Overview of LIGO R&D and Planning for Advanced LIGO Detectors

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NSF R&D Review

Caltech, January 29, 2001

LIGO-G010004-00-M

Program and Mission of the LIGO Laboratory

- **observe gravitational wave sources**;
- develop advanced detectors that approach and exploit the facility limits on interferometer performance;
- operate the LIGO facilities to support the national and international scientific community;
- and support scientific education and public outreach related to gravitational wave astronomy.

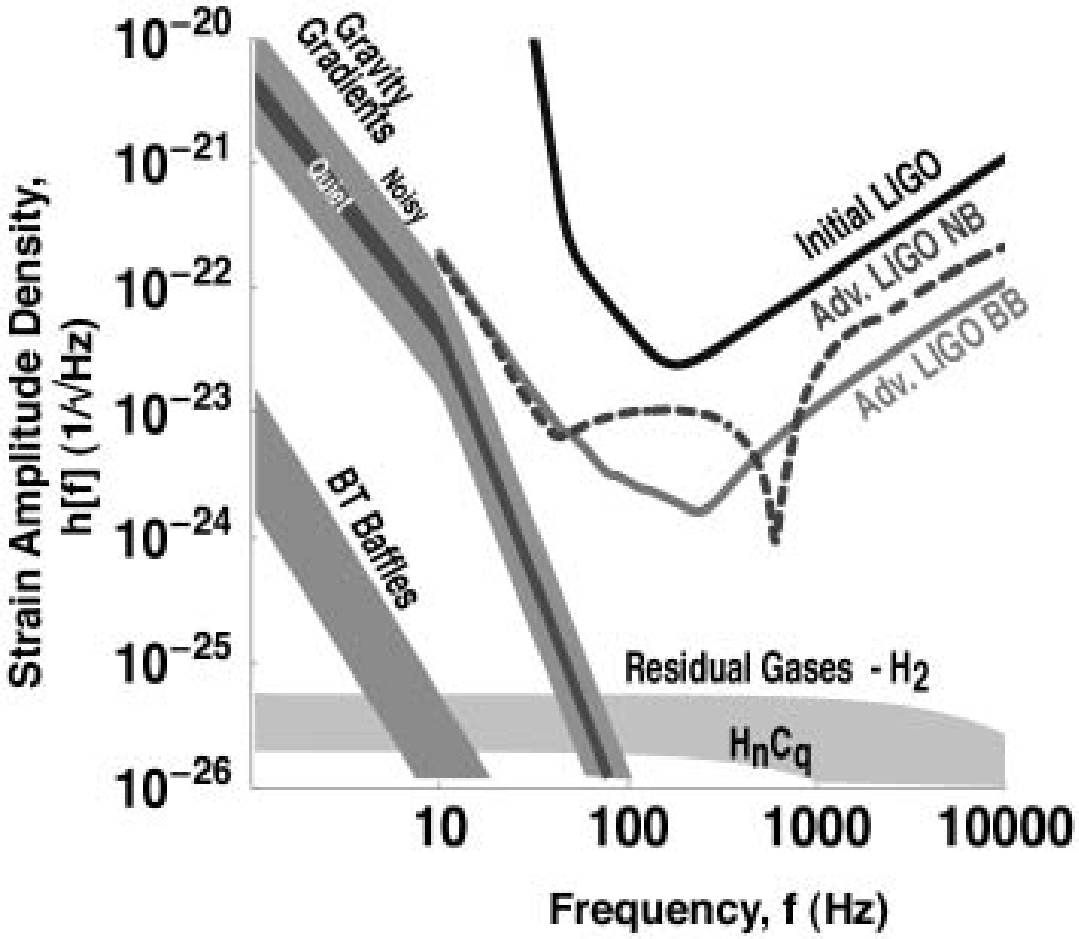
LIGO Proposes To:

- Complete commissioning of the initial LIGO interferometers;
- operate the LIGO interferometers for the initial LIGO Science Run;
- process and analyze the Science Run data and publish the results of the first scientific searches for gravitational wave sources;
- characterize and improve the sensitivity and availability of the operating interferometers;
- ***define interferometer upgrades and carry out a research and development program to underpin future upgrade proposals***;
- support the development and research of the LIGO Scientific Collaboration;
- support the development of the international network of gravitational wave detectors;
- interpret the LIGO program to the public;
- leverage LIGO in educational settings;
- and address new industrial technologies and applications stimulated by the requirements of gravitational wave observation.

The Original Vision for LIGO

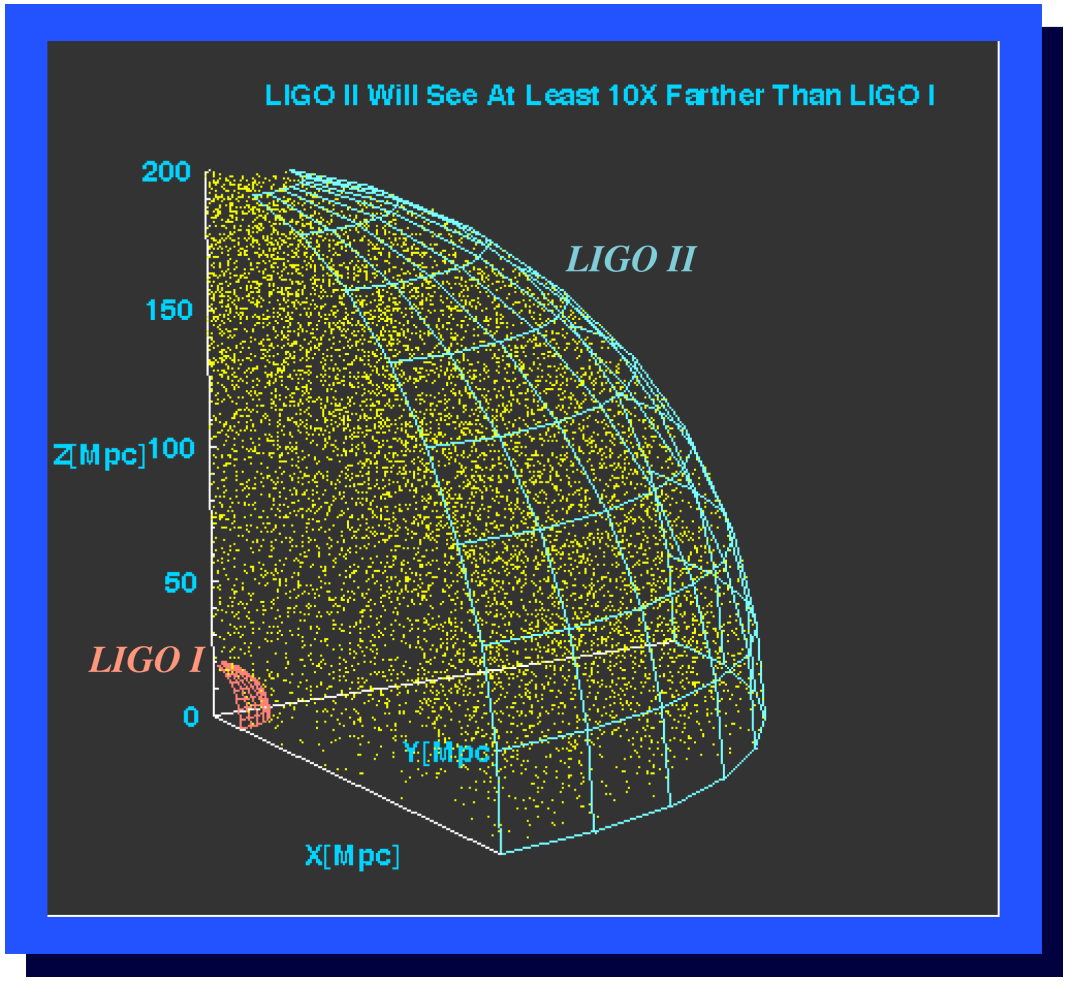
- LIGO was conceived as a **program** to detect gravitational waves
- LIGO construction was approved to provide an initial set of feasible detectors and a set of facilities capable of supporting much more sensitive detectors
- It was planned that the initial detectors would have a **plausible** chance to make direct detections
- It was planned that more sensitive detectors would be required to enable **confident** detection
- This R&D proposal describes the program to enable the exploitation of the large investment in the facilities.

LIGO Facilities Support Detector Upgrades



Advanced LIGO Detector Reach

"...2.5 hours of operation will exceed the integrated observations of the 1 year LIGO Science Run..."



An Example from Thorne Survey

• **Inspiral of NS/NS, NS/BH and BH/BH Binaries:** The table below [15, 2] shows estimated rates $\mathcal{R}_{\rm gal}$ in our galaxy (with masses $\sim 1.4M_\odot$ for NS and $\sim 10M_\odot$ for BH), the distances $\mathcal{D}_{\rm I}$ and $\mathcal{D}_{\rm WB}$ to which initial IFOs and advanced WB IFOs can detect them, and corresponding estimates of detection rates $\mathcal{R}_{\rm I}$ and $\mathcal{R}_{\rm WB}$; Secs. 1.1 and 1.2.

	NS/NS	NS/BH	BH/BH in field	BH/BH in clusters
$\mathcal{R}_{\rm gal}$, yr^{-1}	10^{-6}–5×10^{-4}	$\lesssim 10^{-7}$–10^{-4}	$\lesssim 10^{-7}$–10^{-5}	$\sim 10^{-6}$–10^{-5}
$D_{\rm I}$	20 Mpc	43 Mpc	100	100
$\mathcal{R}_{\rm I}$, yr^{-1}	3×10^{-4} – 0.3	$\lesssim 4\times10^{-4}$ – 0.6	$\lesssim 4\times10^{-3}$ – 0.6	~ 0.04 – 0.6
$D_{\rm WB}$	300 Mpc	650 Mpc	$z = 0.4$	$z = 0.4$
$\mathcal{R}_{\rm WB}$, yr^{-1}	1 – 800	$\lesssim$ 1 – 1500	$\lesssim$ 30 – 4000	$\sim$ 300 – 4000

History of LIGO R&D

- Early R&D leading to initial LIGO took place during the 1970's and 1980's
- Preconstruction R&D for initial LIGO was included in the award for the LIGO construction
  - » LIGO construction $272 million
  - » Preconstruction R&D $20 million (addressing final issues)
  - » Early operations $69 million
- NSF invited proposals for R&D in support of more advanced detectors in 1996
- LIGO Laboratory has been receiving $2.7 million/year of a ~$6.9 million program

LIGO Laboratory Funding To Date

MRE

Fiscal Year	Construction	R&D	Operations	Advanced R&D	Total
Through 1994	35.9	11.2			47.1
1995	85	4			89
1996	70	2.4			72.4
1997	55	1.6	0.3	0.8	57.7
1998	26	0.9	7.3	1.6	35.8
1999	0.2		20.9	2.5	22.5
2000			21.1	2.6	23.7
2001			19.1 (10 months)	2.7	22.9
Total	272.1	20	68.7	10.2	371.1

Role of LIGO Scientific Collaboration …

- A research community around LIGO was formally stimulated as early as 1995
- Following the 1996 McDaniel Panel, the LIGO Scientific Collaboration was formed in 1997
- During 1996, proposals submitted to NSF for R&D support were already highly collaborative
- The 1996 and 1997 R&D plans and proposals were built around certain sensitivity levels as targets for next generation detectors
- During 1999, the Lab/LSC established a reference design for the advanced LIGO detectors

… Role of LIGO Scientific Collaboration

- The LSC and Lab submitted a White Paper and a Conceptual Project plan in late 1999
  - » this was reviewed by NSF ----------> encouraging current R&D
- This LIGO study sharpened the design and the R&D focus
- The R&D program has been highly coordinated across the LSC by the Lab and LSC
  - » all R&D tasks are defined in MOU's with the Laboratory
  - » the program is conducted as the early stages of a construction project
  - » systems engineering is carried out
  - » the R&D is organized with a detailed cost estimate and schedule
  - » monthly coordinating meetings are held to monitor progress

LSC Participation in Advanced LIGO R&D

Australian Consortium for Interferometric Gravitational Astronomy (ACIGA) *Australian National University (ANU), University of Adelaide (AU), and University of Western Australia (UWA)*	13.5 FTE
Caltech Experimental Gravitational-Physics Group	1.3 FTE
German British Collaboration for the Detection of Gravitational Waves (GEO 600) *University of Hannover, Garching, Albert Einstein Institute in Potsdam, University of Glasgow, and Cardiff University*	17 FTE
Institute of Applied Physics of the Russian Academy of Sciences at Nizhny Novgorod	9.5 FTE
Iowa State University, Eddy-Current Subgroup	0.5 FTE
University of Colorado, JILA Gravity Group	1.5 FTE
Louisiana State University, Experimental Relativity Group	1.5 FTE
Moscow State University	10 FTE
National Astronomical Observatory of Japan TAMA Group	2 FTE
Pennsylvania State University Experimental Relativity Group	4.7 FTE
Department of Physics of Southern University and A&M College	1.5 FTE
Stanford Advanced Gravitational Wave Interferometry Group	12 FTE
Syracuse University Experimental Relativity Group	4 FTE
University of Florida Laser Interferometric Gravitational Wave Group	2.5 FTE

The Advanced LIGO Detector

- Fabry-Perot Michelson interferometers
- Power recycling AND signal recycling
- 180 W Nd:YAG laser
- possible sapphire core optics
- much better isolation through the use of a fully active seismic isolation system, and a multiple pendulum suspension with silica suspension fibers

R&D Challenges

- Suspension and test mass thermal noise
- Management of thermal consequences of high laser power
- Prestabilized laser performance
- Seismic isolation
- The controls problem

Approach to Interferometer Upgrades

- Gravitational wave interferometers are “point” designs
  - » substantial improvements in performance are difficult to achieve with incremental upgrades
  - » lowering one noise floor encounters another
  - » changing the performance of one subsystem causes system mismatch with other subsystems
- Installing an interferometer into the vacuum system is a major campaign
  - » much of the campaign overhead is encountered even with subsystem upgrades
- Installing an interferometer has a high cost in missed scientific opportunity

Upgrade should be a major increase in sensitivity

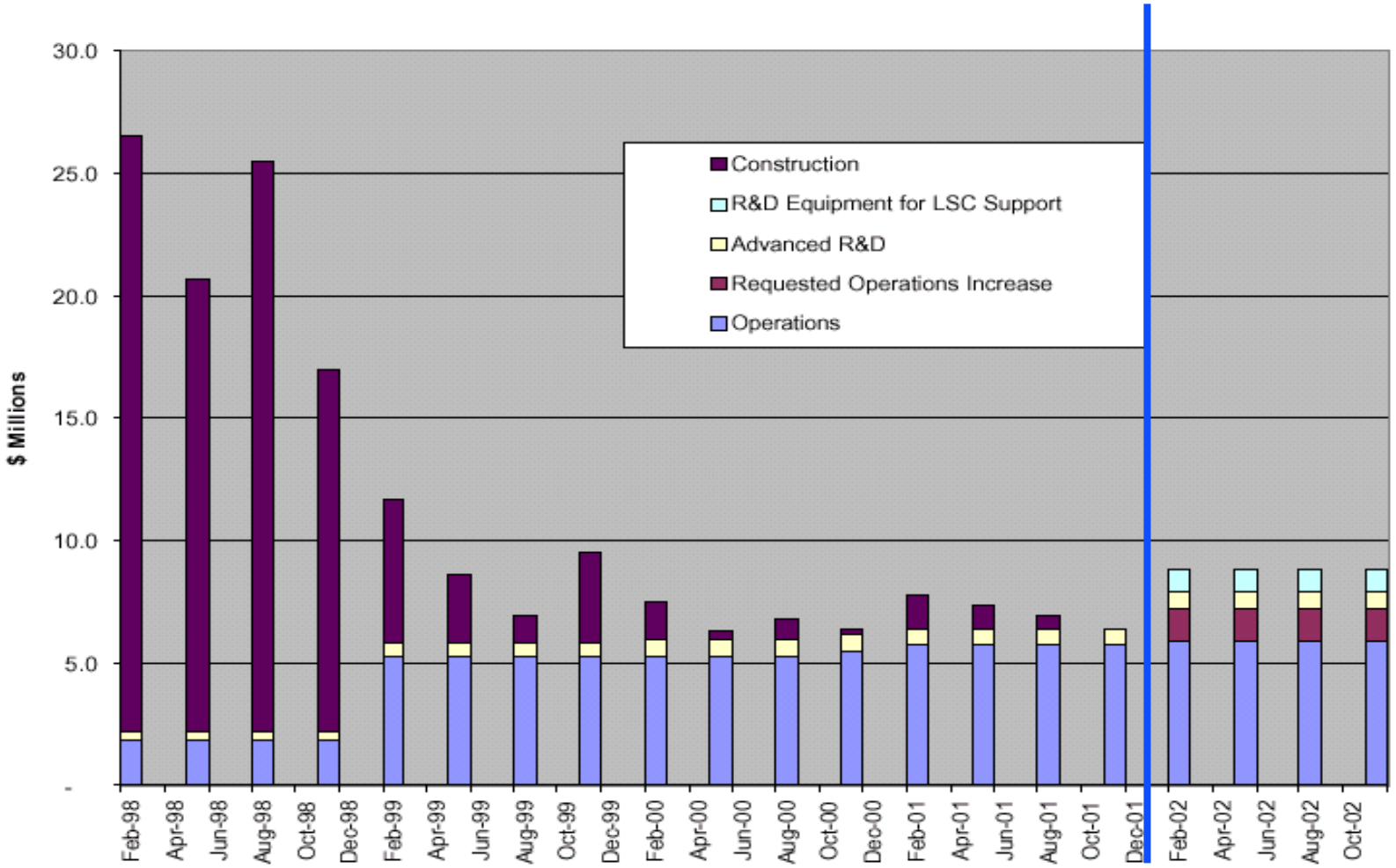
Advanced LIGO Program Assumption

- R&D in progress now
  - » major equipment expenditures in 2001, 2002-2004
- R&D is substantially completed in 2004
  - » some tests are completed in 2005
- Construction funds will be requested for 2004 start
  - » some long lead purchases occur as early as 2003
  - » assembly outside vacuum system takes place in 2005
- Advanced interferometers will be installed beginning in early 2006
  - » when LIGO Science Run I is producing published results

R&D Program Approach to Risk Reduction

- All significant risks are planned for measurement or verification during the proposed program
- Faithful prototypes of advanced LIGO subsystems are fully tested in parallel to operating LIGO
- Goal is to fully qualify all designs before installing in LIGO vacuum system
  - » 40 Meter qualifies controls system
  - » LASTI qualifies the isolation/suspension system and the prestabilized laser/input optics systems
- Installation into LIGO vacuum system occurs when new systems are fully ready and qualified

LIGO Funding Evolution and Proposal Request



Proposal Request

Includes technical support for R&D

	FY 2002 $M	FY 2003 $M	FY 2004 $M	FY 2005 $M	FY 2006 $M	Total $M
Currently Funded Operations	23.63	24.32	25.05	25.87	26.65	125.52
Increase for Full Operations	5.21	5.20	4.79	4.86	4.95	25.01
Advanced R&D	2.77	2.86	2.95	3.04	3.13	14.76
R&D Equipment in Support of LSC Research	3.30	3.84	3.14			10.28
Total Budgets	**34.91**	**36.21**	**35.93**	**33.77**	**34.74**	**175.57**

The R&D Program

- Most work supports Advanced LIGO realization
- Some far reaching research
- All work highly collaborative
- Lab coordinates program through LSC
  - » full cost/schedule planning in use
  - » monthly telecons with each working group
- Engineering and some senior effort supported from Lab Operations
- Big ticket equipment items for LSC program in Lab proposal

Increased Staffing to Support R&D and Modeling

• Increased staff in the Technical and Engineering Support and Detector Support Groups. The Caltech campus-based support to the observatories declines significantly after the Detector is commissioned. However, the increase for the R&D for an advanced LIGO (planned for installation in 2005-2006) is significant and results in a net increase.	$920,868
• Increment for engineering and technician labor (4 FTEs) at Livingston to support the LSC science team responsible for Seismic Isolation development. This effort is for two years only and is non-recurring.	$506,300
• Increased support staff for Modeling and Simulation Group. The increase was suggested by an NSF Review panel.	$282,485

R&D Effort

• Stochastic Noise. LASTI integrated system tests of the advanced seismic isolation and suspension prototypes.	$275,222
• Thermal Noise Interferometer. Direct measurement of test mass thermal noise for initial and advanced LIGO designs.	$176,697
• Advanced Core Optics including Sapphire Optics	$283,937
• Advanced Interferometer Sensing and Control including Photodetector Development	$298,779
• Stiff Seismic Isolation System Development	$46,353
• Auxiliary Optics Systems including Active Thermal Control	$366,088
• Advanced Suspensions including Fiber Research.	$208,725
• Improved Low Frequency Strain Sensitivity.	$345,637
• 40-Meter Advanced R&D. Tests of controls and electronics for a signal and power recycled configuration with the read-out scheme and control topology intended for advanced LIGO.	$235,075
• Advanced Controls & System Identification. Research on application of advanced system identification and control concepts to LIGO.	$188,677
• Advanced (highly stabilized) Input Optics Systems.	$347,423

R&D Equipment in Support of LSC Research Program

- Equipment costs for the development of advanced seismic isolation prototypes.
- Equipment costs for the development of multiple pendulum, fused silica fiber suspension prototypes.
- Materials and manufacturing subcontracts to support the development of sapphire test masses and high Q test mass materials and coatings research.
- Investment and non-recurring engineering costs for a large coating chamber and its commissioning
  - » study of coating strategy in progress

Isolation Research

(STO, SUS, TNI, SEI)

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE, $K)	
ISOLATION						
Sci & PD	MIT	1	0	2.4	3.4	8.1
	CIT	3	0	1.7	4.7	
UG & Grads	MIT	3	0	0.0	3.0	5.0
	CIT	2	0	0.0	2.0	
Eng & Techs	MIT	0	0	2.8	2.8	14.2
	CIT	0	0	6.9	6.9	
	LLO	0	0	4.5	4.5	
Totals (FTE):		9	0	18.3	**27.3**	
Equip. & Supplies		$54	$1,595	0.0	**$1,649**	

N.B.: Does not include LSC research staff.

Lasers & Optics Research

(LAS, OPT, IOS, AOS)

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE, $K)	
LASERS & OPTICS						
Sci & PD	MIT	0	0	0.1	0.1	3.3
	CIT	1	0	2.3	3.3	
UG & Grads	MIT	1	0	0.0	1.0	2.0
	CIT	1	0	0.0	1.0	
Eng & Techs	MIT	0	0	0.0	0.0	2.0
	CIT	0.5	0	1.5	2.0	
Totals (FTE):		3.5	0	3.8	**7.3**	
Equip. & Supplies		$755	$1,706	0.0	**$2,461**	

N.B.: Does not include LSC research staff.

Advanced Interferometer Systems, Sensing & Control (ISC, 40m, SID, SYS)

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE, $K)	
Advanced Interferometer Systems, Sensing & Control (ISC)						
Sci & PD	MIT	0	0	1.7	1.7	6.9
	CIT	2	0	3.2	5.2	
UG & Grads	MIT	1	0	1.0	2.0	5.0
	CIT	3	0	0.0	3.0	
Eng & Techs	MIT	0	0	0.8	0.8	10.2
	CIT	0	0	9.5	9.5	
Totals (FTE):		6	0	16.1	**22.1**	
Equip. & Supplies		$313	$0	0.0	**$313**	

N.B.: Does not include LSC research staff.

Total LIGO Laboratory R&D

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE, $K)	
TOTAL for advanced LIGO R&D (including CRY)						
Sci & PD	MIT	1	0	4.2	5.2	20.3
	CIT	8	0	7.2	15.2	
UG & Grads	MIT	5	0	1.0	6.0	13.0
	CIT	7	0	0.0	7.0	
Eng & Techs	MIT	0	0	3.5	3.5	26.4
	CIT	0.5	0	17.9	18.4	
	LLO	0	0	4.5	4.5	
Totals (FTE):		21.5	0	38.2	**59.7**	
Equip. & Supplies		$1,139	$3,301	0.0	**$4,440**	
				MIT	14.7	
				CIT	40.5	
				LLO	4.5	

N.B.: Does not include LSC research staff.

Major International Roles in Advanced LIGO

- GEO (UK, Germany) project has joined the LSC
  - » Initial LIGO involvement is in data algorithms and analysis
  - » advanced LIGO involvement includes leading roles in suspensions, configurations, prestabilized laser.
  - » GEO is proposing a capital contribution/partnership in construction of advanced LIGO
- ACIGA project has joined LSC
  - » Initial LIGO involvement is in data algorithms and analysis
  - » advanced LIGO involvement includes laser development, sapphire development and high power issues
- Recent discussions have begun with Virgo on collaboration in coating development and in joint data taking and data analysis

Advanced LIGO Plan

- R&D for a baselined detector proceeds through 2004
- LIGO will propose construction to start in 2004
  - » proposal submitted late this year for 2 year review cycle
- Installation commences in 2006
  - » R&D complete
  - » assembly outside vacuum sufficiently advanced
  - » initial LIGO results in publication