R&D for Advanced LIGO 2002-2006
Presentation to PAC

David Shoemaker & Dennis Coyne

LIGO Lab

December 13, 2000

Overview

- Evolution intrinsic to LIGO mission
- Next step in detector design:
  - » Of astrophysical significance if it observes GW signals or if it does not
  - » Limits of reasonable extrapolations of detector physics and technologies
  - » Leads to a realizable, practical instrument
- Much effort is inextricably entwined with LSC research
  - » LIGO Lab provides the majority of the on-task manpower
  - » Lab also coordinates, provides infrastructure/engineering

Overview

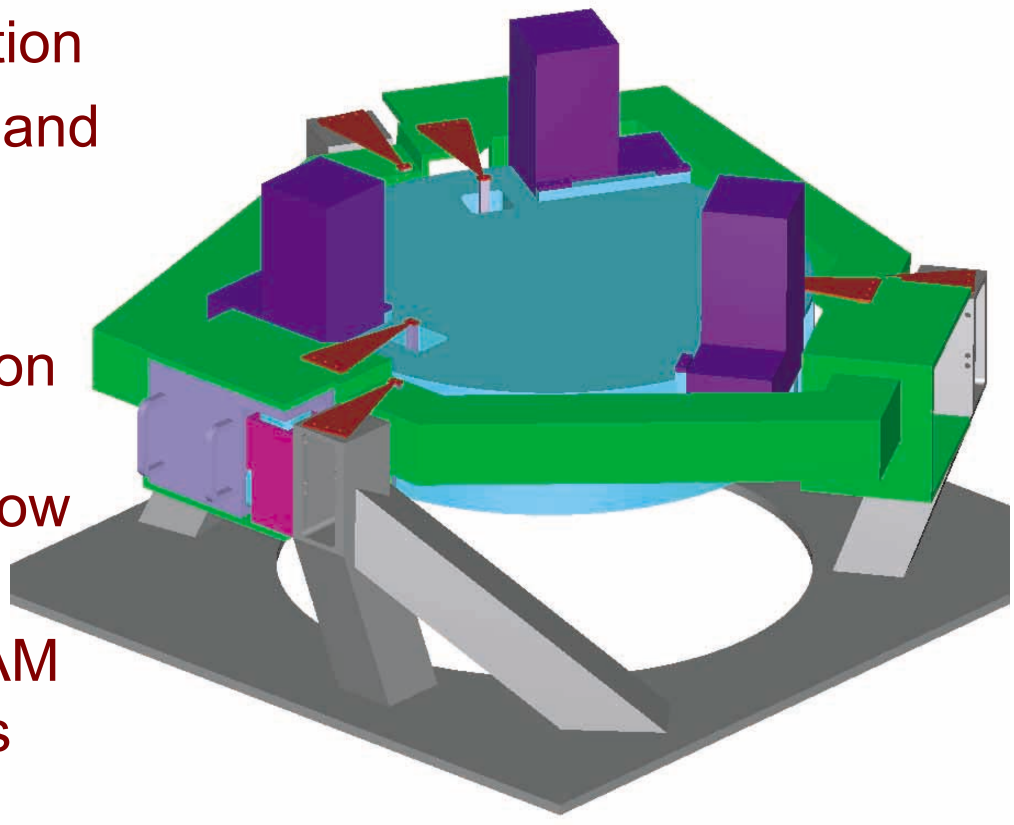
- Talk objectives:
  - » Show scope and character of effort
    - – Touch briefly on all R&D topics
  - » More complete illustrative discussion of seismic isolation
- Talk organization:
  - » Mechanical aspects of design: Isolation, Suspension, Thermal noise, and system tests
  - » Optics: Laser, Test Masses, Input Optics, Auxiliary Optics
  - » Sensing and control: Design and prototype tests
- Detailed technical, schedule, and budget information available

Active Seismic Isolation R&D (SEI): Requirements

- Goal: render seismic noise a negligible limitation to GW searches
  - » Other ‘irreducible’ noise sources limit sensitivity to uninteresting level for frequencies less than ~20 Hz
  - » Suspension and isolation contribute to attenuation
  - » Choose to require a 10 Hz ‘brick wall’
- Goal: reduce or eliminate actuation on test masses
  - » Actuation source of direct noise, also increases thermal noise
  - » Seismic isolation system can reduce RMS/velocity through inertial sensing
  - » Acquisition challenge greatly reduced
  - » Choose to require RMS of $<10^{-9}$ m (order of fringe width)

SEI: Conceptual Design

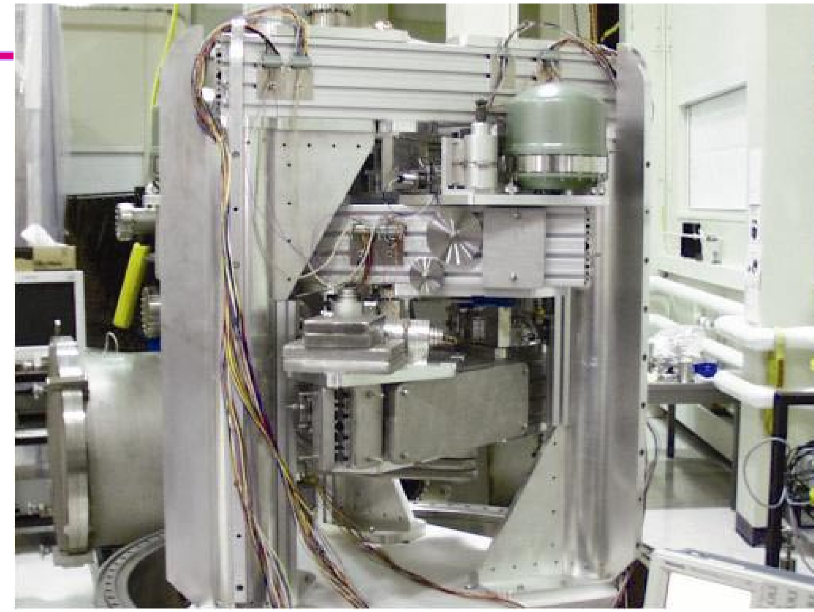
- Two in-vacuum stages in series, external slow correction
- Each stage carries sensors and actuators for 6 DOF
- Stage resonances ~5 Hz
- High-gain servos bring motion to sensor limit in GW band, reach RMS requirement at low frequencies
- Similar designs for BSC, HAM vacuum chambers; provides optical table for flexibility



SEI: Organization

- Initial work done by teams at Caltech, MIT, Stanford, LSU, JILA – significant input from LSC teams, suspension working group
- Strategic organization by Lab of continued development at LLO, with continued LSC scientific leadership (Giaime/LSU)
- Engineering effort and prototype fabrication managed by LLO (Stapfer)
- Next prototype to be installed and tested in Stanford ETF (Lantz)
- Installation and test at MIT LASTI to be performed by development team of engineers/scientists, plus MIT LASTI staff

SEI: Progress and Plans



- Parallel design effort on passive, active systems
  - ✓ 4Q99: Draft requirements and interface established
  - ✓ 2Q00: SAS reference design, prototype tests
  - ✓ 2Q00: Active reference design, prototype tests
  - ✓ 2Q00: Choice of design to pursue
- Prototyping and test of active systems
  - ✓ 3Q00: All 12 DOF active system locked
  - ✓ 4Q00: initial design and demonstrator bid package ready
  - » 4Q01: demonstrator test complete (at Stanford)
  - » 3Q02: HAM prototype standalone testing completed (MIT LASTI)
  - » 1Q03: BSC prototype standalone testing completed (MIT LASTI)

SEI: Manpower and equipment

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)
Active Seismic Isolation (SEI)				
Gerry Stapfer	LLO			0.5
Joe Giaime	LSU			
Sci & PD	MIT			
	CIT	0.5		
UG & Grads	MIT			
	CIT			
Eng & Techs	MIT			
	CIT			0.5
	LLO			3
Totals (FTE):		0.5	0	4
Equip. & Supplies ($K)		$0	$821	$0

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

Suspension Research (SUS)

- Adopting a multiple-pendulum approach
  - » Allows best thermal noise performance of suspension and test mass; replacement of steel suspension wires with fused silica
  - » Offers seismic isolation, hierarchy of position and angle actuation
- Close collaboration with GEO (German/Scots) GW group
  - » Similar design used in GEO-600, being installed now
  - » Great strength in that group to be applied to initial design
  - » LIGO takes over design as we deal with fabrication/installation issues
- Schedule highlights:
  - » 1Q01: Install first fused silica GEO-600 suspension
  - » 2Q02: Controls prototypes complete, in testing
  - » 2Q03: Noise prototypes complete, in testing

Thermal Noise Interferometer (TNI)

- Direct measurement of thermal noise, at LIGO Caltech
  - » Test of models, materials parameters
  - » Search for excesses (non-stationary?) above anticipated noise floor
- In-vacuum suspended mirror prototype, specialized to task
  - » Optics on common isolated table, ~1/2 m arm lengths
- Schedule highlights:
  - ✓ 4Q00: TNI first lock
  - » 2Q01: TNI studies for initial LIGO completed
  - » 2Q01: Sapphire, with Fused Silica suspensions, installed
  - » 1Q03: TNI final Sapphire/fused silica results

Stochastic noise system tests: LASTI

- Full-scale tests of Seismic Isolation and Test Mass Suspension
  - » Takes place in LASTI at MIT: LIGO-like vacuum system
  - » Allows system testing, interfaces, installation practice
  - » Characterization of non-stationary noise, thermal noise
- Subsystem support to LASTI system tests
  - » teams learn how their system works, installs, etc.
  - » MIT support of infrastructure, and collaborative shakedown and test
- Schedule highlights:
  - ✓ 4Q00: Vacuum system qualified, seismic supports in place
  - » 4Q01: ‘infrastructure’ Laser, test cavity, DAQ, etc. tested
  - » 3Q02: HAM isolation testing completed
  - » 2Q03: Suspensions Noise prototypes installed
  - » 2Q04: integrated Isolation/suspension testing completed
  - » 1Q05: PSL-Mode Cleaner integrated performance test completed

Isolation Research
(STO, SUS, TNI, SEI)

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)		
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	3	5
	CIT	2	0	0	2	
Eng & Techs	MIT	0	0	2.75	2.75	13.15
	CIT	0	0	6.9	6.9	
	LLO	0	0	3.5	3.5	
Totals (FTE):		9	0	17.25	**26.25**	
Equip. & Supplies ($K)		$57	$1,535	$0	**$1,592**	

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

Advanced Laser R&D (LAS)

- Require optimal power, given fundamental and practical constraints:
  - » Shot noise: having more stored photons improves sensitivity, but:
  - » Radiation pressure: dominates at low frequencies
  - » Thermal focussing in substrates: limits usable power
- Optimum depends on test mass material, 80 – 180 W
- Power amplifier or MOPA topology in trade study
- Laser Zentrum Hannover/GEO to take lead; LIGO Lab supplies requirements, interface, and test
- Schedule highlights:
  - » 4Q01: laser diode tests done / selection
  - » 1Q02: 100 W demonstration
  - » 2Q02: Laser concept downselect
  - » 2Q04: Install advanced LIGO PSL in the LASTI facility

Advanced Core Optics R&D (OPT)

- A key optical and mechanical element of design
  - » Substrate absorption, homogeneity, birefringence
  - » Ability to polish, coat
  - » Mechanical (thermal noise) performance, suspension design
  - » Mass – to limit radiation pressure noise: ~30-40 Kg required
- Two materials under study, both with real potential
  - » Fused Silica: very expensive, very large, satisfactory performance; familiar, non-crystalline
  - » Sapphire: requires development in size, homogeneity, absorption; high density (small size), lower thermal noise
- Caltech LIGO Lab leads effort, strong LSC input on materials/tests
- Schedule highlights:
  - ✓ 2Q00: m-axis birefringence measured
  - ✓ 3Q00: Initial sapphire refraction index homogeneity measurement
  - » 4Q01: Order LASTI SUS prototype sapphire & fused silica blanks
  - » 2Q02: Selection of test mass material
  - » 3Q03: Dedicated coating chamber installed and commissioned

Input Optics System R&D (IOS)

- Subsystem interfaces laser light to main interferometer
  - » Modulation sidebands applied for sensing system
  - » Beam cleaned and stabilized by transmission though cavity
  - » Precision mode matching from ~0.5 cm to ~10 cm beam
- Challenges in handling high power
  - » isolators, modulators
  - » Mirror mass and intensity stabilization (technical radiation pressure)
- University of Florida takes lead, GEO suspensions, LIGO controls
- Schedule highlights:
  - ✓ 3Q00: Isolator demonstrated (<35 dB) @ 50 W
  - » 2Q02: Demonstration of prototype phase modulation method
  - » 4Q02: Thermal lensing compensation results, optical layout chosen
  - » 1Q04: Install advanced LIGO IO components at LASTI
  - » 1Q05: PSL-Mode Cleaner integrated performance test completed

Auxiliary Optics R&D (AOS)

- Subsystem handles output beams from interferometer
  - » Desired beams matched into photodetectors
  - » Undesired beams ‘dumped’ with negligible backscatter
- Two new challenges requiring R&D:
  - » Substrate thermal focus compensation
  - » Photon actuator for test mass
- LIGO Lab activity
- Thermal focus Schedule Milestones
  - » 1Q01: Proof-of-concept, scaled experiments initial results
  - » 3Q02: Full Scale Radiative Compensator
  - » 4Q04: Full scale Directed Beam Actuation tests complete
- Photon actuator Schedule Milestones
  - » 2Q02: Initial demonstration system assembled
  - » 2Q03: Preliminary test results completed
  - » 2Q04: Final test results on iterated design completed

Lasers & Optics R&D

(LAS, OPT, IOS, AOS)

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)		
LASERS & OPTICS						
Sci & PD	MIT	0	0	0.08	0.08	4.33
	CIT	2	0	2.25	4.25	
UG & Grads	MIT	1	0	0	1	3
	CIT	2	0	0	2	
Eng & Techs	MIT	0	0	0	0	2
	CIT	0.5	0	1.5	2	
Totals (FTE):		5.5	0	3.83	**9.33**	
Equip. & Supplies ($K)		$800	$1,687	$0	**$2,487**	

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

Advanced Interferometer Sensing & Control (ISC)

- Responsible for the GW sensing and overall control systems
- Addition of signal recycling mirror increases complexity
  - » Permits 'tuning' of response to optimize for noise and astrophysical source characteristics
  - » Requires additional sensing and control for length and alignment
- Shift to 'DC readout'
  - » Rather than RF mod/demod scheme, shift interferometer slightly away from dark fringe; relaxes laser requirements, needs photodiode develop
- Requires both proof-of-principle and precision testing (40m)
- LIGO Lab leads, with contributions from LSC, esp. GEO
- Schedule Highlights:
  - » 2Q01: Design Requirements Review
  - » 2Q02: Tabletop DC readout test results
  - » 2Q03: GEO 10m prototype test results/review
  - » 4Q03: Final design complete

40 m RSE Experiment (40m)

- Precision test of selected readout and sensing scheme
  - » Employs/tests final control hardware/software
  - » Dynamics of acquisition of operating state
  - » Frequency response, model validation
- Utilizes unique capability of Caltech 40 meter interferometer --- long arms allow reasonable storage times for light
- Schedule Highlights
  - ✓ 4Q00: LIGO 40 m Lab expansion completed
  - ✓ 1Q01: LIGO 40 m active isolation systems installed
  - » 1Q01: LIGO 40 m Vacuum Envelope commissioned
  - » 1Q01: LIGO 40 m PSL installed
  - » 4Q02: LIGO 40 m suspensions installed
  - » 2Q04: LIGO 40 m RSE experiment completed; further characterization studies & ISC prototype testing continues

Advanced Controls & System Identification (SID)

- Modern controls approach to optimization of system
- Interfaces to existing infrastructure
- Allows both noise performance and robustness to be explored
- Can be static, or apply Adaptive Control techniques if proven
- Schedule Highlights
  - » 4Q02: System identification for the initial LIGO detector
  - » 4Q03: Adaptive control for the initial LIGO detector
  - » 1Q04: Application to 40m configuration testbed
  - » 2Q05: System identification for the advanced LIGO configuration

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

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)		
Advanced Interferometer Systems, Sensing & Control (ISC)						
Sci & PD	MIT	0	0	1.67	1.67	6.87
	CIT	2	0	3.2	5.2	
UG & Grads	MIT	1	0	1	2	5
	CIT	3	0	0	3	
Eng & Techs	MIT	0	0	0.75	0.75	10.23
	CIT	0	0	9.48	9.48	
Totals (FTE):		6	0	16.1	**22.1**	
Equip. & Supplies ($K)		$275	$0	$0	**$275**	

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

Total LIGO Lab R&D

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	Totals (FTE, $K)	
TOTAL for R&D						
Sci & PD	MIT	1	0	4.15	5.15	21.3
	CIT	9	0	7.15	16.15	
UG & Grads	MIT	5	0	1	6	14
	CIT	8	0	0	8	
Eng & Techs	MIT	0	0	3.5	3.5	25.63
	CIT	0.5	0	18.13	18.63	
	LLO	0	0	3.5	3.5	
Totals (FTE):		23.5	0	37.43	**60.93**	
Equip. & Supplies		$1,202	$3,222	$0	**$4,424**	
				MIT	14.65	
				CIT	42.78	
				LLO	3.5	

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

Total Campus Detector Staff Support to Observatories & Data Analysis

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	Totals (FTE)	
TOTAL Campus Detector Staff Support to Observatories & Data Analysis						
Sci & PD	MIT			4.35	4.35	12.53
	CIT			8.18	8.18	
UG & Grads	MIT			2	2	2
	CIT			0	0	
Eng & Techs	MIT			0	0	2.87
	CIT			2.87	2.87	
	Totals (FTE):	0	0	17.4	**17.4**	

N.B.: Does not include support by LSC research staff or the LIGO Lab/CIT Data Analysis Group