Planning for Advanced LIGO

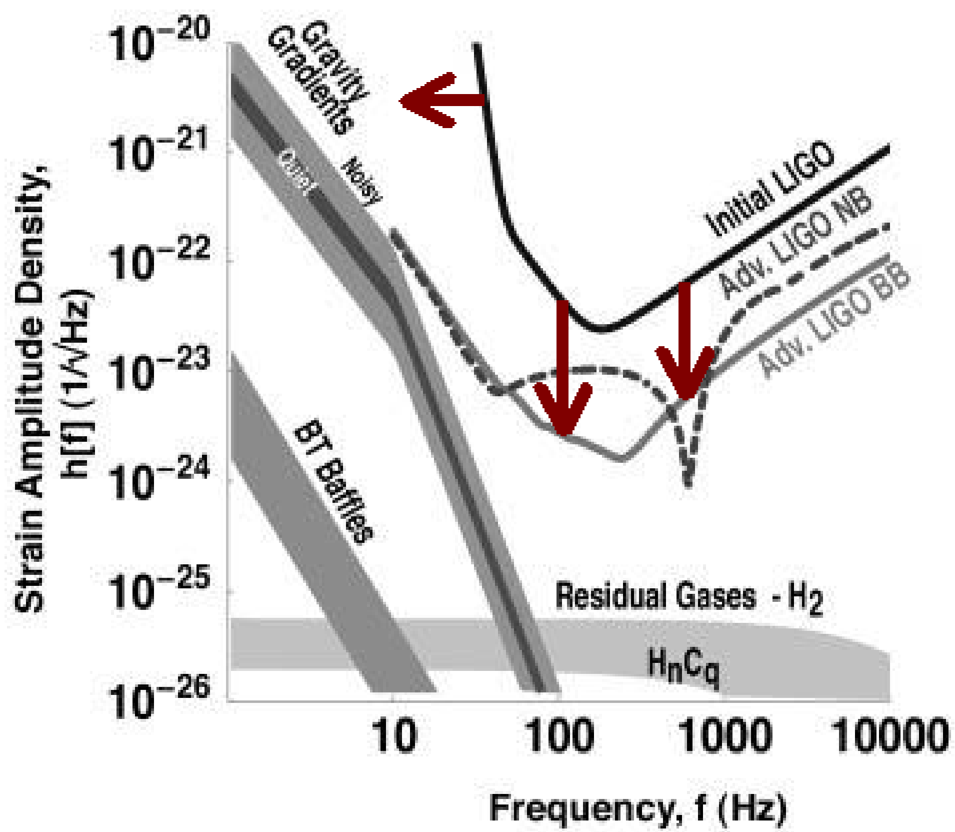
Dennis Coyne & David Shoemaker

LSC Meeting

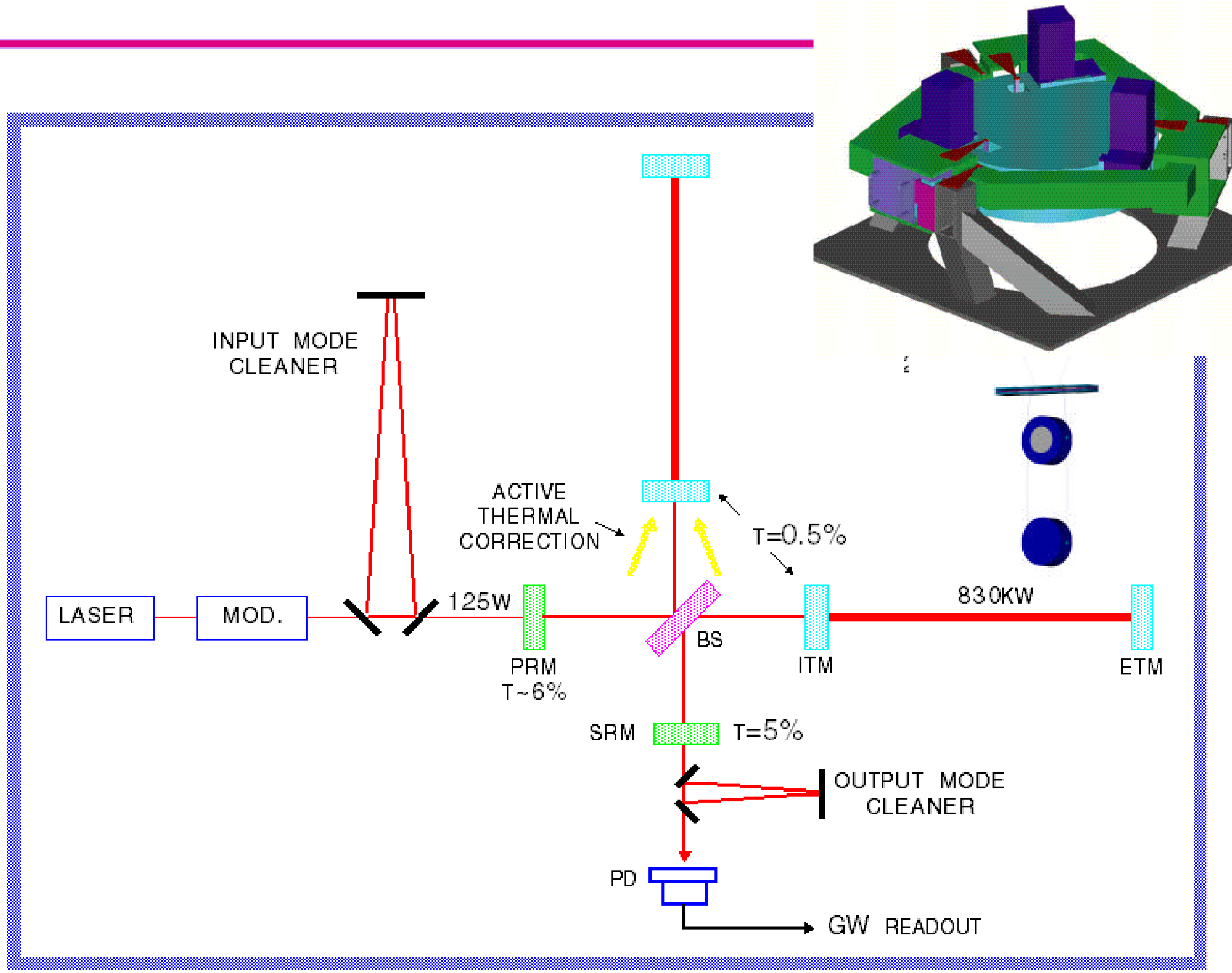
3/14-17/01

Present and future limits to sensitivity

- Advanced LIGO
  - » Seismic noise 40→10 Hz
  - » Thermal noise 1/15
  - » Shot noise 1/10, tunable
- Facility limits
  - » Gravity gradients
  - » Residual gas
  - » (scattered light)
- Beyond Adv LIGO
  - » Thermal noise: cooling of test masses
  - » Quantum noise: quantum non-demolition



Interferometer subsystems

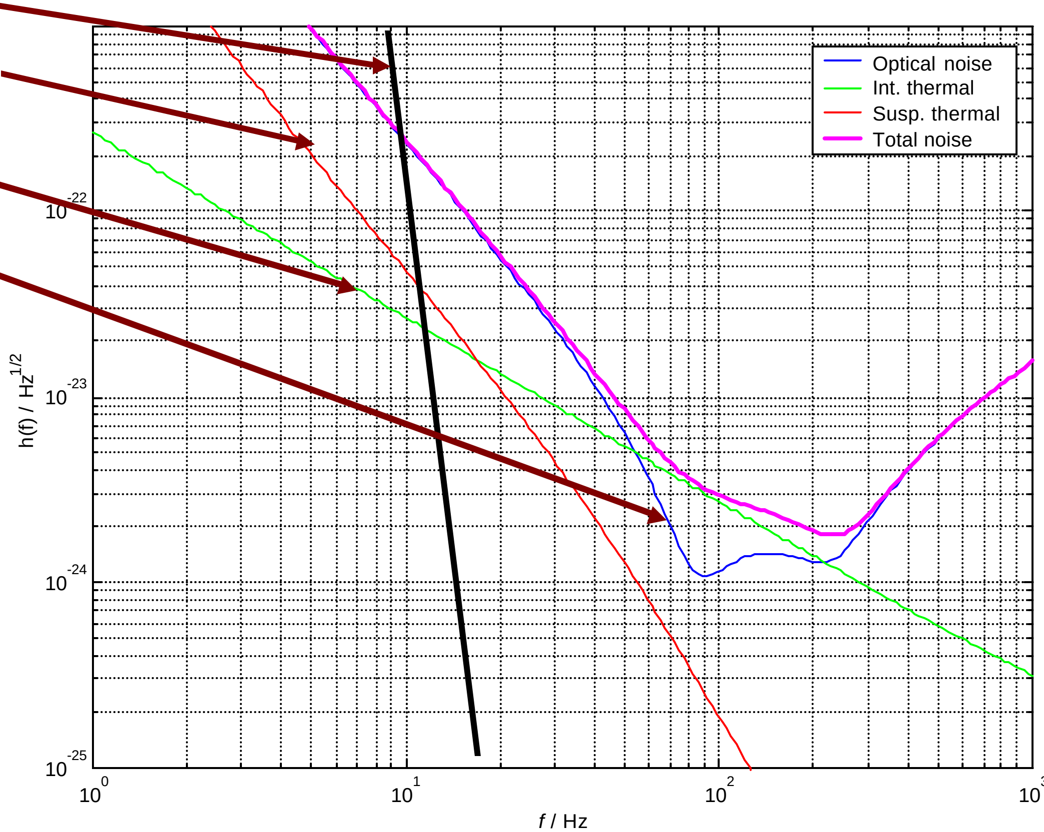


Nominal top level parameters

	Sapphire	Fused Silica
Fabry-Perot arm length	4000 m	
Laser wavelength	1064 nm	
Optical power at interferometer input	125 W	80 W
Power recycling factor	17	17
FP Input mirror transmission	0.5%	0.50%
Arm cavity power	830 kW	530 kW
Power on beamsplitter	2.1 kW	1.35 kW
Signal recycling mirror transmission	6.0%	6.0%
Signal recycling mirror tuning phase	0.12 rad	0.09 rad
Test Mass mass	40 kg	30 kg
Test Mass diameter	32 cm	35 cm
Beam radius on test masses	5.5 cm	5.5 cm
Neutron star binary inspiral range (Bench)	285 Mpc	240 Mpc
Stochastic GW sensitivity (Bench units)	7.8 x 10-9	2.4 x 10-9

Anatomy of the projected detector performance

- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Internal thermal noise
- Unified quantum noise dominates at most frequencies
- 'technical' noise (e.g., laser frequency) levels held, in general, well below these 'fundamental' noises



System trades

- Laser power
  - » Trade between improved readout resolution, and momentum transfer from photons to test masses
  - » Distribution of power in interferometer: optimize for material and coating absorption, ability to compensate
- Test mass material
  - » Sapphire: better performance, but development program, crystalline nature
  - » Fused silica: familiar, but large, expensive, poorer performance
- Lower frequency cutoff
  - » 'Firm', likely, and possible astrophysics
  - » Technology thresholds in isolation and suspension design

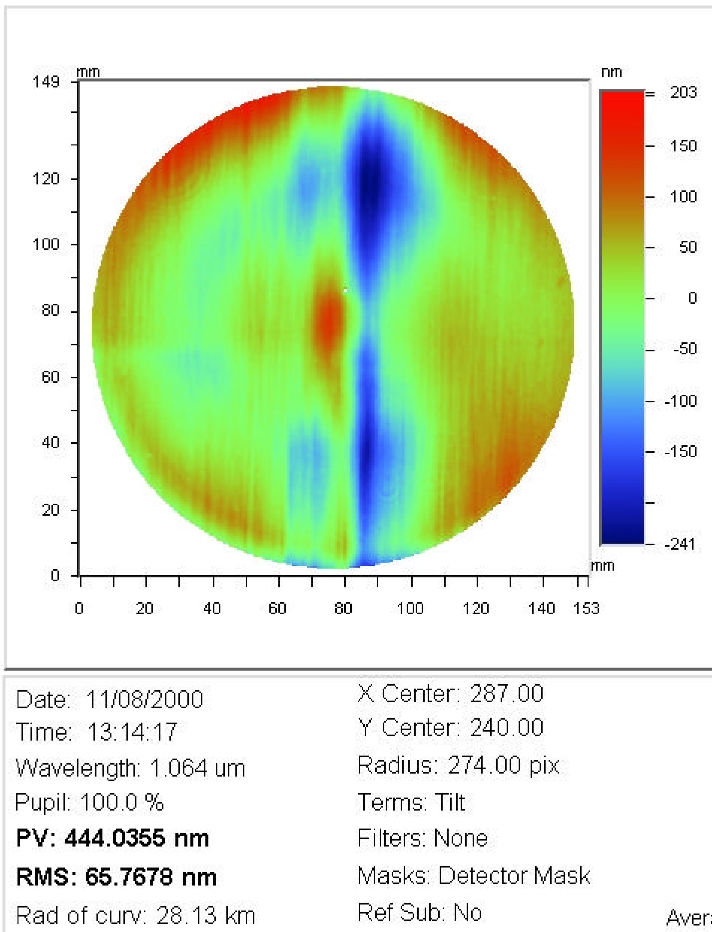
Interferometer subsystems

Subsystem	Function	Implementation	Principal challenges
Interferometer Sensing and Control (ISC)	Gravitational Readout; length and angle control of optics	RF modulation/demod techniques, digital real-time control	Lock acquisition, S/N and bandwidth trades
Seismic Isolation (SEI)	Attenuation of environmental forces on test masses	Low-noise sensors, high-gain servo systems	Reduction of test mass velocity due to 0.01-1 Hz input motion
Suspension (SUS)	Establishing 'Free Mass', actuators, seismic isolation	Silica fibers to hold test mass, multiple pendulums	Preserving material thermal noise performance
Pre-stabilized Laser (PSL)	Light for quantum sensing system	Nd:YAG laser, 100-200 W; servo controls	Intensity stabilization: 3e-9 at 10 Hz
Input Optics (IOS)	Spatial stabilization, frequency stabilization	Triangular Fabry-Perot cavity, suspended mirrors	EO modulators, isolators to handle power
Core Optics Components (COC)	Mechanical test mass; Fabry-Perot mirror	40 kg monolithic sapphire (or silica) cylinder, polished and coated	Delivering optical and mechanical promise; Developing sapphire
Auxiliary Optics (AOS)	Couple light out of the interferometer; baffles	Low-aberration telescopes	Thermal lensing compensation

Development Plan

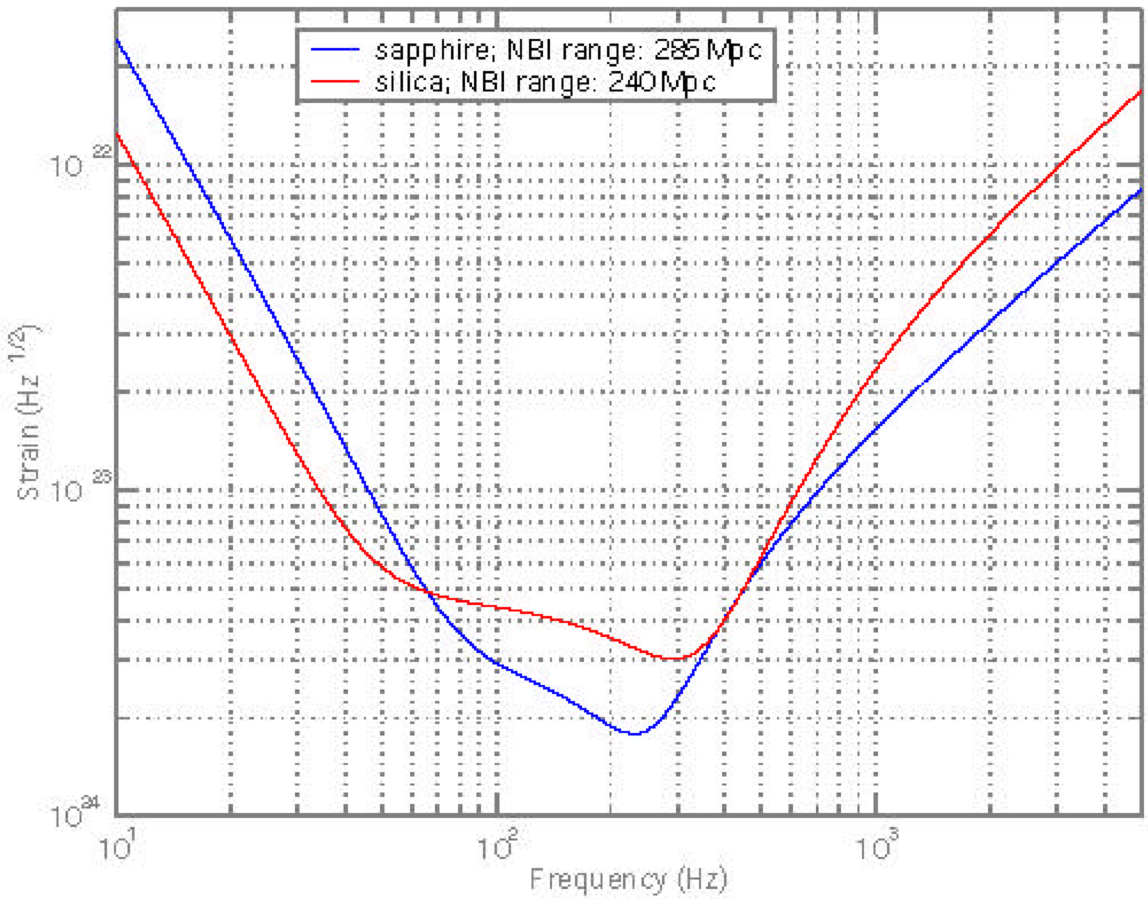
- R&D including Design through Final Design Review
  - » for all long lead or high risk subsystems
  - » LIGO Lab contracts and funds large R&D equipment
- Construction Phase Proposal
  - » Major Research Equipment (MRE) funding
  - » includes 'prosaic' design efforts
- Isolation Test Bed (LASTI)
  - » full scale, integrated suspensions & seismic Isolation testing
  - » in-chamber assembly & installation procedure check-out
  - » possible first article test bed
- Controls Test Beds (GEO 10m and LIGO 40m)
- Integrated Systems Tests
  - » Pre-Stabilized Laser (PSL), Input Mode Cleaner, Suspensions and Seismic Isolation Test at LASTI
  - » Integrated Servo Control Electronics Testing at the LIGO 40m Lab
  - » Possibly early End Test Mass Suspension & Seismic Isolation replacement at a LIGO Observatory

Subsystem Development Plan Highlights



- Core Optics
  - » sapphire material development with Crystal Systems & SIOM
  - » joint mechanical & optical material test matrix in development
  - » spot polishing to compensate for inhomogeneity
  - » coating facility development & low absorption research
    (MLD & Virgo/Lyon)
- Seismic Isolation
  - » Full scale, HAM-type technology demonstrator @ ETF, Stanford
  - » Full scale prototypes (HAM & BSC types) @ LASTI, MIT
- Suspension
  - » U. of Glasgow/GEO takes the lead to PDR, LIGO Lab leads in Final Design
  - » Triple & quad pendulum ‘controls’ & ‘noise’ prototypes tested with the SEI prototypes at LASTI

Sensitivity (sapphire, silica)



Subsystem Development Plan Highlights (continued)

- Laser
  - » Power amplifier or injection-locked topology in trade study
  - » Laser Zentrum Hannover/GEO to take lead; LIGO Lab supplies requirements, interface, and test
  - » Intensity stabilization research at CIT
- Input Optics System (IOS)
  - » University of Florida takes lead, GEO suspensions, LIGO controls
  - » UFL performs enabling high power research on modulators & isolators
- Auxiliary Optics System (AOS)
  - » Substrate thermal focus compensation research @ MIT
  - » Photon actuator for test mass @ CIT
- Interferometer Sensing & Control (ISC)
  - » Shift to 'DC readout' (relaxes laser frequency stabilization requirements)
  - » Requires both proof-of-principle (GEO 10m) and precision testing (40m)
  - » LIGO Lab leads, with contributions from LSC, esp. GEO

Installation & Commissioning Plan

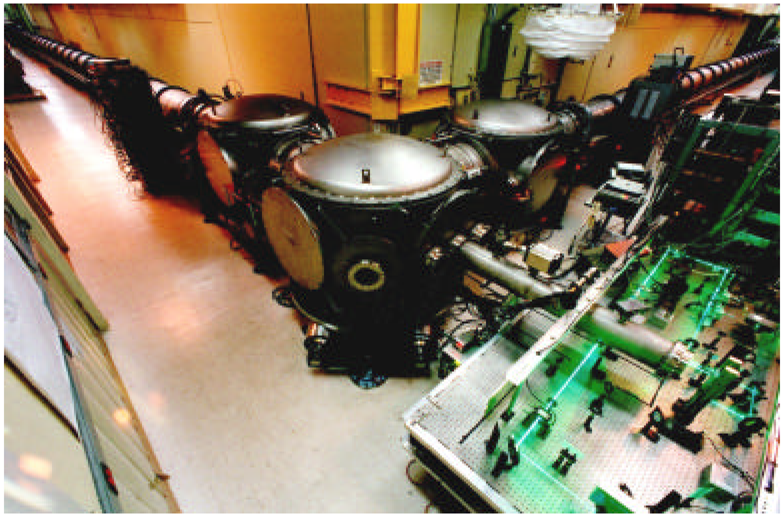
- Minimum of a 1 year of Integrated Science Run Before a Major Upgrade
- Schedule to be Coordinated with International GW Observatories to Keep $\geq$ 2 Detectors Operating
- Start Installation Only When Production & Assembly Pipeline Will Not Limit the Installation Schedule
- Install One Advanced LIGO Interferometer and Incorporate Lessons Leaned into the Subsequent Advanced Interferometers (time lag of ~ 18 months)

LASTI Laboratory

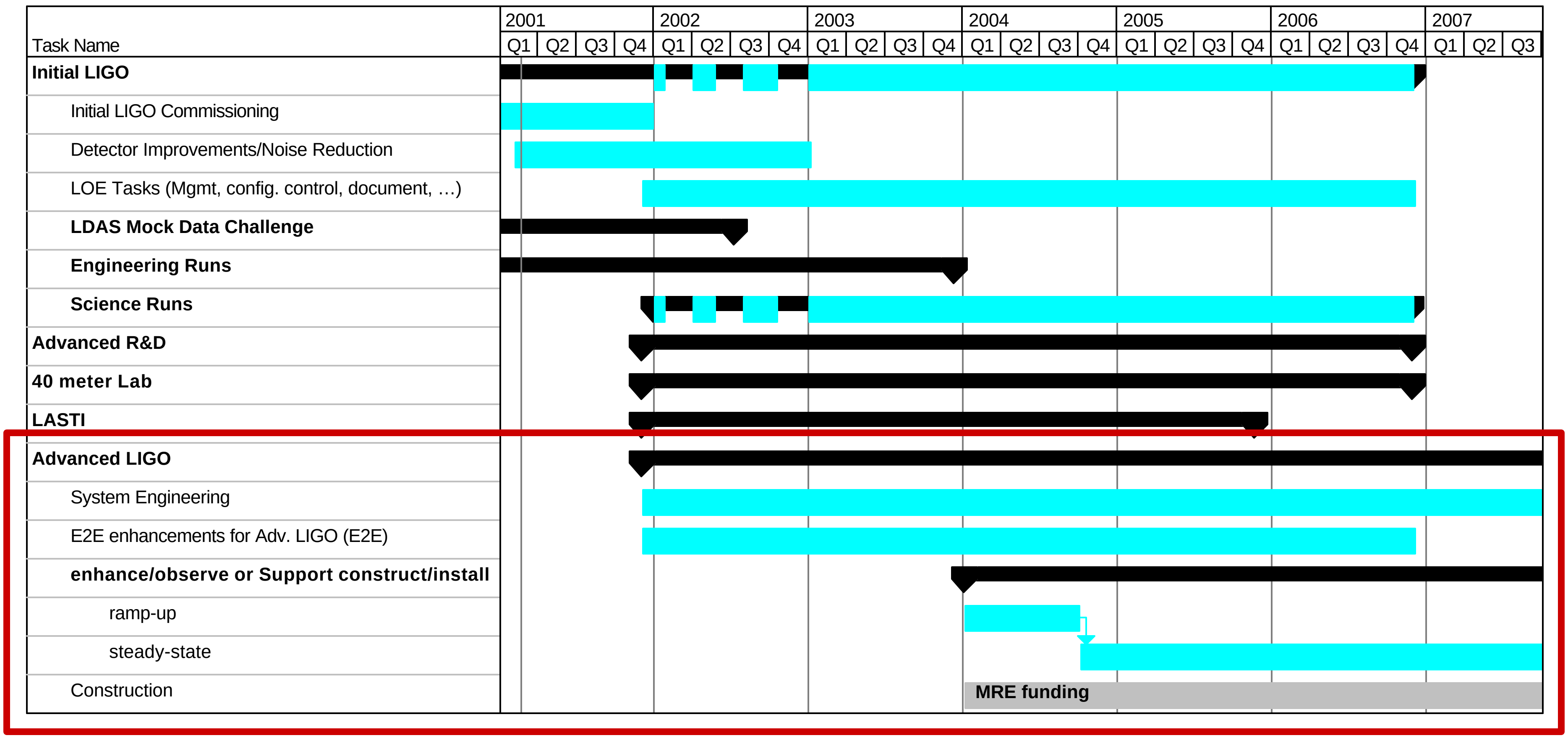
- Full-scale tests of Seismic Isolation and Test Mass Suspension.
  - » Takes place in the LIGO Advanced System Test Interferometer (LASTI) at MIT: LIGO-like vacuum system.
  - » Allows system testing, interfaces, installation practice.
  - » Characterization of non-stationary noise, thermal noise.
- 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: Suspension noise prototypes installed.
  - » 2Q04: integrated Isolation/suspension testing completed.
  - » 1Q05: PSL-Mode Cleaner integrated performance test completed.

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
  - » 2Q01: LIGO 40 m Vacuum Envelope commissioned
  - » 2Q01: LIGO 40 m PSL installed
  - » 4Q02: LIGO 40 m suspensions installed
  - » 2Q04: LIGO 40 m configurations research completed; further characterization studies & ISC prototype testing continues

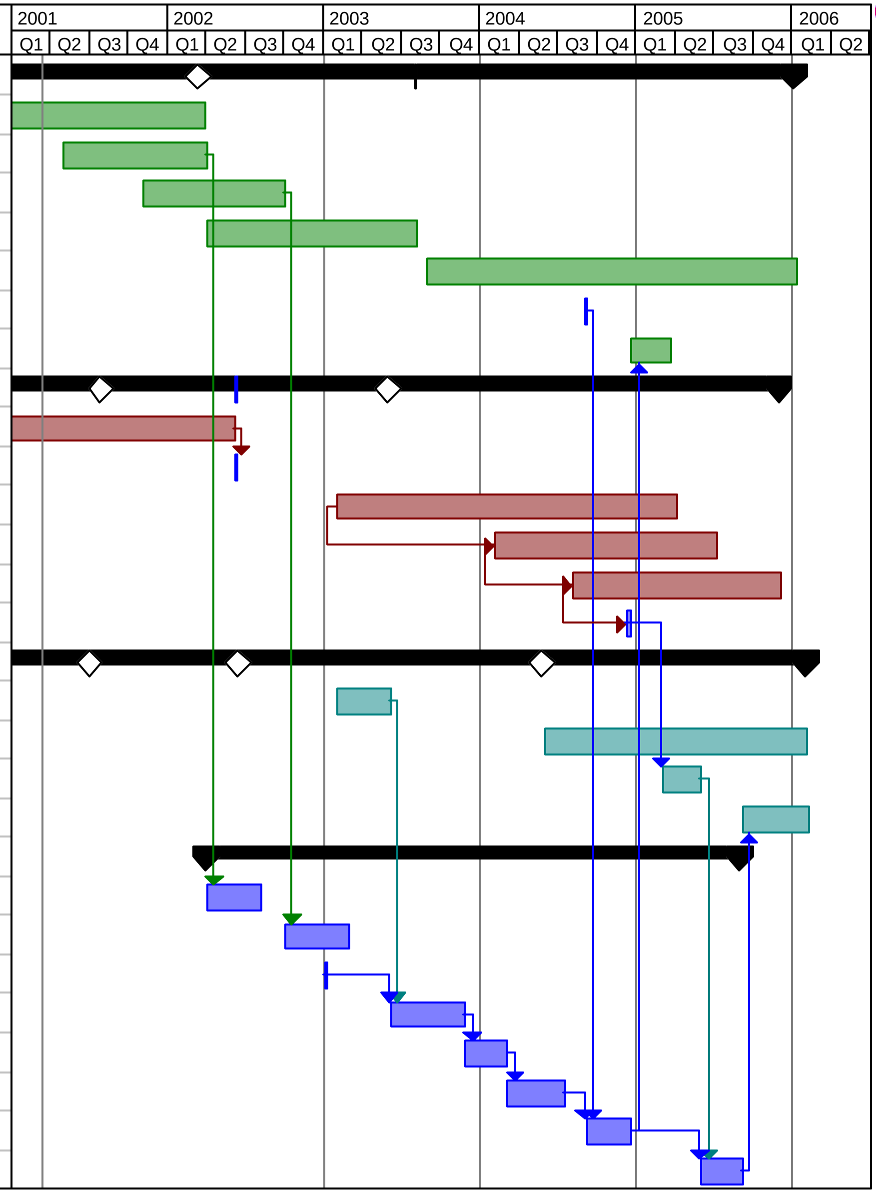


Overall Proposed Schedule



LASTI & Supporting Subsystem Integrated Schedule

ID	Task Name
1	**Seismic Isolation (SEI)**
2	prototype
4	pathfinder fab (HAM)
5	pathfinder fab (BSC)
7	Final Design
9	production
10	first article avail
11	first article rework
12	**Core Optics Components (COC)**
15	Pathfinder-II
16	PDR/ select Sapphire or FS
18	blanks
19	polish
20	coat
21	IFO1 set avail from QA
22	**Suspension (SUS)**
26	'noise' prototype fab
28	production
29	first article assy
30	Rework/IFO1 Assy complete
31	**LASTI Experiments/Tests**
32	HAM SEI stand-alone testing
33	BSC SEI stand-alone tests
34	'noise' optics ready
35	assy/instal/test 'noise' SUS proto.
36	cavity tests
37	PSL-MC Integ Test
38	SEI 1st Article Test
39	SUS 1st Article Test

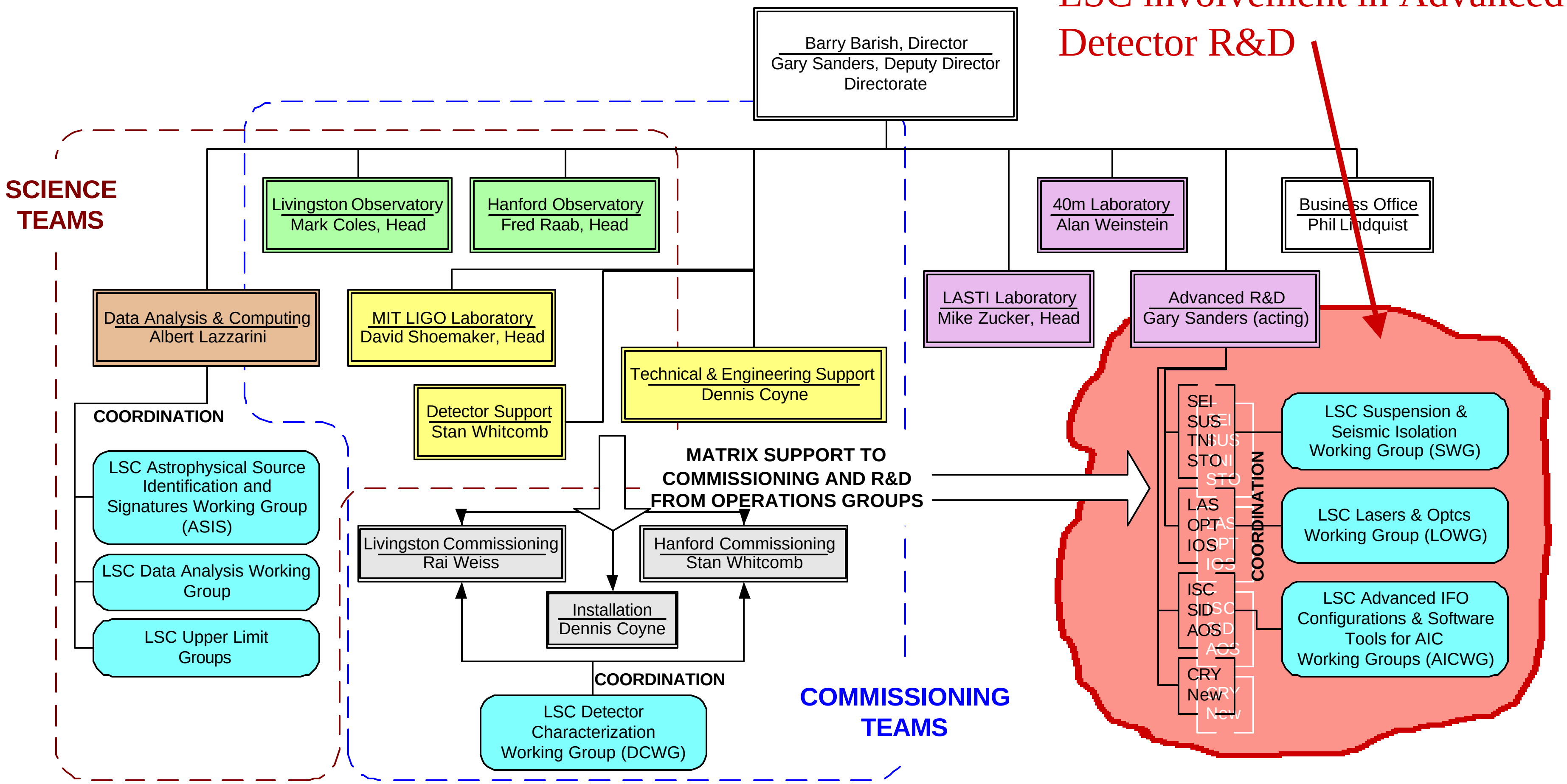


Advanced LIGO R&D Milestones

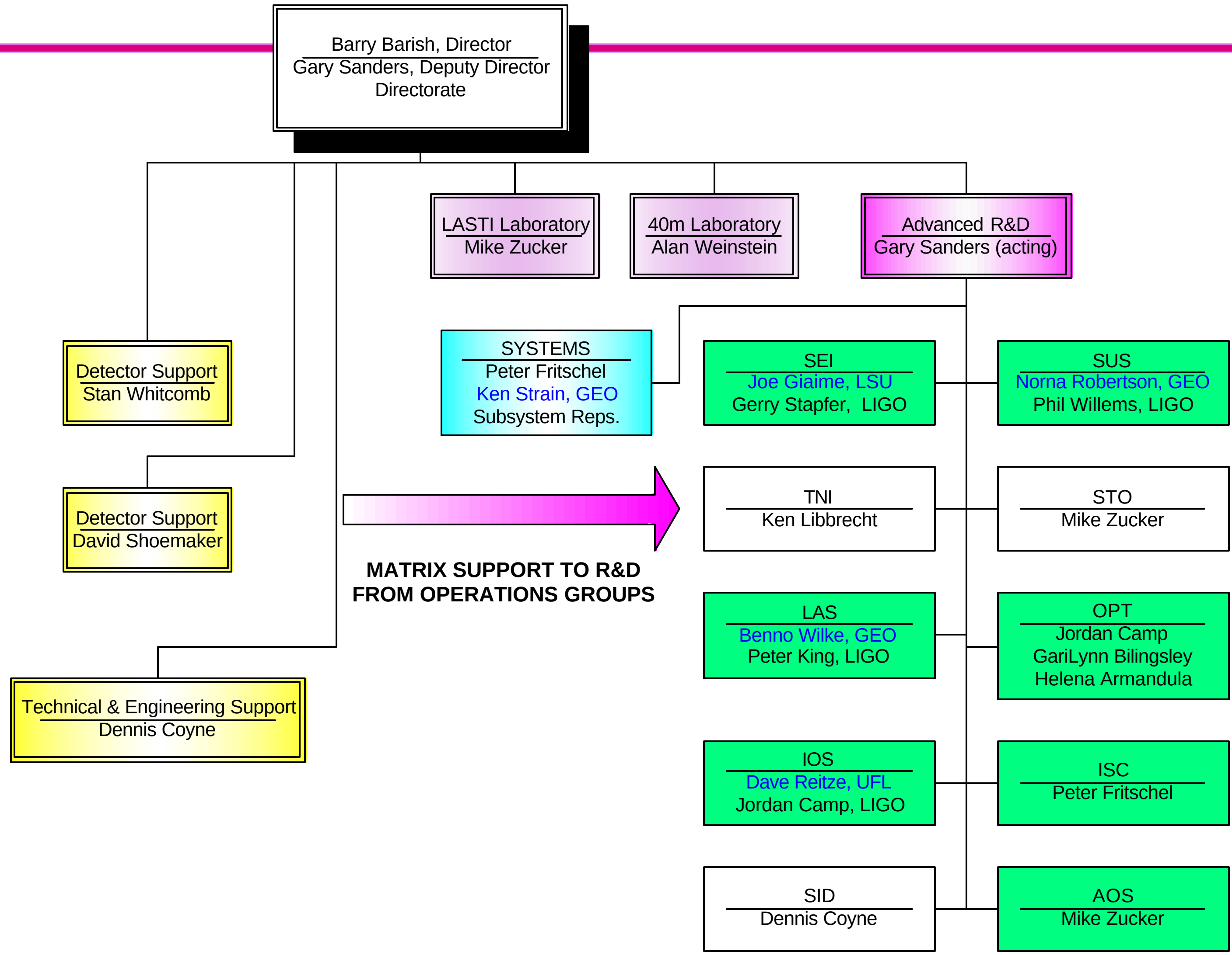
Subsystem	Milestone	Date	Changed from Proposal	Notes
Seismic Isolation (SEI)	SEI PDR	Mar-02	*	delay in prototype procurement
	SEI FDR	Aug-03		
Core Optic Components (COC)	COC PDR/ select Sapphire or FS	Jun-02		
	COC FDR	Jun-03		
	order for optics placed	Feb-03		
	COC set for 1st interferometer available	Dec-04		
Suspensions (SUS)	SUS PDR	Jun-02		
	SUS FDR	Jun-04		
Stochastic Noise/LASTI	LASTI SEI stand-alone tests completed	Mar-03		
	LASTI SEI/SUS cavity tests completed	Jun-04		
	LASTI PSL-MC Integ Test completed	Mar-05		
Pre-Stabilized Laser (PSL)	PSL PDR	Dec-02	*	PSL dates changed due to subsequent planning with GEO
	PSL FDR	Dec-04	*	
	PSL delivered to LASTI	Aug-04	*	
Input Optcs (IO)	IO PDR	Jul-03	*	IO delayed intentionally to match with other subsystem timelines
	IO FDR	Jul-04	*	
Interferometer Sensing & Control	ISC PDR	Aug-02		
	ISC FDR	Dec-03		
Resonant Signal Extraction (RSE)	construction complete	Jun-03		
	interferometer locked	Jun-04		
	control system qualified	Dec-05		
Auxiliary Optics System (AOS)	active optics compensation FDR	Dec-04		
	photon drive FDR	Sep-04		

Organization

LSC involvement in Advanced Detector R&D



Organization



LIGO R&D Program

- Focussed on Advanced LIGO Conceptual Design
  - » Exciting astrophysical sensitivity
  - » Challenging but not unrealistic technical goals
  - » Advances the art in materials, optics, lasers, servocontrols
- A tight and rich collaboration
  - » NSF-funded research
  - » International contributors
- Program planned to mesh with fabrication of interferometer components leading to installation of new detectors in 2006
  - » Lessons learned from initial LIGO
  - » Thorough testing at Campus Labs to minimize impact on LIGO observation
  - » Coordination with other networked detectors to ensure continuous global observation

Summary of NSF Reviews of the Advanced LIGO R&D

- R&D Sub-Panel:
  - » "The proposal for R&D regarding an advanced LIGO detector contains a set of significant technical challenges that, if met, will provide a design for a gravitational wave detector that should be capable of yielding extremely exciting science."
  - » "We believe that the LIGO Laboratory, in consort with the LSC, is capable of carrying out, and is ready to carry out, the R&D program described in the proposal."
- Operations & Scientific Research Sub-Panel:
  - » "The proposed budgets for LIGO Laboratory Operations, the scientific research program, and the R&D for Advanced LIGO are justified and adequate to carry out the proposed activities."
  - » "NSF should continue to fund the LSC member institutions and the gravitational wave research at a level that makes it possible to exploit the full scientific potential of the LIGO facility."

Advanced LIGO Proposal (FY2004 MRE funding start)

- July 2001 Draft MRE Proposal from the LIGO Lab
- Oct 2001 Final MRE Proposal from the LIGO Lab
- Nov 2001 NSF Panel Review
- Nov 2002 NSB approval

The LIGO Lab will continue to work very closely with the larger LSC to prepare and present the MRE proposal to the NSF