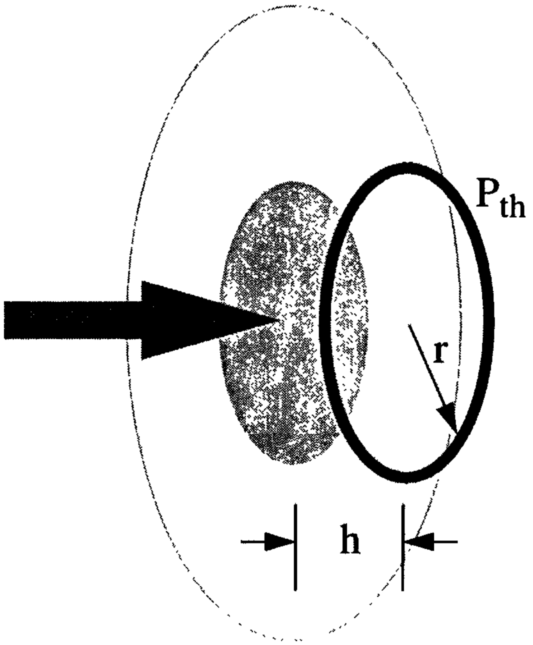
Thermal Actuation Concepts

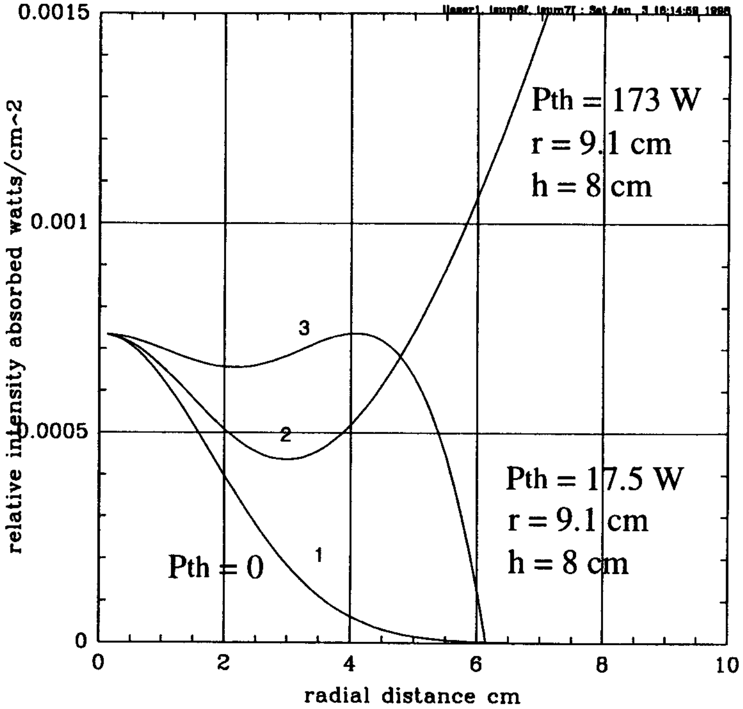
Radiative load tailoring



Scanned beam heating

Preliminary result: 1-d radiative loading from a circular filament[1]





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[1] R. Weiss, "Note on thermal compensation of thermal lensing by mirrors" (12/97)

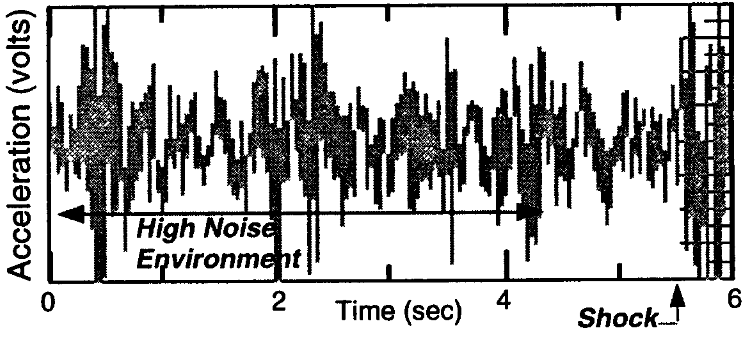
Adaptive Core Optics Timetable

Milestone	*Target*
Coupled thermal/optical model development	9/99
Test interferometer construction	3/00
Sensor prototype construction & test	9/00
Radiative coupling actuator prototype test	3/01
Scanning actuator prototype test	9/01
Control algorithm development	6/02
Loop closure on test interferometer	9/02
Engineering design for suspended interferometer test	6/03
Suspended interferometer test	10/03

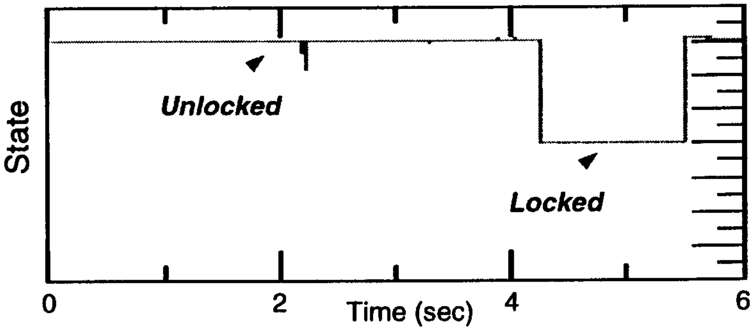
ADVANCED CONTROL TECHNIQUES: MOTIVATION

- Challenging detector availability goals have been established for the LIGO observatories:
  - ›› Single interferometer operations > 90% of the time with minimum of 40 hr. continuous lock periods
  - ››Double coincidences > 85% time and triple coincidences > 75% time with 100 hr. minimum continuous lock periods
- 40 m prototype experience:
  - ››Limited periods of continuous interferometer lock will be the main contributor to detector down-time (40m prototype lock durations vary from seconds to a few hours)
    - —Control system instabilities caused by drifts in the interferometer system parameters
    - —Displacement noise events which kick the interferometer out of lock

Ground Excitation vs Time



State of Interferometer vs Time



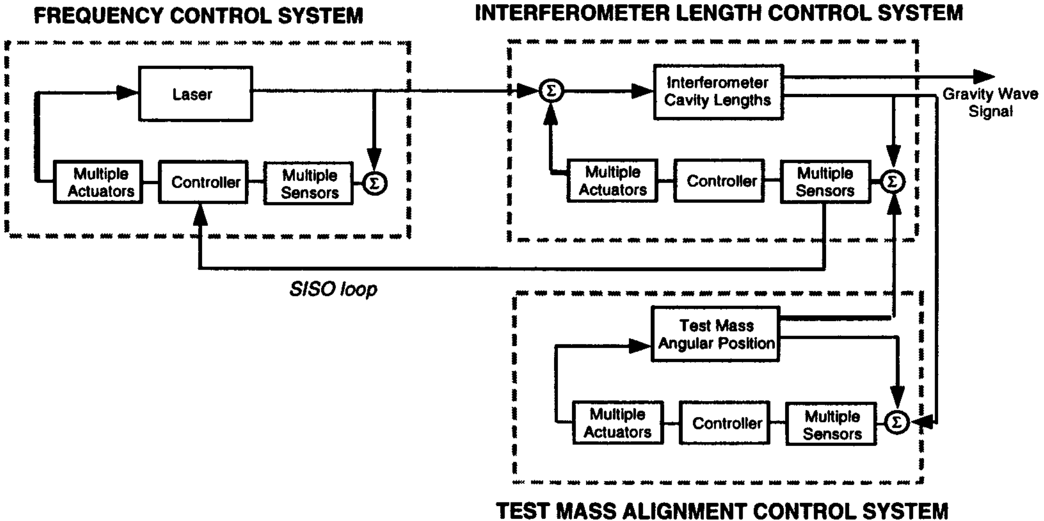
ADVANCED CONTROL TECHNIQUES: BACKGROUND

- LIGO has frequency, length and alignment servo-control loops
  - The optical model for the length control system is a 4x4 matrix of transfer functions:

$$H_{ij}(s) = G_{ij} \cdot \frac{\left(1 + \frac{s}{z_{ij}}\right)}{\left(1 + \frac{s}{p_{ij}}\right)}$$

The 4 degrees of freedom are the common mode arm cavity length *L+*, the differential arm cavity length *L-*, the Michelson difference *l-*, and the Michelson common mode length *l+*

  - The interferometer optical alignment model is a 10x10 matrix of transfer functions whose elements have a similar form

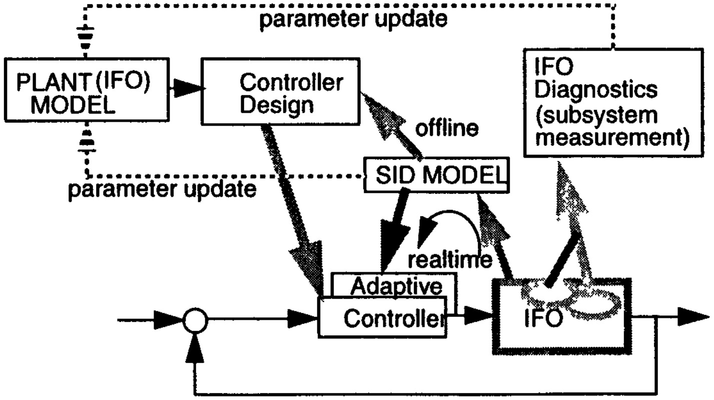


ADVANCED CONTROL TECHNIQUES: BACKGROUND (continued)

- Potential hardware imperfections, model errors, unknowns or parameters subject to drift which could effect control system robustness include:
  - Beamsplitter reflectivity ≠ 50%
  - Mixer phase error
  - Deviations from resonance
  - Visibility variation
  - Fabry-Perot cavity input and end test mass absorption (resulting in radius of curvature changes)
  - Sensor & actuator cross-talk (optical, mechanical & electrical)
  - Alignment/length Coupling
  - Modulation depth & phase variation

ADVANCED CONTROL TECHNIQUES: STRATEGY

- System identification will be used in conjunction with subsystem diagnostic and measurement techniques to update our understanding of the system and its control
- Once the system susceptibilities are understood, an adaptive controller can be formulated to compensate
- SID and Adaptive Control are mature technologies;
  The application to Interferometry is unique

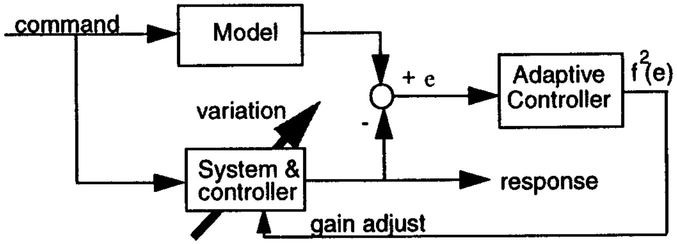


ADVANCED CONTROL TECHNIQUES: SYSTEM IDENTIFICATION

- System Identification (SID) is an empirical approach to modeling interferometer system dynamics
  - Non-parametric identification (i.e. frequency response estimation)
  - Parametric system models (e.g. state space representation)
- For LIGO we seek a <u>recursive</u>, real-time <u>parameter identification</u> of the multi-input/multi-output optical response of the interferometer in <u>Detection Mode</u>:
- Many techniques are available and will be explored; Potential candidates include:
  - Generalized Least Squares and Maximum Likelihood Estimators (e.g. the Prediction Error Method) are computationally simple
  - Observer/Kalman Filter Identification (OKID) -- time domain based, can be extended to identification of closed loop effective controller/observer combination (Observer Controller Identification, OCID)
  - State-Space Frequency Domain (SSFD) identification -- frequency domain based (can use spectrum analyzers)

ADVANCED CONTROL TECHNIQUES: ADAPTIVE CONTROL

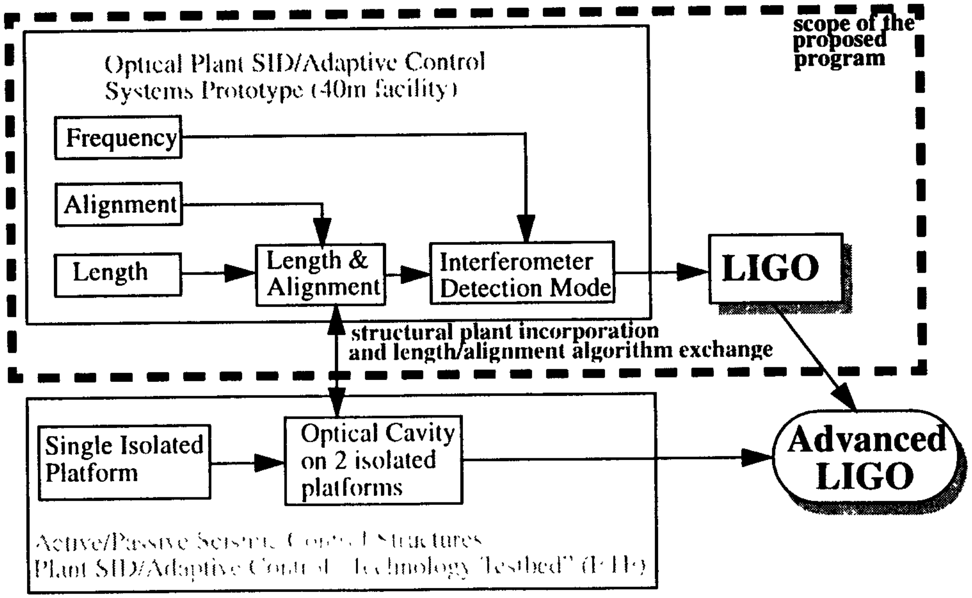
- Adaptive Control can improve sensitivity while maintaining robustness to disturbances and plant variations
- Adaptive control time scales:
  - milliseconds for the ordinary feedback
  - many minutes for updating the control parameters and performing SID
- Possible adaptive control algorithm: Model Reference Adaptive Control



ADVANCED CONTROL TECHNIQUES:

COLLABORATORS & RESPONSIBILITIES

- Stanford Univ. plans to explore system identification and adaptive control on advanced seismic isolation and suspension subsystems
- LIGO will concentrate on identification and control (length, alignment and frequency) of the optical plant for a power recycled configuration



- GEO plans to explore adaptive control for autonomous and tele-remote operation

ADVANCED CONTROL TECHNIQUES: WORK PLAN

- System Identification:

  - The 40 m prototype will be used as the principal testbed for different SID schemes (ETF as secondary testbed for single cavity length/alignment control)

  - Sequence:
    1. Investigate and categorize events/sources that unlock the interferometer
    2. SID for four length loops separately to identify model parameters (poles, zeros and gains)
    3. Length system as a Multi-Input Multi-Output (MIMO) system, including cross-couplings between the loops
    4. Establish whether ambient, in-situ, stochastic excitation is sufficient for determining the model parameters with required accuracy -- or establish calibrated external stimulus requirements/design
    5. SID for wavefront sensor based alignment system (MIMO system)
    6. SID for combined length and alignment system
    7. SID for frequency control system
    8. SID for entire system

  - Off-line SID can be accommodated with the current 40 m data acquisition (DAQS) system

  - The 40 m DAQS can also be used, with additional real-time software & hardware (VME processor and DSP), to perform recursive SID

  - Once an on-line method has been tested and verified on the 40 m prototype it will then be adapted to LIGO (add IO length and alignment control)

ADVANCED CONTROL TECHNIQUES: WORK PLAN (continued)

- Adaptive Control:
  - The 40 m prototype will serve as a testbed
  - Control will be made adaptive, where beneficial, based upon analysis of SID results
  - Requires the planned 40 m electronics retrofit with "LIGO-like", VME-based, digital controls
  - Computation will be implemented on another dedicated VME processor with an associated Digital Signal Processor (DSP), networking board and reflective memory
  - Once the adaptive control is demonstrated to improve 40m prototype performance, it will be ported, with necessary changes, to the initial LIGO interferometer system
- The performance of the system in terms of availability (increased lock acquisition time) and decreased noise level will be compared in a series of long duration (order of a week) data runs

Advanced control plan milestones and dates

Milestone	*Target*
SID application to 40m	6/99
Adaptive Control application to 40m	6/00
SID application to LIGO	12/99
Adaptive Control application to LIGO	6/01

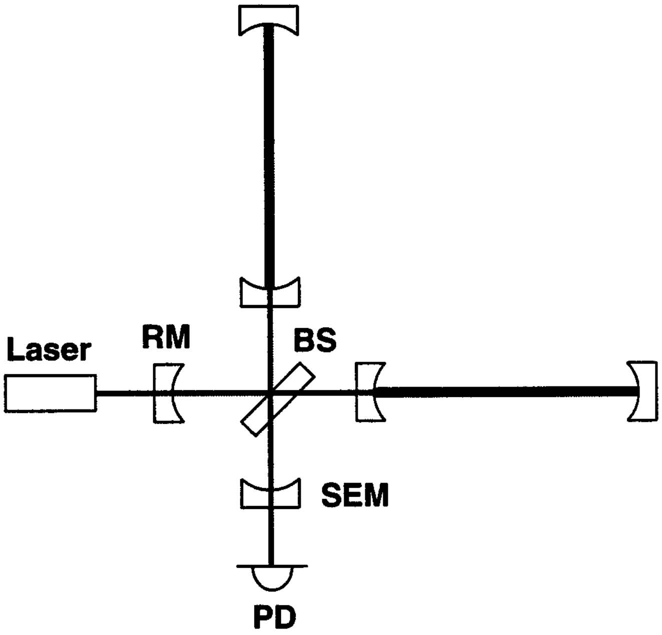
Resonant Sideband Extraction Fixed Mass Interferometer

James Mason

January 22, 1998

- A promising optical configuration for enhanced LIGO
- Features!
  - ››Higher storage time for carrier light in the arm cavities
    - – Less or no power recycling necessary
    - – Reduced thermal load on the beamsplitter
    - – Possible elimination of the optics and electronics for control of the recycling degree of freedom
  - ››Detector response is tunable
    - – Narrow-band, improved sensitivity about a frequency of interest possible with appropriate choice of optical parameters

Resonant Sideband Extraction



- Addition of mirror at output port

  ››Forms a coupled cavity system for the signal sidebands

  — Output mirror reflectivity and output cavity length (phase) used to tune detector transfer function

  — RSE uses output cavity to lower storage time for the signal sidebands by making the output cavity resonant

  — Changing phase in the output cavity changes the resonant frequency of the coupled cavity system

Previous Research, Planned Research

- Proof of principle achieved
  - ››Heinzel, Mizuno, et al., Phys. Lett. **A217** (1996)p.305
    - No power recycling
    - External modulation
    - Dither locking and pickoffs used to lock cavities
- Issues to be investigated in this fixed mass interferometer experiment
  - ›› Using frontal (Schnupp) modulation, develop a signal extraction scheme to control the 5 degrees of freedom
  - ››Investigate lock acquisition
  - ››Investigate the "tunability" of the interferometer
- Long term goals
  - ››Comparison with a dual recycled table-top experiment being carried out in parallel at University of Florida
  - ››Downselect between these two schemes to be implemented in a suspended interferometer

Current Status

- Work to date, in progress
  - ››Mathematical models used to predict behavior
  - ››Nominal set of optical parameters chosen
    - – Optical path lengths, mirror parameters, modulation frequencies
  - ››A signal extraction scheme has been worked out
    - – A second, which would facilitate filtering of the RF sidebands, is being explored
  - ››A lab has been set up
  - ››High bandwidth mirror mounts are being fabricated and tested
    - – Used in MIT's alignment FMI, first notable resonance at 60 kHz
- What's next (short term)
  - ››Begin fabrication of photodiodes for signal extraction
  - ››Finish fabrication and characterization of mounts
  - ››Begin interferometer construction and testing
    - – Control system design and optics layout

NSF Review of LIGO Laboratory Advanced R&D Proposal

Resource Overview

Phil Lindquist

January 22, 1998

Summary Proposal Budget

		Funds Requested					
Line	**Description**	**FY 1997**	**FY 1998**	**FY 1999**	**FY 2000**	**FY 2001**	**Total**
A	Senior Personnel						
B1	Post Doctoral	18,779	158,730	272,747	257,843	244,802	952,901
B2	Other Professionals	28,233	304,851	406,372	408,045	399,682	1,547,183
B3	Graduate Students	48,683	70,767	98,267	98,267	98,267	414,251
B4	Undergraduate Students						
B5	Secretarial/Clerical						
C	Fringe Benefits	14,751	115,895	169,780	166,472	161,121	628,019
	Total Salaries, Wages, Fringe	110,446	650,243	947,166	930,627	903,872	3,542,354
D	Equipment	460,685	1,124,100	749,500	670,500	749,000	3,753,785
E	Travel	26,348	67,090	72,962	83,759	83,759	333,918
F	Participant Costs						
G1	Materials & Supplies	30,176	100,538	161,391	169,465	163,114	624,684
G2	Publication Costs						
G3	Consultant Services						
G4	Computer Services						
G5	Subawards	50,000	193,000	129,000	262,300	258,300	892,600
G6	Other (GRA Benefits)	32,280	56,613	78,613	78,613	78,613	324,732
H	**Total Direct**	709,935	2,191,584	2,138,632	2,195,264	2,236,658	9,472,073
I	**Indirect Costs**	90,065	483,655	687,400	688,740	665,124	2,614,984
J	**Total Direct and Indirect**	800,000	2,675,239	2,826,032	2,884,004	2,901,782	12,087,057

Staffing Resource Requirements

		Full Time Equivalent (FTE)					
Line	Description	FY 1997	FY 1998	FY 1999	FY 2000	FY 2001	Total
A	Senior Personnel						
B1	Post Doctoral	0.42	3.55	6.10	5.77	5.48	21.32
B2	Other Professionals	0.37	4.18	5.57	5.59	5.49	21.20
B3	Graduate Students	2.59	3.86	5.36	5.36	5.36	22.53
B4	Undergraduate Students						
B5	Secretarial/Clerical						
C	Total	3.38	11.59	17.03	16.72	16.33	65.05

Funding by Task

	Funds Requested					
Task	**FY 1997**	**FY 1998**	**FY 1999**	**FY 2000**	**FY 2001**	**Total**
Stochastic Noise Sources	126,749	923,238	868,638	711,638	865,638	3,495,901
Thermal Noise Interferometer	161,714	320,533	246,533	168,533	158,533	1,055,846
LasersHigh Power Laser	10,000	334,250	298,500	368,500	368,500	1,379,750
Core Optics Development	150,522	296,611	367,186	557,116	542,116	1,913,551
Sapphire Core Optics	128,405	327,863	267,842	331,842	313,246	1,369,198
Advanced Photodetectors	-	119,166	131,333	124,333	112,833	487,665
Adaptive Optics	-	-	108,333	99,333	99,833	307,499
Advanced Controls	-	17,560	211,750	196,792	115,167	541,269
Resonant Sideband Extractio	222,610	335,919	325,919	325,919	325,919	1,536,286
Total	**800,000**	**2,675,140**	**2,826,034**	**2,884,006**	**2,901,785**	**12,086,965**

Equipment Funding By Task and Fiscal Year

Line	D

Sum of Total	FY					
Task	1997	1998	1999	2000	2001	Grand Total
1. STO	86,000	439,000	267,000	110,000	264,000	1,166,000
2. TNI	92,000	169,000	95,000	10,000		366,000
3. LAS		180,000		70,000	70,000	320,000
4. OPT	90,000	95,000	159,000	255,000	230,000	829,000
5. SAP	28,000	74,000		24,000	24,000	150,000
6. PDT		87,000	69,000	62,000	50,500	268,500
7. AOP			49,000	40,000	40,500	129,500
8. CTR			40,500	29,500		70,000
9. RSE	164,685	80,000	70,000	70,000	70,000	454,685
Grand Total	460,685	1,124,000	749,500	670,500	749,000	3,753,685

Advanced R&D Proposal Budgets Detail

Task	FY	Line	Description	FTEs	Direct	Benefits	GRAs	Overhead	Total
1. STO	1997	D	Data Acquisition System		83,000				83,000
1. STO	1997	D	Machining		3,000				3,000
1. STO	1998	D	Matlab		10,000				10,000
1. STO	1998	D	Instrumentation		50,000				50,000
1. STO	1998	D	BSC Isolation		379,000				379,000
1. STO	1999	D	Seismic Upgrades		30,000				30,000
1. STO	1999	D	Suspensions, Controllers, Optics						-
1. STO	1999	D	HAM Isolation		237,000				237,000
1. STO	2000	D	Prototyping Equipment		60,000				60,000
1. STO	2000	D	Seismic Upgrades		30,000				30,000
1. STO	2000	D	Vacuum Equipment		20,000				20,000
1. STO	2000	D	Suspensions, Controllers, Optics		-				-
1. STO	2001	D	Seismic Upgrades		40,000				40,000
1. STO	2001	D	Vacuum Equipment		10,000				10,000
1. STO	2001	D	Prototyping Equipment		40,000				40,000
1. STO	2001	D	Suspensions, Controllers, Optics		34,000				34,000
1. STO	2001	D	2nd Prototype - Suspensions, Controls, Optics		140,000				140,000
1. STO Total									1,166,000

Advanced R&D Proposal Budgets Detail

Task	FY	Line	Description	FTEs	Direct	Benefits	GRAs	Overhead	Total
2. TNI	1997	D	700 mW NPRO Laser		32,000			-	32,000
2. TNI	1997	D	Optical Table (Synch Lab)		15,000			-	15,000
2. TNI	1997	D	Optics and General Lab Hardware		15,000			-	15,000
2. TNI	1997	D	PSL Cavity Mirrors		15,000			-	15,000
2. TNI	1997	D	PSL Electronics		5,000			-	5,000
2. TNI	1997	D	Soft Wall Clean Room		10,000			-	10,000
2. TNI	1998	D	Actuator Hardware		10,000				10,000
2. TNI	1998	D	Fiber Pulling Hardware		75,000				75,000
2. TNI	1998	D	Frame Machining		15,000				15,000
2. TNI	1998	D	High Purity Fused Silicon Suspension		5,000				5,000
2. TNI	1998	D	PSL Pre-mode Cleaner		8,000				8,000
2. TNI	1998	D	Reflective/Anti-reflective Coatings		10,000				10,000
2. TNI	1998	D	Test Masses and Suspensions		10,000				10,000
2. TNI	1998	D	Turbo Pump Stations		10,000				10,000
2. TNI	1998	D	Vacuum Accessories		8,000				8,000
2. TNI	1998	D	Vacuum System Moving		8,000				8,000
2. TNI	1998	D	Wavefront Sensing Hardware Electronics		5,000				5,000
2. TNI	1998	D	Wavefront Sensing Hardware Optics		5,000				5,000
2. TNI	1999	D	Data Acquisition Electronics		25,000				25,000
2. TNI	1999	D	In-vacuum Mounts		10,000				10,000
2. TNI	1999	D	Miscellaneous Optics		15,000				15,000
2. TNI	1999	D	Optics Mounts		5,000				5,000
2. TNI	1999	D	Pre-Amps, Oscilloscopes, RF Electronics		15,000				15,000
2. TNI	1999	D	Suspended Mode Cleaner Cavity		15,000				15,000
2. TNI	1999	D	Suspended Mode Cleaner Suspension		10,000				10,000
2. TNI	2000	D	Computer and Interface Hardware		5,000				5,000
2. TNI	2000	D	Miscellaneous Electronics		5,000				5,000
2. TNI Total									366,000

Advanced R&D Proposal Budgets Detail

Task	FY	Line	Description	FTEs	Direct	Benefits	GRAs	Overhead	Total
3. LAS	1998	D	Lightwave 10 W Laser for Stanford MOPA		100,000			-	100,000
3. LAS	1998	D	Analyzer Cavity for Frequency Noise Measurement		40,000				40,000
3. LAS	1998	D	Stabilization Optics for Laser		40,000				40,000
3. LAS	2000	D	Test Rig for Laser Characterization		70,000				70,000
3. LAS	2001	D	Test Rig for Laser Characterization		70,000				70,000
3. LAS Total									320,000

Advanced R&D Proposal Budgets Detail

Task	FY	Line	Description	FTEs	Direct	Benefits	GRAs	Overhead	Total
4. OPT	1997	D	Laser, IR Modulators and Isolators, Optics		80,000				80,000
4. OPT	1997	D	Machining		10,000				10,000
4. OPT	1998	D	Bulk Absorption Metrology - Hardware		55,000				55,000
4. OPT	1998	D	Damage Test Setup		40,000				40,000
4. OPT	1999	D	Bulk Absorption Metrology - Glass Development		30,000				30,000
4. OPT	1999	D	Chemical Cleaning		4,000				4,000
4. OPT	1999	D	Coating Absorption Uniformity		20,000				20,000
4. OPT	1999	D	Coating Uniformity Metrology		10,000				10,000
4. OPT	1999	D	In Situ Cleaning		30,000				30,000
4. OPT	1999	D	Phase Shifting IFO Environmental Isolation		5,000				5,000
4. OPT	1999	D	Phase Shifting IFO Infrastructure Hardware		10,000			-	10,000
4. OPT	1999	D	Phase Shifting IFO Interferometer Hardware		30,000				30,000
4. OPT	1999	D	Lensing Compensation Material		20,000				20,000
4. OPT	2000	D	Lensing Compensation Test Setup Hardware		40,000				40,000
4. OPT	2000	D	Bulk Absorption Metrology - Glass Development		45,000				45,000
4. OPT	2000	D	Chemical Cleaning		5,000				5,000
4. OPT	2000	D	Coating Absorption Uniformity		15,000				15,000
4. OPT	2000	D	Coating Uniformity Metrology		15,000				15,000
4. OPT	2000	D	In Situ Cleaning		30,000				30,000
4. OPT	2000	D	Lensing Compensation Test Setup Hardware		30,000				30,000
4. OPT	2000	D	Phase Shifting IFO Environmental Isolation		10,000				10,000
4. OPT	2000	D	Phase Shifting IFO Infrastructure Hardware		15,000				15,000
4. OPT	2000	D	Phase Shifting IFO Interferometer Hardware		50,000				50,000
4. OPT	2001	D	Bulk Absorption Metrology - Glass Development		60,000				60,000
4. OPT	2001	D	Chemical Cleaning		5,000				5,000
4. OPT	2001	D	Coating Absorption Uniformity		10,000				10,000
4. OPT	2001	D	Coating Uniformity Metrology		15,000				15,000
4. OPT	2001	D	In Situ Cleaning		30,000				30,000
4. OPT	2001	D	Lensing Compensation Test Setup Hardware		30,000				30,000
4. OPT	2001	D	Phase Shifting IFO Environmental Isolation		10,000				10,000
4. OPT	2001	D	Phase Shifting IFO Infrastructure Hardware		15,000				15,000
4. OPT	2001	D	Phase Shifting IFO Interferometer Hardware		55,000				55,000
4. OPT Total									829,000

Advanced R&D Proposal Budgets Detail

Task	FY	Line	Description	FTEs	Direct	Benefits	GRAs	Overhead	Total
5. SAP	1997	D	Crystal Systems Sapphire		28,000			-	28,000
5. SAP	1998	D	Half Size Sapphire Blanks		37,000			-	37,000
5. SAP	1998	D	Sapphire Test Samples		37,000			-	37,000
5. SAP	2000	D	Half Size Sapphire Blanks		12,000			-	12,000
5. SAP	2000	D	Sapphire Test Samples		12,000			-	12,000
5. SAP	2001	D	Half Size Sapphire Blanks		12,000			-	12,000
5. SAP	2001	D	Sapphire Test Samples		12,000			-	12,000
5. SAP Total									150,000

Task	FY	Line	Description	FTEs	Direct	Benefits	GRAs	Overhead	Total
6. PDT	1998	D	Lightwave 126 Nd:YAG Laser		40,000			-	40,000
6. PDT	1998	D	Digitizer/Data Logger		5,500				5,400
6. PDT	1998	D	Miscellaneous Optics		3,000				3,000
6. PDT	1998	D	Photo Detector Samples and NRE		7,500				7,500
6. PDT	1998	D	Power Meter		1,800				1,800
6. PDT	1998	D	Pulsed Nd:YAG		15,000				15,000
6. PDT	1998	D	RF Preamplifier		800				800
6. PDT	1998	D	XY Scan Stage and Control		3,500				3,500
6. PDT	1998	D	Miscelaneous Optics		5,000				5,000
6. PDT	1998	D	Miscellaneous Electronics		5,000				5,000
6. PDT	1999	D	Pulsed Nd:YAG		50,000				50,000
6. PDT	1999	D	Photo Detector Samples and NRE		10,000				10,000
6. PDT	1999	D	Thermal Test Chamber		4,000				4,000
6. PDT	1999	D	Cabling and Terminations		5,000				5,000
6. PDT	2000	D	AO Modulator and Driver		6,000				6,000
6. PDT	2000	D	Engineering Prototype Head Electronics		10,000				10,000
6. PDT	2000	D	Engineering Prototype Head Optical/Mechanical		30,000				30,000
6. PDT	2000	D	EO Modulators		9,000				9,000
6. PDT	2000	D	RF Power Amps		3,000				3,000
6. PDT	2000	D	Thermal Test Chamber		4,000				4,000
6. PDT	2001	D	EO Protection Shutter and Control		5,500				5,500
6. PDT	2001	D	Miscellaneous Test Optics and Electronics		5,000				5,000
6. PDT	2001	D	Software Licensing		5,000				5,000
6. PDT	2001	D	VME Crate and Instrumentation		35,000				35,000
6. PDT Total									268,500

Advanced R&D Proposal Budgets Detail

Task	FY	Line	Description	FTEs	Direct	Benefits	GRAs	Overhead	Total
7. AOP	1999	D	Actuator Drive Power Electronics		4,000				4,000
7. AOP	1999	D	Beam Imaging and Frame Grabber		15,000			-	15,000
7. AOP	1999	D	Low Power Probe Laser		5,000				5,000
7. AOP	1999	D	Miscellaneous Electronics Components		2,500				2,500
7. AOP	1999	D	Miscellaneous Optical Components		1,000				1,000
7. AOP	1999	D	Prototype Thermal Filiament Actuator		10,000				10,000
7. AOP	1999	D	Schack-Hartmann Sensor and Interface		6,000				6,000
7. AOP	1999	D	Test Optic		1,500				1,500
7. AOP	1999	D	Thermal Coupling Test Stand Mechanical Components		4,000				4,000
7. AOP	2000	D	IR Pumping Laser		25,000				25,000
7. AOP	2000	D	Radial WFS Prototype		15,000				15,000
7. AOP	2001	D	Acoustic/Thermal Isolation Housing		5,000				5,000
7. AOP	2001	D	Control Loop Electronics and Software		10,000				10,000
7. AOP	2001	D	Galvo Scanning System, Drivers, Controls		10,000				10,000
7. AOP	2001	D	Miscellaneous Electronics Components		2,500				2,500
7. AOP	2001	D	Miscellaneous Optical Components		10,000				10,000
7. AOP	2001	D	Test Optics		3,000				3,000
7. AOP Total									129,500

Advanced R&D Proposal Budgets Detail

Task	FY	Line	Description	FTEs	Direct	Benefits	GRAs	Overhead	Total
8. CTR	1999	D	40 meter SID Analog to Digital Converters		2,000				2,000
8. CTR	1999	D	40 meter SID CPU		3,500			-	3,500
8. CTR	1999	D	40 meter SID Digital Signal Processor		5,000				5,000
8. CTR	1999	D	40 meter SID Miscellaneous Hardware and Cables		5,000				5,000
8. CTR	1999	D	40 meter SID Netrwork Card		3,000				3,000
8. CTR	1999	D	40 meter SID Reflective Memory Boards		5,000				5,000
8. CTR	1999	D	40 meter SID Sensors		15,000				15,000
8. CTR	1999	D	Mounting Racks		2,000				2,000
8. CTR	2000	D	40 meter Prototype Analog to Digital Converters		16,000				16,000
8. CTR	2000	D	40 meter Prototype CPU		3,500				3,500
8. CTR	2000	D	40 meter Prototype Digital Signal Processor		5,000				5,000
8. CTR	2000	D	40 meter Prototype Reflective Memory Boards		5,000				5,000
8. CTR Total									70,000

Advanced R&D Proposal Budgets Detail

1/15/98

Task	FY	Line	Description	FTEs	Direct	Benefits	GRAs	Overhead	Total
9. RSE	1997	D	Computer		7,000			-	7,000
9. RSE	1997	D	Diagnostics and General Electronics		44,000			-	44,000
9. RSE	1997	D	Electronics		5,000			-	5,000
9. RSE	1997	D	Laser (Lightwave 126-1064-100)		21,000			-	21,000
9. RSE	1997	D	Miscellaneous Tools, Fasteners, etc.		6,685			-	6,685
9. RSE	1997	D	Optical Electronics		16,000			-	16,000
9. RSE	1997	D	Optical Supplies (hardware)		13,000			-	13,000
9. RSE	1997	D	Optical Table		22,000			-	22,000
9. RSE	1997	D	Optics (Mirrors and Lenses)		30,000			-	30,000
9. RSE	1998	D	Control Electronics		10,000				10,000
9. RSE	1998	D	Electronic Intstrumentation		60,000				60,000
9. RSE	1998	D	Optical Device		5,000				5,000
9. RSE	1998	D	Optics (Mirrors and Lenses)		5,000				5,000
9. RSE	1999	D	Control Electronics		13,333				13,333
9. RSE	1999	D	Electronic Intstrumentation		13,333				13,333
9. RSE	1999	D	Optical Device		10,000				10,000
9. RSE	1999	D	Optics (Mirrors and Lenses)		33,333				33,333
9. RSE	2000	D	Control Electronics		13,333				13,333
9. RSE	2000	D	Electronic Intstrumentation		13,333				13,333
9. RSE	2000	D	Optical Device		10,000				10,000
9. RSE	2000	D	Optics (Mirrors and Lenses)		33,333				33,333
9. RSE	2001	D	Control Electronics		13,333				13,333
9. RSE	2001	D	Electronic Intstrumentation		13,333				13,333
9. RSE	2001	D	Optical Device		10,000				10,000
9. RSE	2001	D	Optics (Mirrors and Lenses)		33,333				33,333
9. RSE Total									454,685

Task	FY	Line	Description	FTEs	Direct	Benefits	GRAs	Overhead	Total
4. OPT	1998	G5	Mirror Blanks		120,000				120,000
4. OPT	1999	G5	Coating Process Loss		20,000				20,000
4. OPT	1999	G5	Coating Process Uniformity		20,000				20,000
4. OPT	2000	G5	Polishing Development		40,000				40,000
4. OPT	2000	G5	Coating Process Loss		15,000				15,000
4. OPT	2000	G5	Coating Process Uniformity		15,000				15,000
4. OPT	2000	G5	Lensing Compensation Material		25,000				25,000
4. OPT	2000	G5	Polishing Development		38,300				38,300
4. OPT	2001	G5	Coating Process Loss		15,000				15,000
4. OPT	2001	G5	Coating Process Uniformity		15,000				15,000
4. OPT	2001	G5	Lensing Compensation Material		25,000				25,000
4. OPT	2001	G5	Polishing Development		88,300				88,300
4. OPT Total									436,600

Advanced R&D Proposal Budgets Detail

Task	FY	Line	Description	FTEs	Direct	Benefits	GRAs	Overhead	Total
5. SAP	1997	G5	Subcontract (SIOM)		50,000			14,363	64,363
5. SAP	1998	G5	Coating Evaluation Half Size Blanks		12,000			-	12,000
5. SAP	1998	G5	Coating Half Size Blanks		13,000			-	13,000
5. SAP	1998	G5	Polishing Evaluation		8,000			-	8,000
5. SAP	1998	G5	Polishing Half Size Blanks		16,000			-	16,000
5. SAP	1998	G5	Sample Composition Evaluation		16,000			9,192	25,192
5. SAP	1998	G5	Sample Optical evaluation		8,000			4,596	12,596
5. SAP	1999	G5	Coating Evaluation Half Size Blanks		6,000			-	6,000
5. SAP	1999	G5	Coating Half Size Blanks		8,000			-	8,000
5. SAP	1999	G5	Full Size Blank Acquisition		30,000				30,000
5. SAP	1999	G5	Polishing Half Size Blanks		30,000				30,000
5. SAP	1999	G5	Sample Composition Evaluation		7,000			4,022	11,022
5. SAP	1999	G5	Sample Optical evaluation		8,000			4,596	12,596
5. SAP	2000	G5	Coating Evaluation Half Size Blanks		6,000			-	6,000
5. SAP	2000	G5	Coating Half Size Blanks		8,000			-	8,000
5. SAP	2000	G5	Full Size Blank Acquisition		30,000				30,000
5. SAP	2000	G5	Full Size Blank Coating and Evaluation		14,000			-	14,000
5. SAP	2000	G5	Full Size Blank Evaluation		2,000			-	2,000
5. SAP	2000	G5	Full Size Blank Polishing		16,000			-	16,000
5. SAP	2000	G5	Polishing Evaluation		8,000			-	8,000
5. SAP	2000	G5	Polishing Half Size Blanks		30,000				30,000
5. SAP	2000	G5	Sample Composition Evaluation		7,000			4,022	11,022
5. SAP	2000	G5	Sample Optical evaluation		8,000			4,596	12,596
5. SAP	2001	G5	Coating Evaluation Half Size Blanks		5,000			-	5,000
5. SAP	2001	G5	Coating Half Size Blanks		8,000			-	8,000
5. SAP	2001	G5	Full Size Blank Acquisition		30,000				30,000
5. SAP	2001	G5	Full Size Blank Coating and Evaluation		7,000			-	7,000
5. SAP	2001	G5	Full Size Blank Evaluation		1,000			-	1,000
5. SAP	2001	G5	Full Size Blank Polishing		8,000			-	8,000
5. SAP	2001	G5	Polishing Evaluation		4,000			-	4,000
5. SAP	2001	G5	Polishing Half Size Blanks		30,000				30,000
5. SAP	2001	G5	Sample Composition Evaluation		7,000			4,022	11,022
5. SAP	2001	G5	Sample Optical evaluation		15,000				15,000
5. SAP Total									505,407