LIGO Advanced Detector R&D Proposal

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LIGO Research and Development Program Components

NSF "Task"	Period	R&D Activity
LIGO Construction (MRE + RRA)	1991 - 1997	in support of design and fabrication of initial LIGO
LIGO Operations	1997 - 2001	characterize initial detector systems and do gravity wave research
Visitors Program (pending)	1997 - 2001	support intermediate and long term visitors for LIGO R&D
Research Experience for Undergraduates (REU) Site (pending)	1997 - 2001	support undergraduate research within LIGO
Advanced Detector R&D (pending)	1997 - 2001	Support R&D to define new subsystems and new types of detectors

Operations Supported R&D

- Gravitational wave research
- Physics environment monitoring and correlations
- Diagnostics and correlations with interferometer output
- Materials, mechanical, electronic stability
- Optical contamination, materials outgassing, laser cleaning
- Residual gas instability
- Light scattering from tubes
- Linear and nonlinear servo operation, acquisition, stability
- Availability, reliability modeling
- Site to site correlations
- Geodesy, optical, GPS

This research will contribute to physics bottom line of LIGO

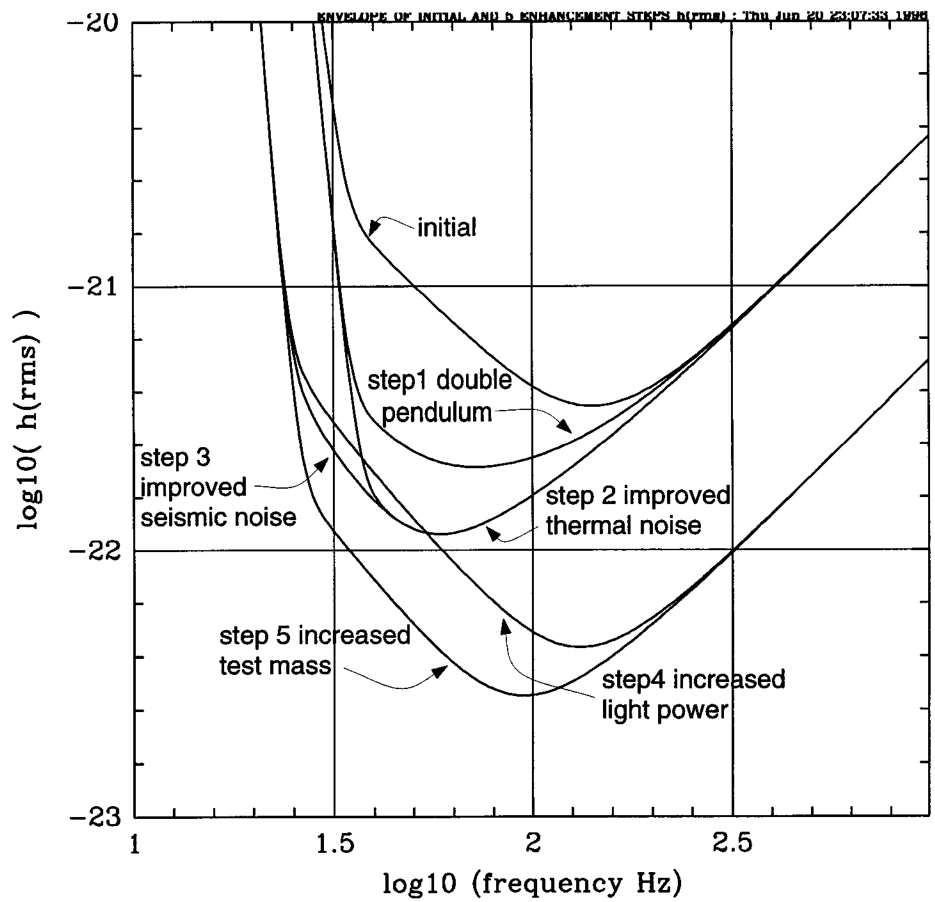
What We Propose

- A program of research to define advanced subsystems intended to be enhancements to the initial LIGO interferom- eters
- A program of research to define new advanced detectors
- A five year program in each thrust
  - ›› Some areas of research will enable implementation proposals
  - ›› Some research areas will not be completed and will become part of a following R&D proposal
- A program based upon the benchmark gravitational wave sources, but intended to be flexible if the course of physics research dictates a different evolution of LIGO capabilities

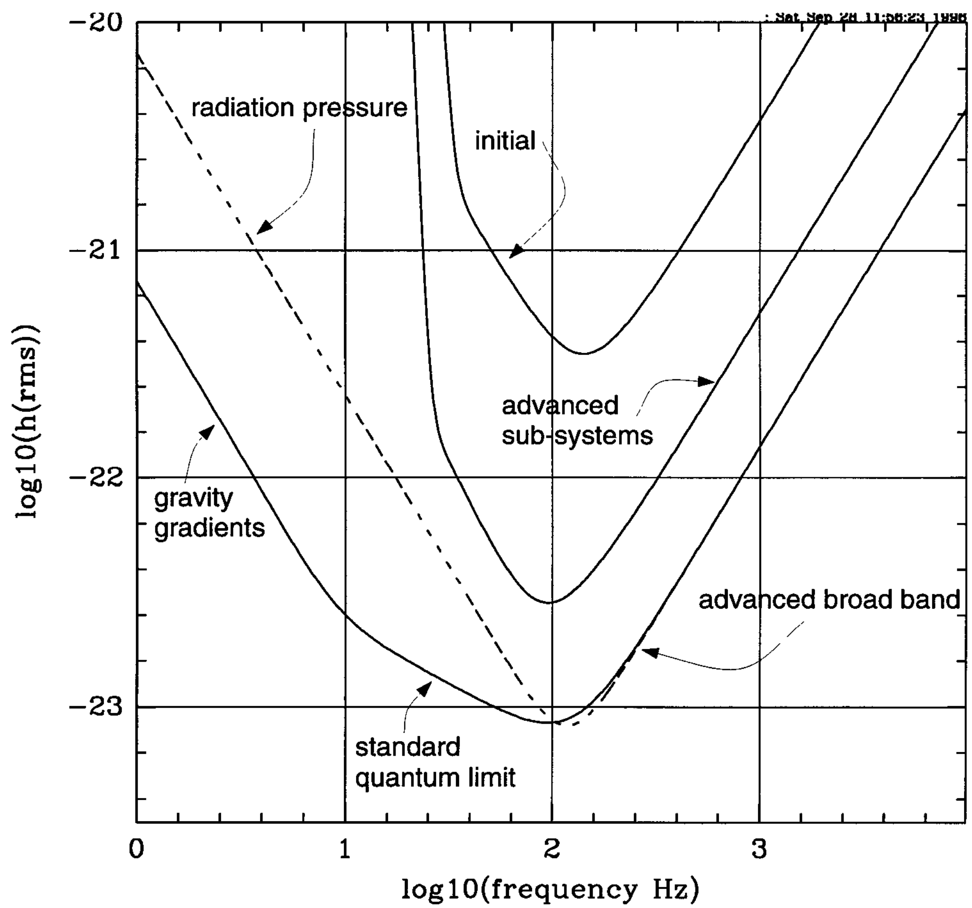
Collaboration

- Most proposed tasks are highly collaborative, involving institutions outside the LIGO Project
- These institutions will separately propose their required resources
    - ››very few subcontracts from LIGO to collaborators
- The proposed program is the LIGO R&D program and collaborators may propose other activities for their institutions
- It is our intention that this collaboration is the “training wheels” for the larger LIGO Collaboration. This is an important development in building this experimental field and it follows the recommendations of the McDaniel Report.

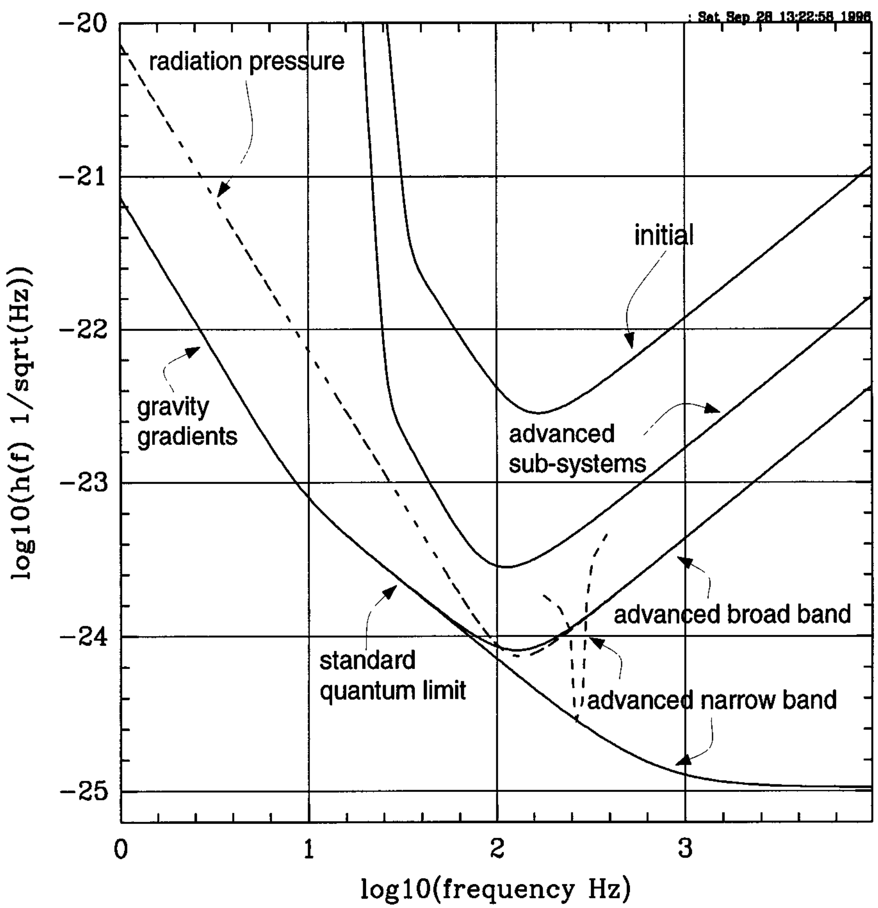
Steps in the Advanced Subsystems Research



h_{rms} Noise Envelopes for Initial LIGO and Advanced Subsystems/Detectors



Amplitude Spectral Strain Noise Expressed as an Equivalent h(f)



Astrophysics Motivations

Kip Thorne will discuss this subject

LIGO Funding by NSF Task and by Year

Fiscal Year	*Construction*	*R&D*	*Operations*	*Proposed* *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**	**1.7**	**58.6**
1998	**27.1**		**7.3**	**2.7**	**37.1**
1999			**20.9**	**2.7**	**23.6**
2000			**21.1**	**2.7**	**23.8**
2001		**10 months >**	**19.1**	**2.6**	**21.7**

All funds shown in 'then'-year $M

Noise Classification

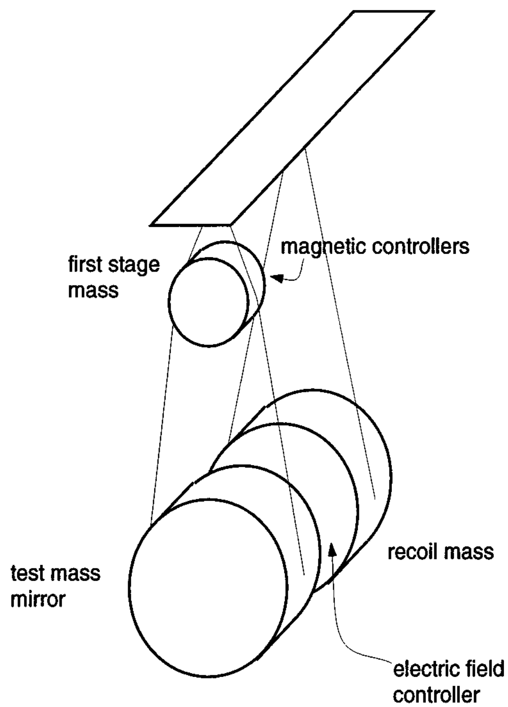
- *Sensing noise* - errors in the measurement of the optical phase introduced by scattered fields and the finite number of quanta being counted
- *Random forces* - stochastic processes that induce apparent test mass motions including thermal excitation of test masses, suspensions, seismic excitation, classical gravity gradients induced by terrestrial and atmospheric density fluctuations, radiation pressure fluctuations, etc.
- *Technical noise* - Non-fundamental sources of measurement noise such as electromagnetic interferences, environmental disturbances, imperfections in the instrumentation, etc.

Advanced Subsystems R&D

- Double Pendulum Suspension
- Reduced Thermal Noise
- Reduced Internal Test Mass Thermal Noise: Sapphire
- Higher Laser Power and Core Optics for Higher Power
- Increased Mass (Sapphire)

Double Pendulum Suspension

One Concept:



- Added isolation from thermal noise of seismic isolation
- Reduce actuator force dynamic range
- Remove test mass magnets which degrade Q
- Reduce magnetic field and domain jump noise on test mass
- Additional stage of $(f_0/f)^2$ isolation

Double Pendulum Suspension R&D

- Initial Phase

  ››Stanford, GEO and LIGO will study GEO design and LIGO requirements, leading to a design configuration suitable for LIGO

  ››Syracuse will study test mass losses vs. materials and attachments

  ››Stanford will continue fiber growing studies

  ››GEO will carry out realistic suspended element performance tests

  ››GEO actuator development will be used by LIGO to support studies of actuators suitable for LIGO

- Prototype Test Phase

  ››A set of LIGO-compatible prototypes will be fabricated and tested in a LIGO test interferometer

  GOAL IS CONSTRUCTION PROPOSAL AT END OF THIS RESEARCH

Double Pendulum Work Plan

Significant Events	*Responsible*	*Date*
Control system requirements developed	Stanford	Fall 1997
GEO control system analyzed	GEO	Fall 1997
Configuration chosen	LIGO, GEO	Fall 1998
Suspension fibers research mature	Stanford, Syracuse	Fall 1998
Attachment system research mature	Syracuse, GEO, LIGO	Fall 1998
Actuator technology research mature	LIGO	Fall 1998
Integration/selection of technologies	All	Winter 1998
Initial prototype constructed	LIGO, Stanford	Spring 1999
Initial prototype testing finished	LIGO or GEO	Fall 1999
Final design ready for fabrication, unification with thermal noise research	LIGO, Stanford	Spring 2000
Final design installed in test interferometer	LIGO	Spring 2001
Interferometer tests finished	All	Spring 2002

Reduced Thermal Noise Research

- Early phases support double pendulum suspension
- This research continues through double pendulum work and beyond, as an ongoing activity

Reduced Thermal Noise Work Plan

Topic	*Responsible*
SiO_2 Materials	Syracuse
SiO_2 Materials	Moscow State
Al_2O_3 Materials (sapphire)	See separate section on sapphire
Si Materials and flexures	Stanford
Attachments	Moscow State, Syracuse,Stanford
Test mass Q measurement	Syracuse
Noise correlations	*LIGO (Adv. Detector research)*
Test suspension design and construction	Part of double suspension research
Complete system test in sensitive ifo	Part of double suspension research

Reduced Test Mass Internal Noise: Sapphire Development

- Develop the techniques to grow, polish and coat sapphire with all of the required tolerances to enable them to be used as end test masses in LIGO and VIRGO.
- Investigate the absorption, birefringence and optical homogeneity with the goal of demonstrating suitability for the input test masses in LIGO and VIRGO.
- Investigate alternatives to the current wire suspensions which would not degrade the high intrinsic Q of the sapphire and which give higher suspension Q's.

Reduced Test Mass Internal Noise: Sapphire Development

Significant Events	*Responsible*	*Date*
Sample Characterization Complete	LIGO, VIRGO, UWA	July 1997
Test Masses (2) Delivered	LIGO, VIRGO	Jan. 1998
Test Mass Polishing and Figure Characterization Complete	CSIRO	July 1998
Test Mass Q, Absorption Birefringence Characterization Complete	LIGO, VIRGO, UWA	Dec. 1998
First Monolithic Suspension Results	UWA	July 1999

Higher Laser Power

- Continues LIGO development of 10 W 1064 nm for initial LIGO with Stanford and Lightwave
- Lightwave will continue development with rod geometry master oscillator-powered amplifier (MOPA) with an SBIR proposal
- LIGO will work with Stanford to apply LIGO requirements to a slab geometry design

  ››A Lightwave 10 W laser will be used as the master oscillator for the resulting 100 W prototype which will be fully investigated

- This program is planned for three years, leading to an engineering proposal to be carried out with industry

Core Optics for Higher Power

- Goal of 100 W laser is phase sensitivity of $3 \times 10^{-11} \text{rad}/\sqrt{Hz}$
- Achieve this by raising laser power OR by reducing optical losses OR by both
- This program proposes to follow on to LIGO Pathfinder program by extension to more demanding:

  ››optical metrology - principally of mirror polish and coating phase distortions

  ››optimum polishing technique for LIGO requirements

  ››control of coating uniformity and absolute optical characteristics such as reflectivity and loss

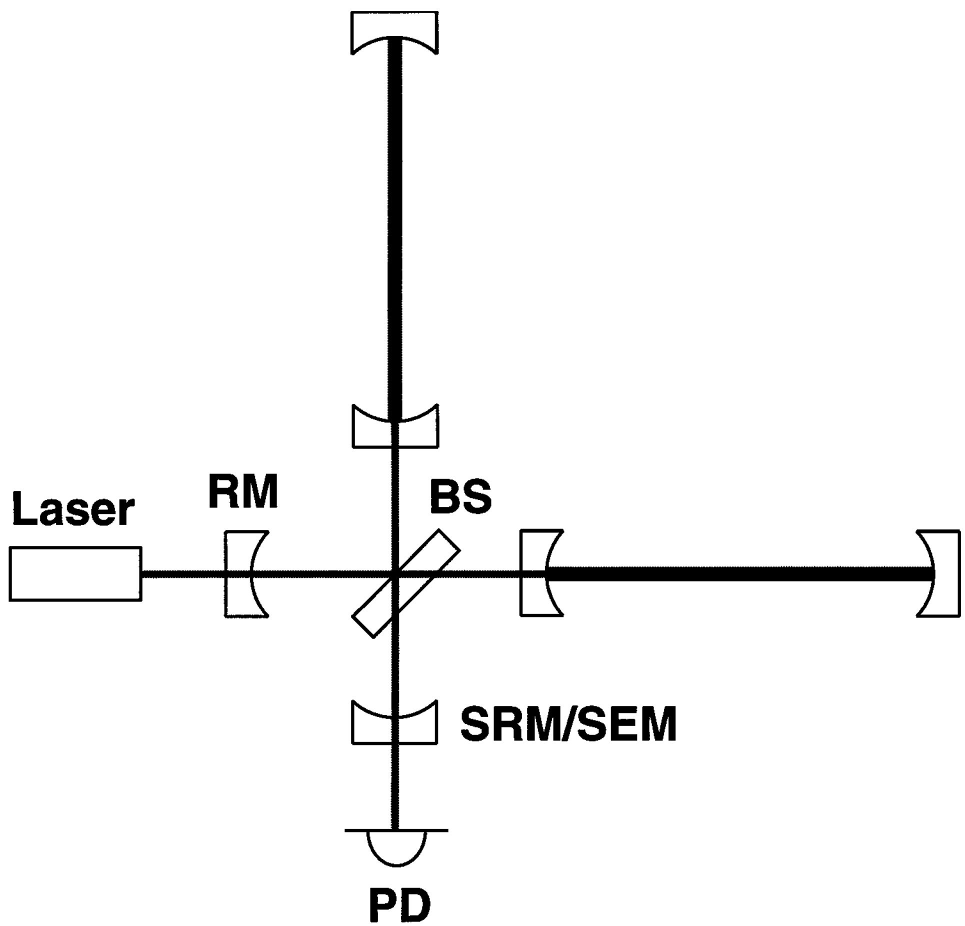
Core Optics for Higher Power

Responsibilities	*Collaborators*	*Schedule Initiate--- Complete*
Full precision phase mapping @ 1064 nm of surface figure (upgrade)	LIGO and industry	1998 (mid)--- 1999(late)
Acquire, install, characterize micro-roughness instrument	LIGO and industry	1997(mid)--- 1998(early)
Fully calibrated surface scatter/loss test bed (upgrade)	VIRGO LIGO and industry	1998(early)--- 1998(late)
≤ 1ppm level coating loss measurements. ≤ ± 10% bulk substrate loss mapping	EMU / VIRGO	1999(mid)--- 2001
Design and fabricate developmental silica mirror substrates (quantity ~30)	LIGO and industry	1998 (early)--- 1998(mid)
Surface polishing optimization	LIGO and industry	1998(late)--- 2002(early)
Coating uniformity development	LIGO and industry, VIRGO	1998(late)--- 2002(mid)

Advanced Detector R&D

- Resonant Sideband Extraction and Signal Recycling
- Advanced Seismic Isolation
- Signal Processing
- Measurement and Feedback of Thermal Noise

Resonant Sideband Extraction and Signal Recycling



Signal Recycling (Dual Recycling)

- Additional recycling mirror placed at the antisymmetric (signal) port to increase signal storage time
- Signal recycling can be used to narrow band the interferometer by adjusting sensitive peak frequency

Resonant Sideband Extraction

- Same general arrangement of antisymmetric port recycling mirror, but arm cavities have much higher finesse and mirror is used to reduce signal storage time
- Sensitivity can be same as in signal recycling with reduced optical power on the beam splitter
- Can also be used in a narrow band configuration

RSE/SR Research Program

- University of Florida will study dual recycling in a tabletop experiment lasting two years
- LIGO will study resonant sideband extraction in a tabletop experiment lasting two years
- An analytic study will be made by LIGO of suitable future interferometer configurations using the entire range of possibilities promised by these two techniques
    - ››modeling of interferometer sensitivity and response
    - ››modeling of optical sensitivity to distortions using paraxial FFT methods
- Following tabletop experiments, one of the techniques will be studied in a large scale test in a LIGO test interferometer

Advanced Seismic Isolation

- Initial LIGO measurement band limited by seismic noise at 40 Hz
- Goal of research is to:

  ››push this envelope down to about 1 Hz such that the limiting noise source for the interferometer becomes gravity gradients

  ››reduce the dynamic range required of the fine control actuators by providing isolation to frequencies as low as the microseismic peak (0.17 Hz).
- Three approaches:

  ››LIGO MIT Stacis active system from Barry Controls does not meet low frequency requirements

  ››JILA 3-stage active system promises low frequency performance

  ››Virgo passive stack is tall and requires additional material qualification

Advanced Seismic Isolation Work Plan

Pgm	Significant Events	Responsible	Date
Near Term	Improved Stacis Isolators: Design, Fab & Unit Test	LIGO, Stanford	Dec 1999
Near Term	Improved Stacis Isolators: 2km IFO Tests Completed	LIGO, Stanford	Dec 2000
Long Term	Requirements & Interface Definition	LIGO, JILA, Stanford	Mar 1998
Long Term	Preliminary Design	JILA, Stanford, LIGO	Jan 1999
Long Term	Final Design	JILA, Stanford, LIGO	Jan 2000
Long Term	Fabrication Completed	JILA	Jan 2001
Long Term	Unit Test Completed	JILA	Dec 2002

This research is expected to extend into the next five year research period

Staffing

LIGO (MIT and Caltech) Staffing Requirements

Category	*FY1997 FTE*	*FY1998 FTE*	*FY1997-2001 FTE Total*
scientist	2	4.5	20
postdoctoral	2.5	3	14.5
graduate student	2	3	14
engineer	0	0.5	2.5
technician	2	2.5	12
Total FTE	8.5	13.5	63.0

Top Level Activity Plan

Task	*FY1997*	*FY1998*	*FY1999*	*FY2000*	*FY2001*
Adv. Subsystem					
Double Suspension					
Thermal Noise					
Sapphire Test Mass					
Seismic Isolation					
100 W Laser					
Core Optics					
Adv. Detectors					
Sig. Rec./Res. S. E.					
Seismic Isolation					
Signal Processing					
Thermal Noise					
Test Interferometers					
Conversion to 1064 nm					

LIGO Funding Request

Task	*FY1997*	*FY1998*	*5 YEAR TOTAL*
Adv. Subsystem			
Double Suspension	$211K	$281K	$809K
Thermal Noise	$22K	$42K	$134K
Sapphire Test Mass	$106K	$38K	$227K
Seismic Isolation	$10K	$31K	$177K
100 W Laser	$181K	$231K	$725K
Core Optics	$85K	$116K	$835K
Adv. Detectors			
Sig. Rec./Res. S. E.	$116K	$146K	$578K
Seismic Isolation	0	$28K	$305K
Signal Processing	0	0	$151K
Thermal Noise	0	0	$20K
M&S TOTAL	$732K	$912K	$3960K
STAFF TOTAL	$1009K	$1752K	$8460K
TOTAL	$1741K	$2664K	$12420K

Collaboration

- For 1997, LIGO has appointed Seiji Kawamura and Mike Zucker as Task Leaders for Advanced Detector R&D
- We will work with our collaborators to form effective coordination of this research
  - Periodic group meetings of each task group
  - Periodic meetings of the LIGO Collaboration
  - Widely circulated progress reports
  - An annual comprehensive workshop
  - Institutional representation

Collaboration

- This collaborative proposal combines
  - ›› LIGO expertise in system design and LIGO capability to integrate into detector system
    - expertise in system tradeoffs
    - unique facilities
    - extensive research with suspended optics interferometers
  - ›› expert research groups (including LIGO) around the world
- During the next six months, the collaboration will be formed
- January, 1997 Aspen Meeting will focus on Advanced Detector R&D

During 1997...

- Modify 40 Meter Interferometer and MIT Interferometer to accommodate double pendulum, 100 W laser, RSE/SR research
- Analyze double pendulum control system with GEO
- Complete sapphire sample characterization
- Define 100 W laser research with Lightwave
- Acquire micro-roughness instrument and initiate characterization research
- Commence resonant sideband extraction table top experiment and supporting analytical work

THESE ACTIVITIES INDEPENDENT OF NSF REVIEW OF COLLABORATORS