Status of LIGO

Barry Barish

PAC Meeting - LHO

December 12, 2000

LIGO Plans

schedule

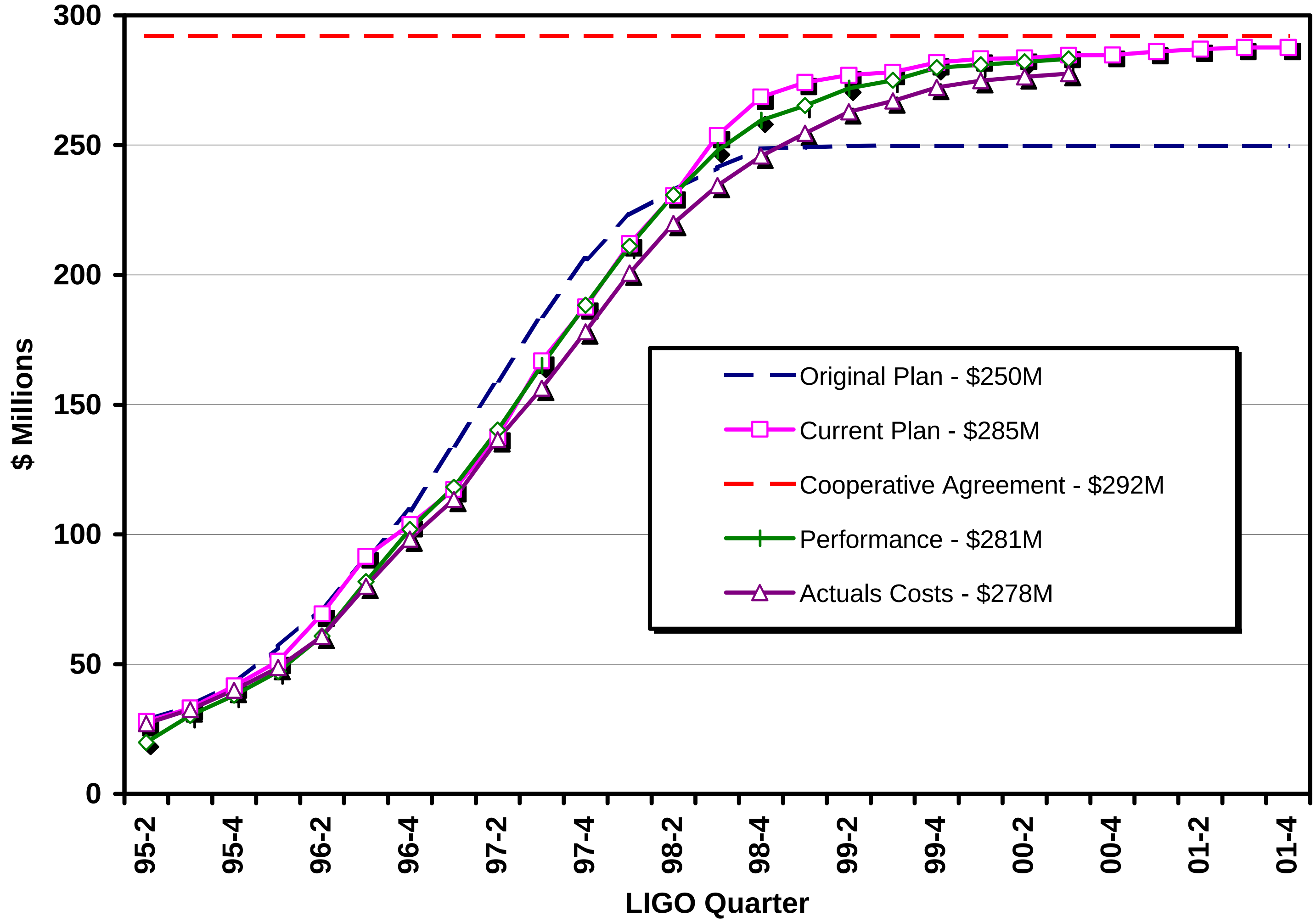
1996	Construction Underway	(mostly civil)
1997	Facility Construction	(vacuum system)
1998	Interferometer Construction	(complete facilities)
1999	Construction Complete	(interferometers in vacuum)
2000	Detector Installation	(commissioning subsystems)
2001	Commission Interferometers	(first coincidences)
2002	Sensitivity studies	(initiate LIGOI Science Run)
2003+	LIGO I data run	(one year integrated data at $h \sim 10^{-21}$)
2005+	Begin LIGO II installation	

Construction Project
status

- 98% complete
- construction project will finish on the budget & schedule
- Hanford buildings complete
  - » last laboratory building
    - – contract A&E design
- Livingston complete
  - » last laboratory building
    - – contracting construction

LIGO Project

construction and related R&D costs



Project Milestones

facilities construction

Milestone Description	PMP Date		Actual Completion Date	
	Washington	Louisiana	Washington	Louisiana
Initiate Site Development	03/94	08/95	03/94	06/95
Beam Tube Final Design Review	04/94		04/94	
Select A&E Contractor	11/94		11/94	
Complete Beam Tube Qualification Test	02/95		04/95	
Select Vacuum Equipment Contractor	03/95		07/95	
Complete Performance Measurement Baseline	04/95		04/95	
Initiate Beam Tube Fabrication	10/95		12/95	
Initiate Slab Construction	10/95	01/97	02/96	01/97
Initiate Building Construction	06/96	01/97	07/96	01/97
Accept Beam Tubes and Covers	03/98	03/99	03/98	10/98
Joint Occupancy	09/97	03/98	10/97	02/98
Beneficial Occupancy	03/98	09/98	03/98	12/98
Accept Vacuum Equipment	03/98	09/98	11/98	01/99
Initiate Facility Shakedown	03/98	03/99	11/98	01/99

Interferometers
international network

LIGO (Washington)

LIGO (Louisiana)

LIGO Facilities

beam tube enclosure

- **minimal enclosure**
- **reinforced concrete**
- **no services**

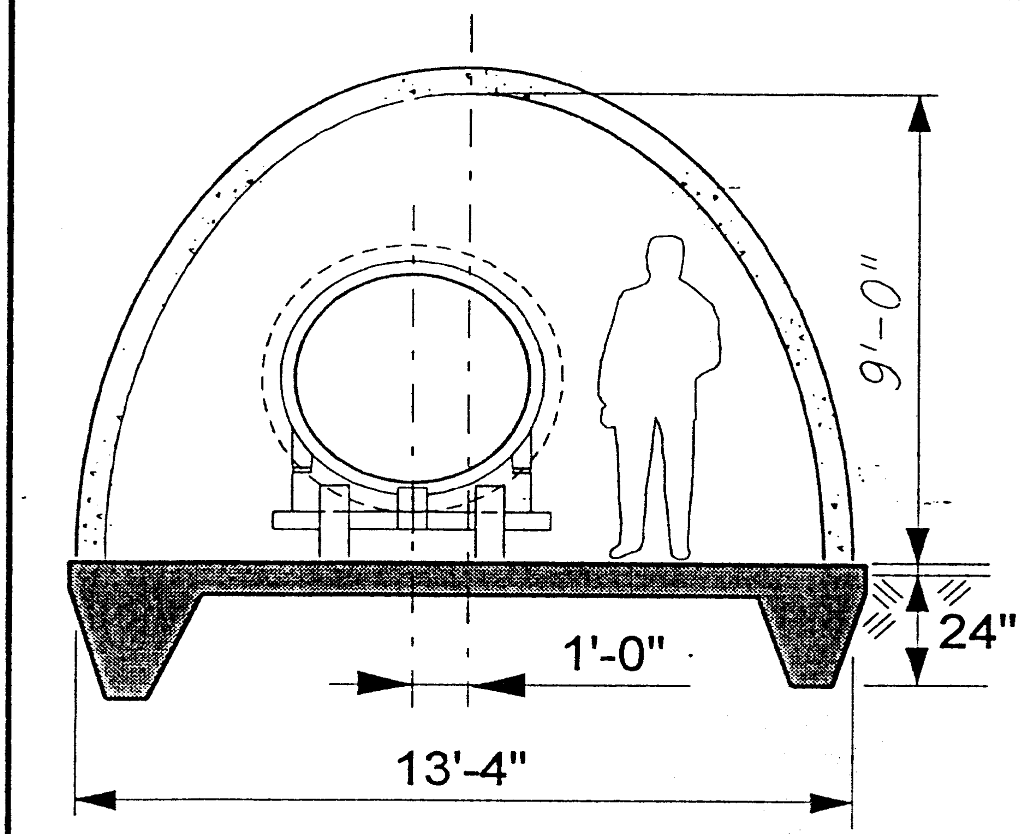


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

LIGO
beam tube

- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- girth welded in portable clean room in the field

1.2 m diameter - 3mm stainless
50 km of weld

NO LEAKS !!

Beam Tube Bakeout

	Outgassing Rates Corrected to 23 °C (all except H_2 are upper limits)									
Molecule	**Goal[1]**	**HY2 [2]**	**HY1**	**HX1**	**HX2**	**LY2**	**LY1**	**LX1**	**LX2**	**Unit**
H_2	4.7	4.8	6.3	5.2	4.6	2.6	3.46	6.6	4.3	10^{-14} torr liters/sec/cm^2
CH_4	4800	<90	<22	<0.9	<10	<24	<3.9	<3	<4.0	10^{-19} torr liters/sec/cm^2
H_2O	1500	<4	<20	<1.8	<0.8	<3	<0.9	<0.6	<10	10^{-18} torr liters/sec/cm^2
CO	650	<14	<9	<5.7	<2	<5	<10	<8	<5	10^{-18} torr liters/sec/cm^2
CO_2	2200	<40	<18	<2.9	<8.5	<10	<6	1.1	<8	10^{-19} torr liters/sec/cm^2
$O+C_2H_6$	7000	<2	<14	<6.6	<1.0	<1.9	<3.6	<1.1	<1.1	10^{-19} torr liters/sec/cm^2
$H_nC_pP_q$	50-2[3]	<15	<8.5	<5.3	<0.4	<20	<25	<1.9	<4.3	10^{-19} torr liters/sec/cm^2
Air leak	10	<2	<1	<0.4	<1.6	<10	23	<3.5	<0.7	10^{-10} torr liter/sec/cm^2

[1] Goal: maximum outgassing to achieve pressure equivalent to 10^{-9} torr H_2 using only pumps at stations.

[2] Hanford "Y" are modules designated HY1, HY2; "X" arm, HX1, HX2; Livingston, LY1, LY2, LX1, and LX2

[3] Goal for hydrocarbons depends on weight of parent molecule; range given corresponds with 100-300 AMU.

Project Milestones

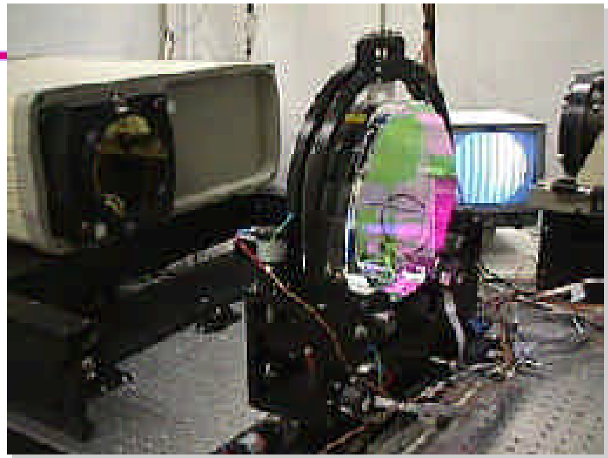
detector construction

Milestone Description	PMP Date		Actual/Projected Completion Date	
	Washington	Louisiana	Washington	Louisiana
Beam Splitter Chamber (BSC) Final Design Review	04/98		08/98	
Core Optics Support Final Design Review	02/98		11/98	
Horizontal Access Module (HAM) Seismic Isolation Final Design Review	04/98		06/98	
Core Optics Components Final Design Review	12/97		05/98	
Detector System Preliminary Design Review	12/97		10/98	
Input/Output Optics Final Design Review	04/98		03/98	
Pre-stabilized Laser (PSL) Final Design Review	08/98		03/99	
Control and Data Systems Networking Ready for Installation	04/98		03/98	
Alignment (Wavefront) Sensing Final Design Review	04/98		07/98	
Control and Data Systems Data Acquisition Final Design Review	04/98		05/98	
Length Sensing and Control System Final Design Review	05/98		07/98	
Physics Environment Monitoring Final Design Review	06/98		10/97	
Initiate Interferometer Installation	07/98	01/99	07/98	01/99
Begin Coincidence Tests	12/00		03/01 (Projected)	

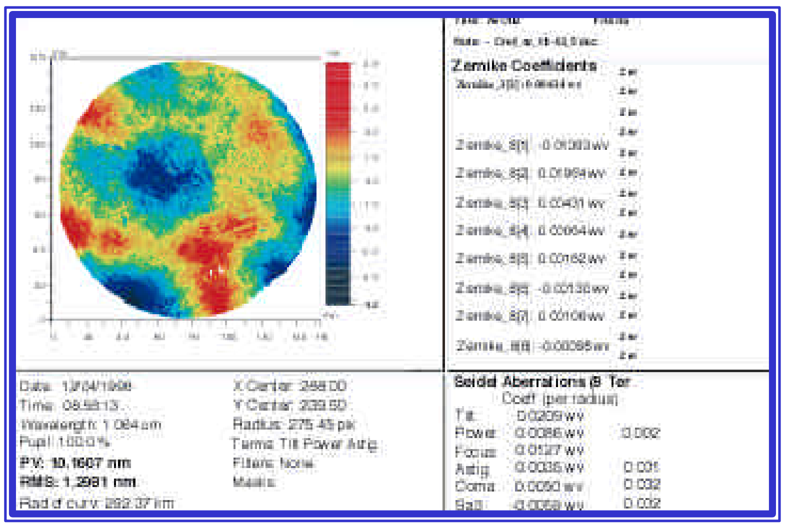
Detector
installation and commissioning

- **Impressive progress! But, cumulative loss of schedule**
  - » **up to 7 months**
  - » **we have changed strategy**
  - » **hard to measure the final milestone against the original schedules**
- **Basic Strategy:**
  - » **simultaneous installation at both observatories (optimum staff utilization)**
  - » **time phased installation of subsystems (leveling load on experts)**
  - » **significant participation & support from observatory staff (training)**
  - » **early install of in-vacuum components (fab/ assy/ install. risk reduction)**
  - » **early as possible system integration & commissioning (early warning)**
  - » **Hanford 2km Mission: problem finding/ solving (‘pathfinder’)**
  - » **Livingston 4km Mission: robust implementation & characterization**
  - » **Hanford 4km:defer: defer implementation to minimize rebuilding**

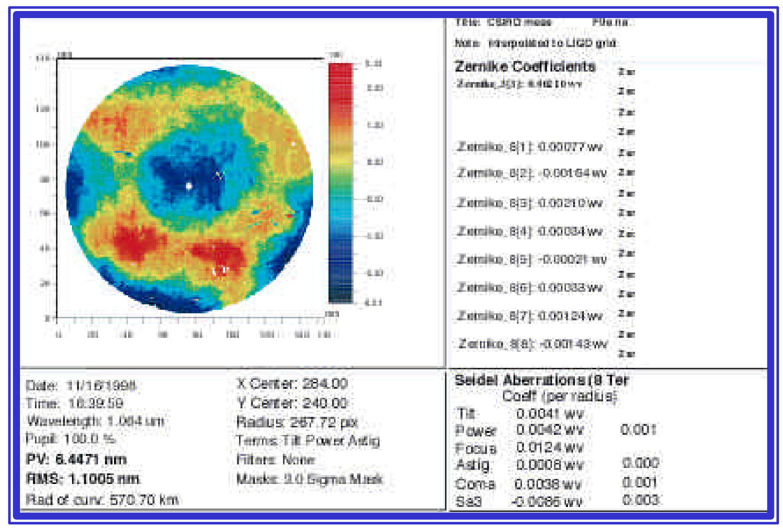
Core Optics
fused silica



- **Surface uniformity < 1 nm rms**
- **Scatter < 50 ppm**
- **Absorption < 2 ppm**
- **ROC matched < 3%**
- **Internal mode Q's > 2 x 10^6**



Caltech data



CSIRO data

Commissioning *configurations*

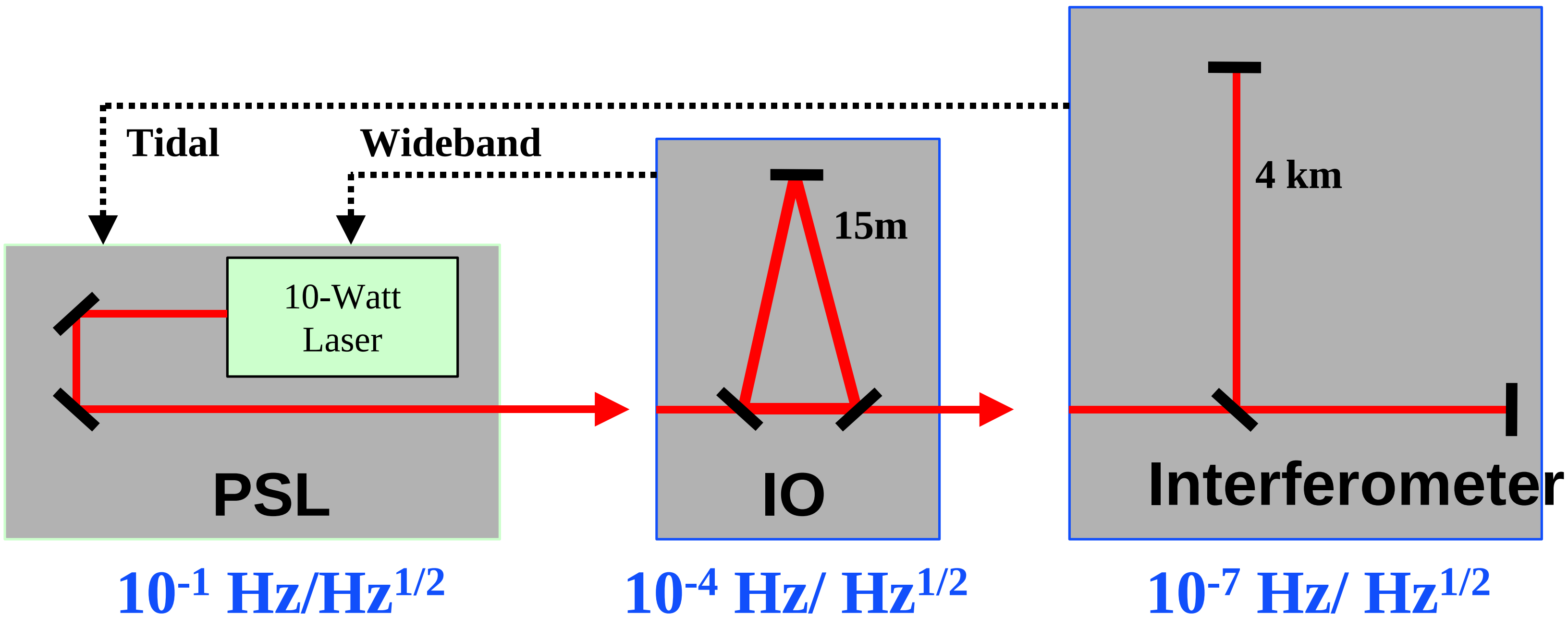
- **Mode cleaner and Pre-Stabilized Laser**
- **2km one-arm cavity**
- **short Michelson interferometer studies**

- **Lock entire Michelson Fabry-Perot interferometer**

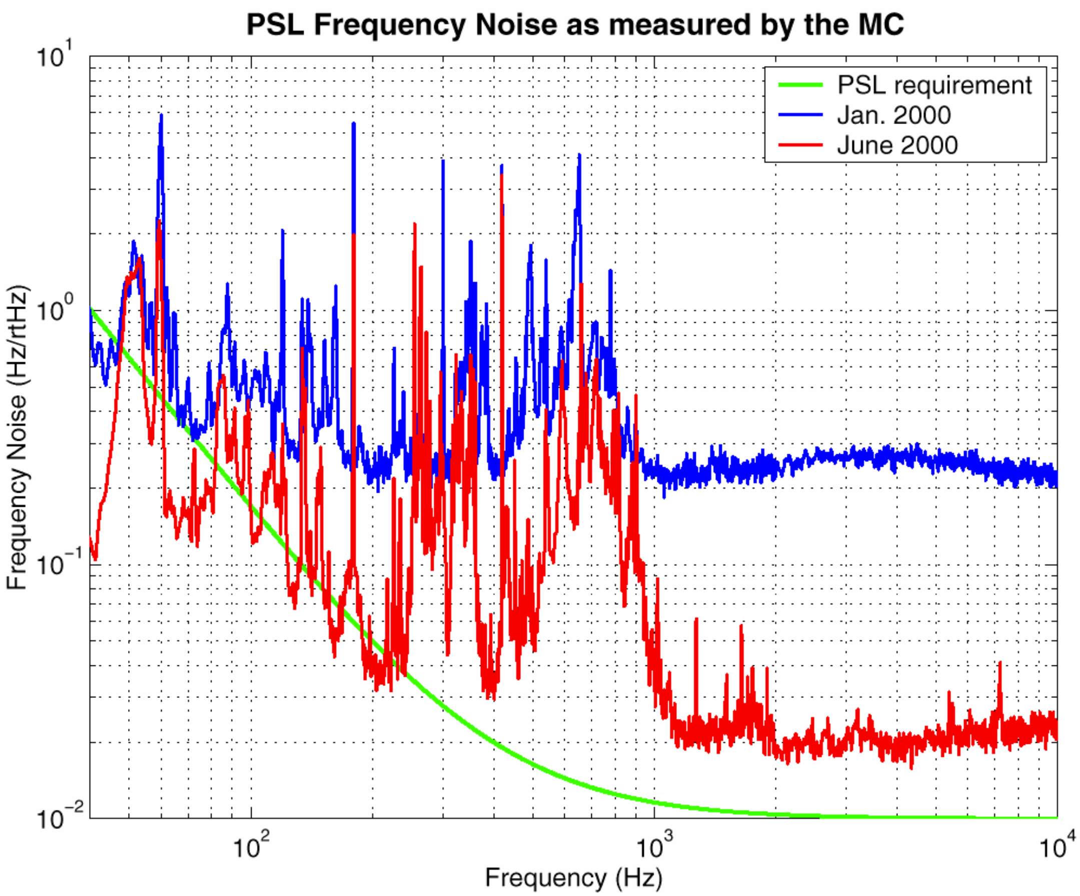
“First Lock”

Laser *stabilization*

- **Deliver pre-stabilized laser light to the 15-m mode cleaner**
  - **Frequency fluctuations**
  - **In-band power fluctuations**
  - **Power fluctuations at 25 MHz**
- **Provide actuator inputs for further stabilization**
  - **Wideband**
  - **Tidal**



Prestabalized Laser
performance

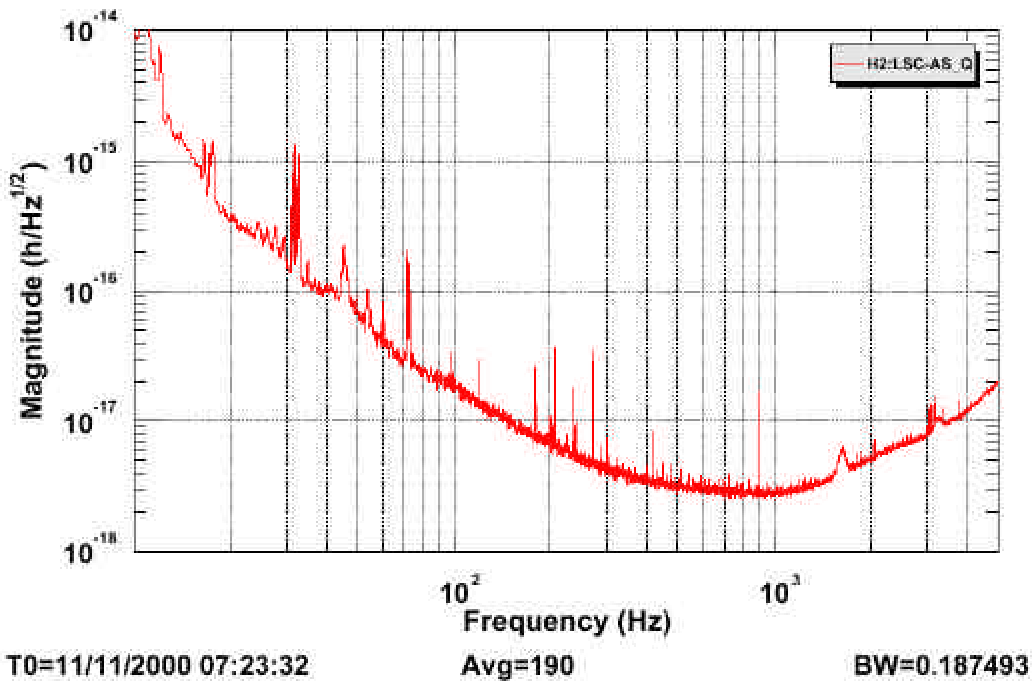


- > 18,000 hours continuous operation
- Frequency and lock very robust
- TEM_{00} power > 8 watts
- Non-TEM_{00} power < 10%

Strain Sensitivity

Nov 2000

2-km Hanford Interferometer



- operating as a Michelson with Fabry-Perot arms
- reduced input laser power (about 100 mW)
- without recycling
- noise level is a factor of 10^4-10^5 above the final specification
- sources of excess noise are under investigation

NSF Panel response …

exit debriefing (May 11, 2000)

"Installation and commissioning of the detector systems at both the Hanford Observatory and the Livingston Observatory are going well. Although there appears to be an up to seven month schedule slip in some of the early milestones, this is not expected to delay the completion of commissioning by the end of 2001. An early science run with all interferometers in coincidence is planned to begin in January 2002."

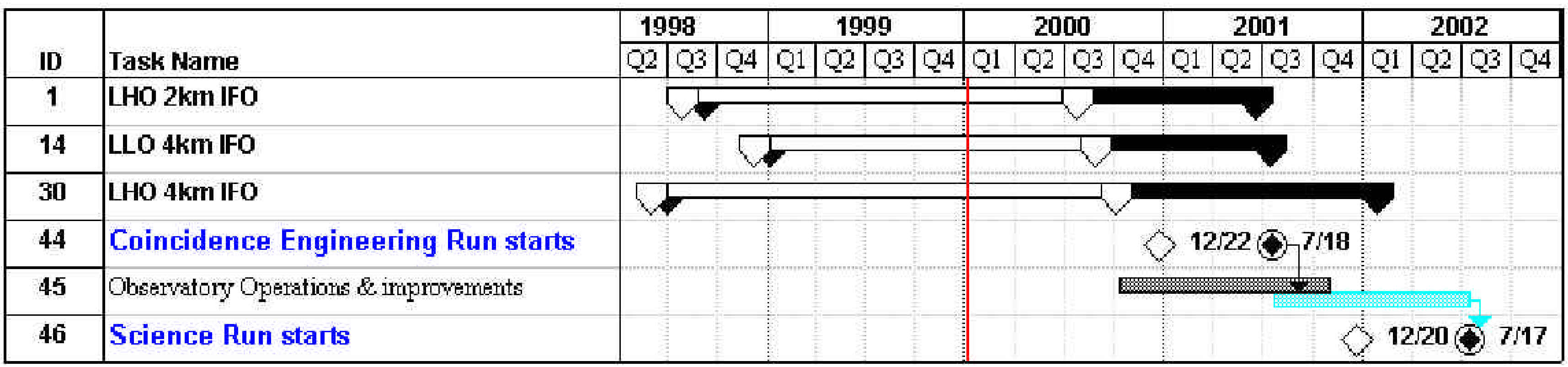
"The committee urges LIGO to prioritize running time on the interferometers during the commissioning phase in order to increase their sensitivity and the reliability of their systems, to provide early data samples to the LSC during engineering runs, and to take advantage of lessons learned as soon as possible."

Strategy Evolving: Look Over the Original Planning Horizon

- Slow the installation into 3rd interferometer (LHO 4-km) to permit use of reworked components
- Move to coincidence running as soon as 2 interferometers are at useful sensitivity
  - » makes coincidence data stream available earlier than waiting for triple coincidence
- Path to Science Run should be smoother with this approach
  - » 3 interferometer Science Run begins mid-2002
  - » First search papers by mid-2002 based upon engineering running?!
    - – Engineering run guided by engineering needs, but...
    - – We are scientists, not just instrument builders.

Revised Schedule

As proposed to the NSF – May 2000



Significant Events

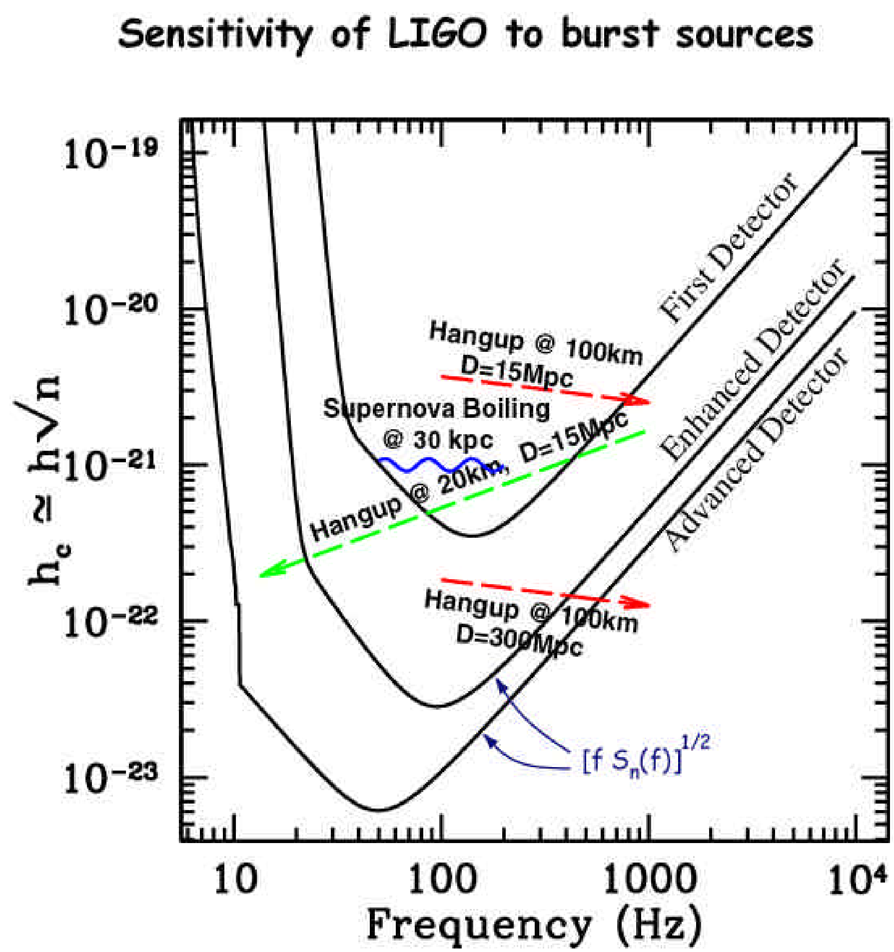
Hanford **2km** **interferometer**	Single arm test complete installation complete interferometer locked	6/00 8/00 12/00
Livingston **4km** **interferometer**	Input Optics completed interferometer installed interferometer locked	7/00 10/00 2/01
Coincidence Engineering Run **(Hanford 2km & Livingston 4km)**	Initiate Complete	7/01 7/02
Hanford **4km** **interferometer**	All in-vacuum components installed interferometer installed interferometer locked	10/00 6/01 8/01
LIGO I Science Run **(3 interferometers)**	Initiate Complete (obtain 1 yr @ $h \sim 10^{-21}$)	7/02 1/05

LIGO I Science Run
(~2002-2005)

GOAL: one integrated year of data @ *h* ~ 10^{-21}

LSC LIGO I Collaboration

Institution
Caltech - CACR
Caltech - CaRT
Cal. State Dominguez Hills
Carleton University
Cornell
GEO 600
Harvard-Smithsonian
Inter-University Centre for Astronomy and
LSU
Oregon University
Penn State
Syracuse University
University of Florida
University of Michigan
University of Texas - Brownsville
University of Wisconsin-Milwaukee
LIGO Hanford
LIGO Livingston
LIGO MIT
LIGO Caltech



Progress & Plans

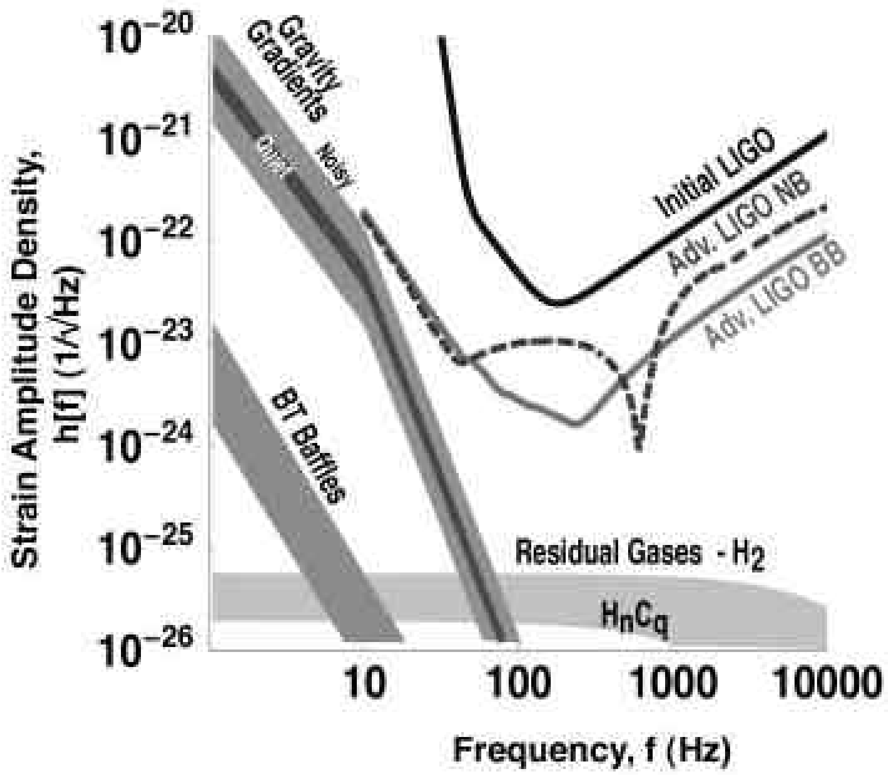
Advanced LIGO

GRAVITY GRADIENTS: the band of gravity gradient noise during quiescent times and during noisier times. Improvements below these limits are possible by taking suitable measures to change the local surface topography to reduce the effects of Rayleigh surface waves and road noise. Hughes and Thorne (Phys.Rev. D58 (1998) 122002).

BEAM TUBE BAFFLES: the upper limit of the spectrum band corresponds to limits deduced from as-built baffles, BT vibration, and initial LIGO mirror properties.. The lower part of the band corresponds to mirrors having surface smoothness 10X better than initial LIGO.

RESIDUAL GASES: the upper limit of the band corresponds to 10^{-9} torr residual partial pressure of H_2 using all BT pump ports. The lower portion of the band corresponds to the partial pressure of higher mass hydrocarbons (AMU~100). Further pressure improvements are possible by taking suitable measures to continuously cool the BT walls thermoelectrically.

Limiting noise sources for LIGO facilities



- The initial LIGO sensitivity limits are everywhere at least 70x above the facilities limits. The curves labeled Adv. LIGO NB and BB correspond to the narrow-band and broad-band sensitivities of candidate next generation LIGO interferometers.

LIGO

LSC

Aug 2000

LSC Collaboration

- LIGO I and LIGO II
- Council Members
- access to data
- authorship of paper

Non-LSC

- visitors
- collaborations with data exchange
  - -astronomers
  - -interferometers

Institution	Heads	FTE	IGO I Heac	LIGO I FTE
ACIGA	22	13.5	0	0
Caltech - CACR	3	0.7	3	0.7
Caltech - CaRT	6	2.4	1	0.4
Caltech - CEGG	2	1.6	1	0.4
Cal. State Dominguez Hills	4	1.9	4	1.9
Carleton University	1	0.8	1	0.8
Cornell	3	2.6	3	2.6
GEO 600	57	47.7	57	30.5
Harvard-Smithsonian	2	1.3	2	1.3
Inst. of Applied Physics - R	9	6.5	0	0
Inter-University Centre for	5	2.2	5	2.2
Iowa State University	1	0.5	0	0
JILA (Univ. of Colorado)	5	1.5	0	0
Louisiana Tech	4	1	4	1
LSU	10	5.8	9	4
Moscow State University	9	9	0	0
NAOJ - TAMA	5	2	0	0
Oregon University	8	5.1	8	5.1
Penn State	6	5.3	5	3.6
Stanford University	18	11.7	0	0
Syracuse University	5	5	2	1
University of Florida	13	10.3	13	8.8
University of Michigan	4	2.8	4	2.8
University of Texas - Brow	4	2.5	4	2.5
University of Wisconsin-Mi	8	5	8	5
Total: Non-LIGO Laborator	**214**	**148.7**	**134**	**74.6**
LIGO Hanford	20	20	20	20
LIGO Livingston	13	13	13	13
LIGO MIT	15	15	15	15
LIGO Caltech	63	63	63	63
Total: LIGO Laboratory	**111**	**111**	**111**	**111**
Total: LSC	**325**	**259.7**	**245**	**185.6**

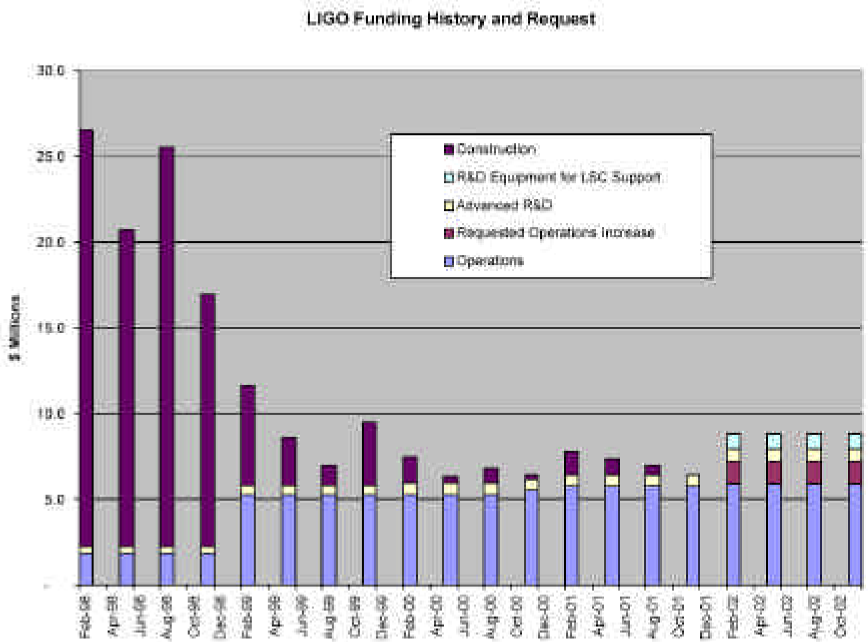
Highlights

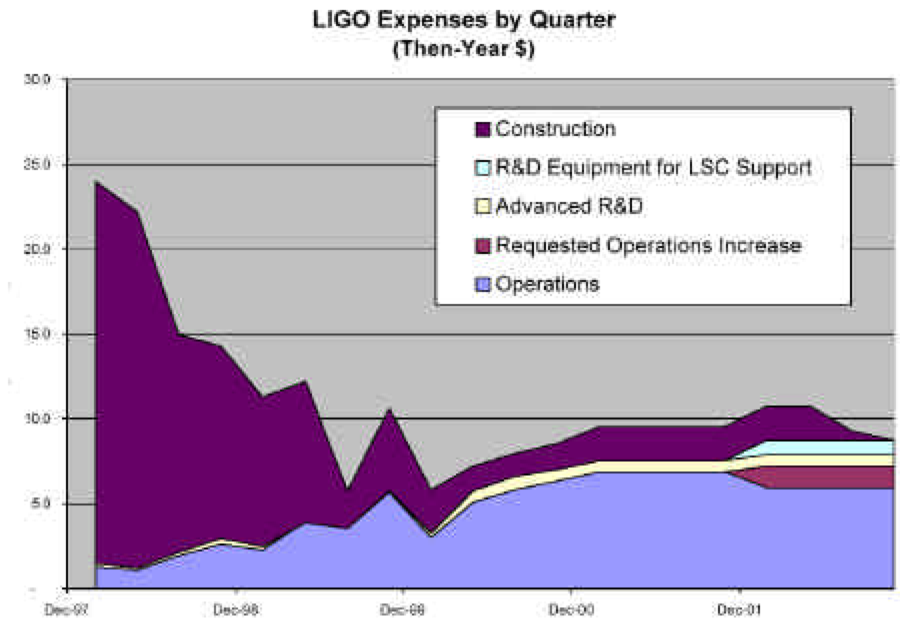
since last PAC mtg

- A "24-hour" engineering data run [E1] was carried out using the single 2 km arm
- The 2K in-chamber installation complete at LHO (May 2000)
- The Laboratory decided to support the "stiff" technical approach for further LIGO II development. (June 2000)
  - » **Technical Review Report to Lab Directorate + Decision Memo**
- First fringes were seen from a recycled Michelson in LHO corner station (June 2000)
- LHO 2K power recycled Michelson locked and y-arm end test mass illuminated (July 2000)
- Mock Data Challenge - LSC (August 2000)
- First Lock – October 2000
- [E2] Engineering Run – November 2000

LIGO Operations Renewal

Budget Requests





	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**

Incremental Support for LSC R & D

- the magnitude of the planned research for the LIGO upgrade requires more extra funds for equipment from LIGO Laboratory
- NSF panel recommended these large R&D be centrally managed
- costs are non-recurring.
- TOTAL request: $10.3M spread over FY02-04

- 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.
- Equipment costs for the development of a test mass, photon actuator prototype.

Requested Increment - Operations

•	Additional LIGO Scientific Collaboration (LSC) support at the sites. Visitor activity at the sites has increased dramatically during the Engineering runs.	$254,678
•	Fast network connections (WAN OC3) as recommended by an NSF review panel.	$540,500
•	Annual equipment maintenance and replacement. LIGO is installing nearly $4 million of computing equipment for LIGO Data Analysis and Computing. The estimate assumes a 25 percent replacement rate per year plus overhead. The missing budget was recommended by an NSF review panel.	$1,378,728
•	Annual replacement and maintenance of the control room data acquisition and control hardware plus overhead. The estimated value of the computer and network infrastructure at both sites is $3 million (10 percent maintenance and replacement costs). The estimated value of the custom electronics and embedded computers is also $3 million (5 percent maintenance and replacement costs).	$513,800
•	Additional staffing and stipends to support Outreach Programs at the sites.	$249,848
•	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
•	Increased support staff for Modeling and Simulation Group. The increase was suggested by an NSF Review panel.	$282,485
•	Additional staff for site Operations. This includes two FTEs at each of the sites to support seven day-per-week, twenty-four hour per day Operation of the interferometers with adequate coverage consistent with experience to date and the recommendations of our safety review panels. In addition three site FTEs are for LDAS and CDS maintenance, and two partial Post Doctoral positions are proposed in partnership with the University of Florida and Southern Louisiana University.	$558,485
•	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

Conclusions

- **Good progress over past six months**
  - » **construction project nearly complete**
  - » **technical decision on seismic/suspension system for advanced LIGO detector**
  - » **first mock data challenge was performed**
  - » **full interferometer has been locked**
  - » **successful one week engineering run with recombined interferometer with large LSC support**
- **Next months**
  - » **review of LIGO renewal proposal**
  - » **lock LLO interferometer**
  - » **first coincidence engineering run**