LIGO

Introduction

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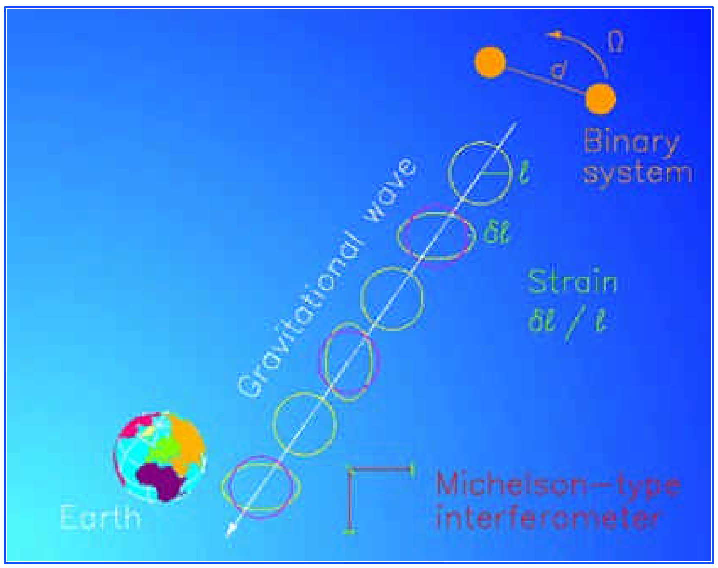
Operations Proposal Review
NSF Operations Subpanel
February 26, 2001

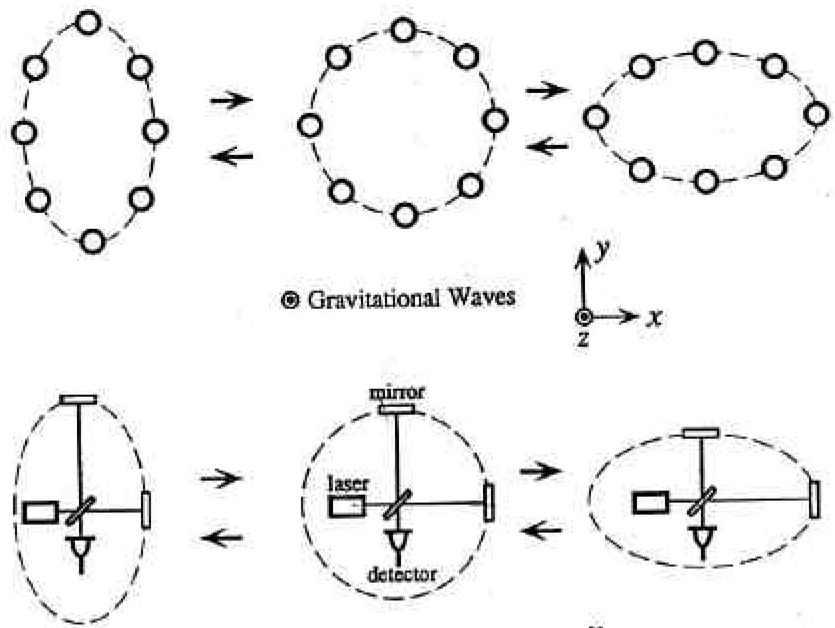
LIGO-G010036-00-M

Interferometers
terrestrial

Suspended mass Michelson-type interferometers on earth's surface detect distant astrophysical sources

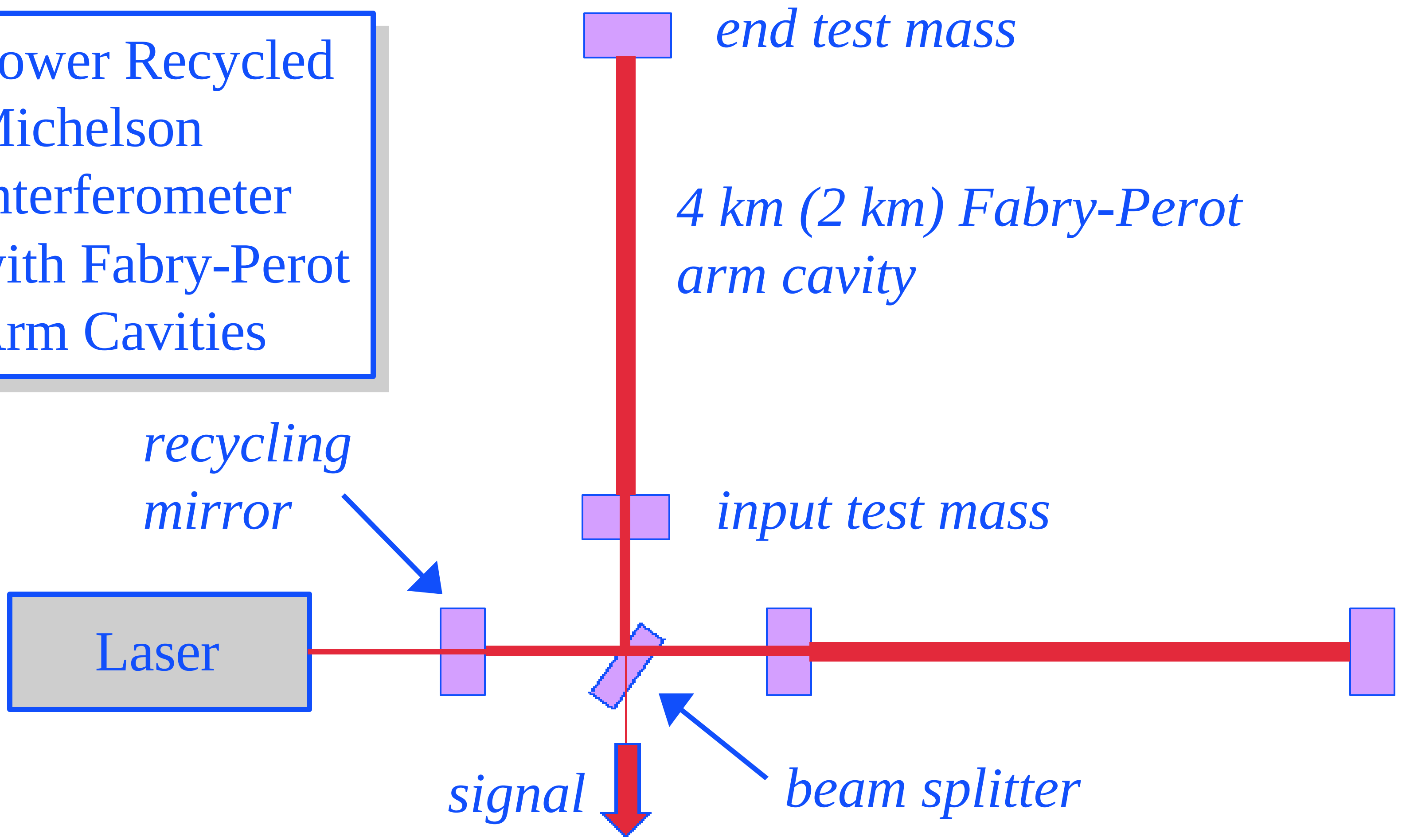
International network (LIGO, Virgo, GEO, TAMA) enable locating sources and decomposing polarization of gravitational waves.





LIGO Interferometers

Power Recycled Michelson Interferometer with Fabry-Perot Arm Cavities

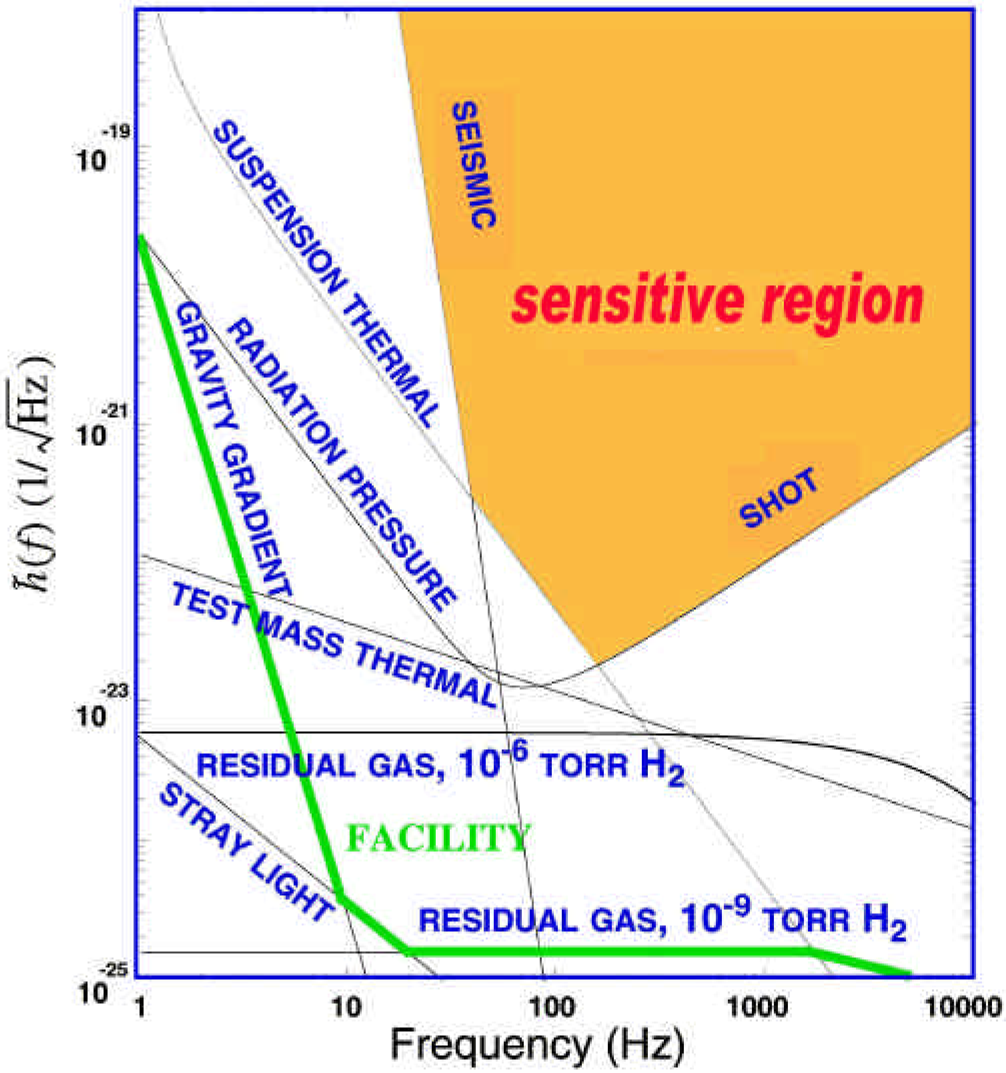


LIGO I

the noise floor

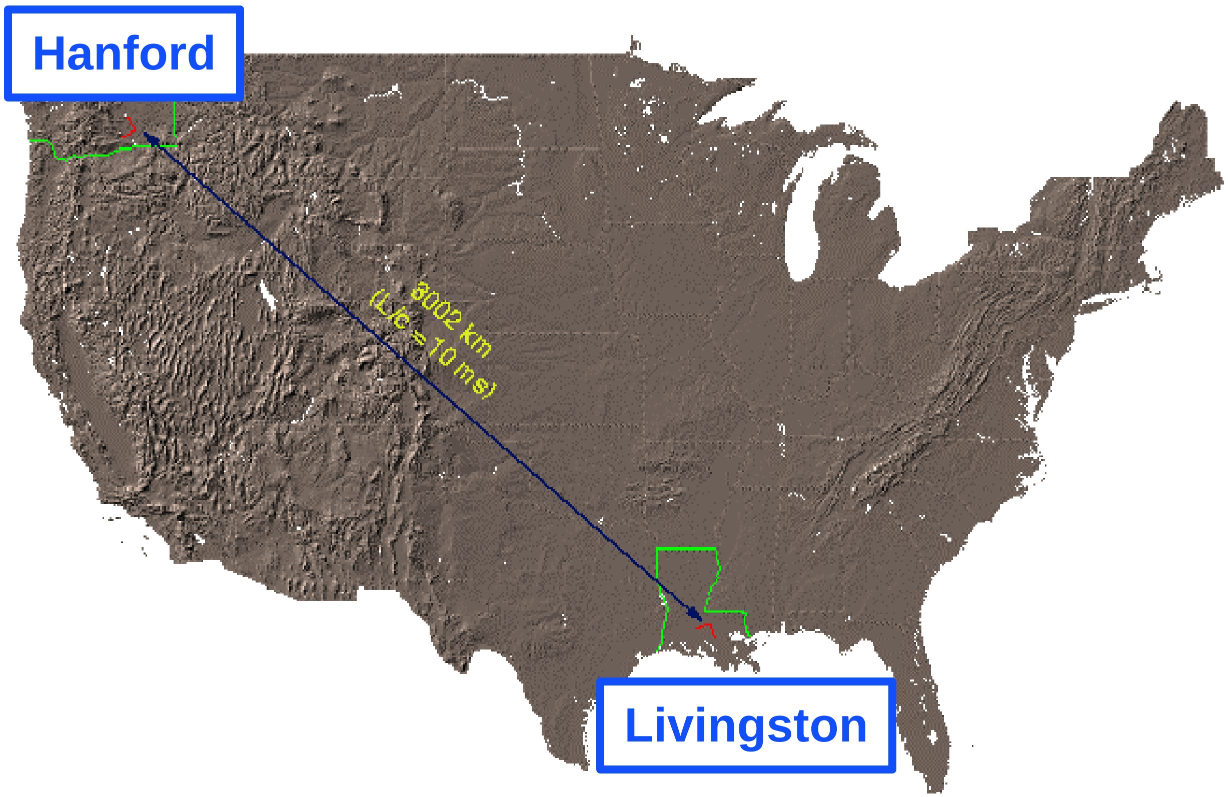
- **Interferometry is limited by three fundamental noise sources**
  - **seismic noise at the lowest frequencies**
  - **thermal noise at intermediate frequencies**
  - **shot noise at high frequencies**

- **Many other noise sources lurk underneath and must be controlled as the instrument is improved**



▪Two Sites - Three Interferometers

- »**Single Interferometer** non-gaussian level
  ~50/hr
- »**Hanford (Doubles)** correlated rate (x1000)
  ~1/day
- »**Hanford + Livingston** uncorrelated (x5000)
  <0.1/yr



Coincidences between LLO & LHO

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 LIGO I Science Run)
2003+	LIGO I data run	(one year integrated data at $h \sim 10^{-21}$)
2006+	Begin ‘advanced’ LIGO installation	

Budget History

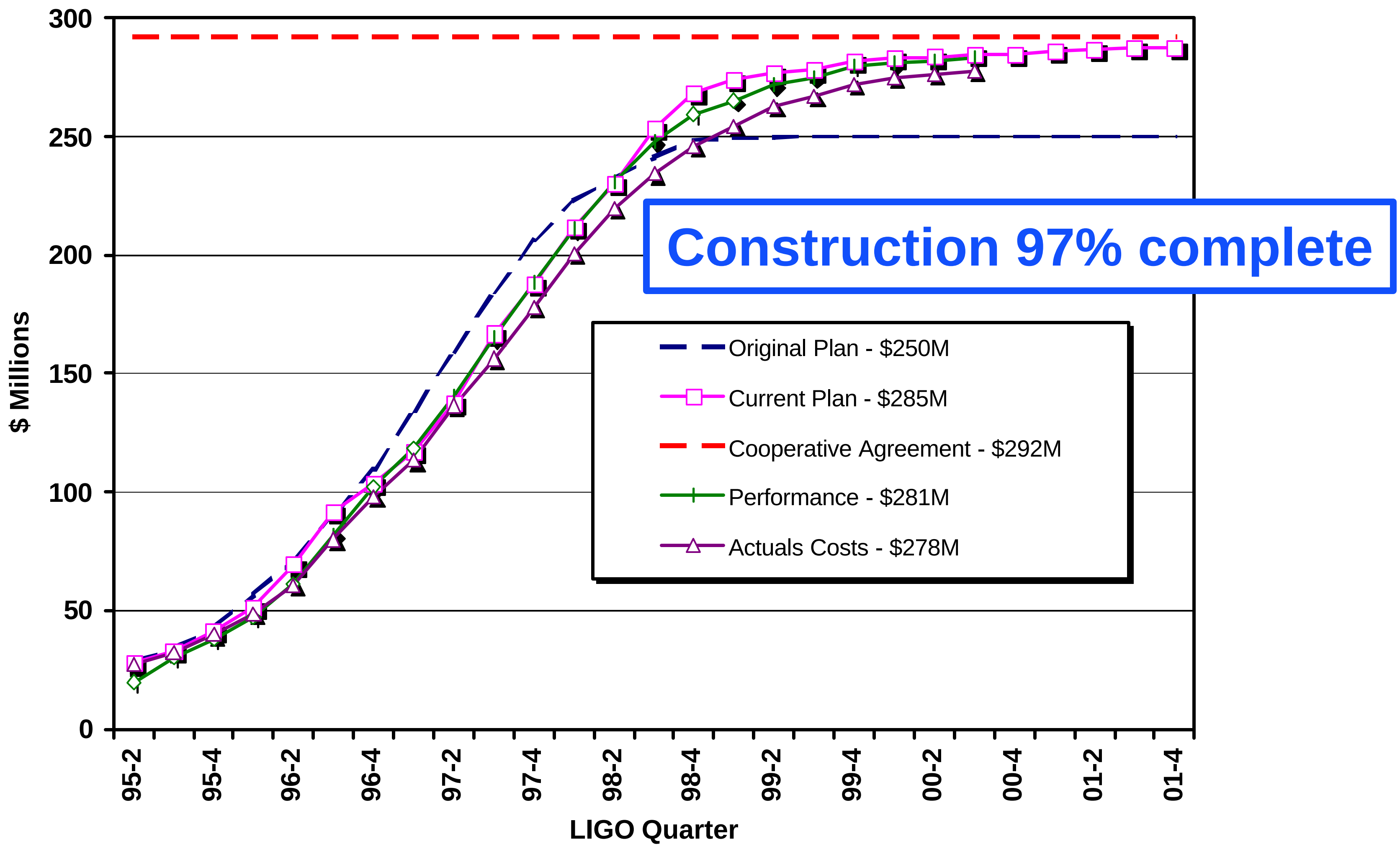
MRE Funds

Fiscal Year	Construction ($M)	R&D ($M)	Operations ($M)	Advanced R&D ($M)	Total ($M)
1992 - 94	35.90	11.19	-	-	47.09
1995	85.00	3.95	-		88.95
1996	70.00	2.38	-		72.38
1997	55.00	1.62	0.30	0.80	57.72
1998	26.00	0.86	7.30	1.82	35.98
1999	0.20	-	20.78	2.28	23.26
2000	-	-	21.10	2.60	23.70
2001	-	-	19.10 (10 Months) **22.92 (12 Months)**	**2.70**	21.80 **25.6 (12 Months)**
Total	272.10	20.00	68.58	10.20	370.88

Construction Project **Operations**

LIGO Project

construction and related R&D costs



LIGO

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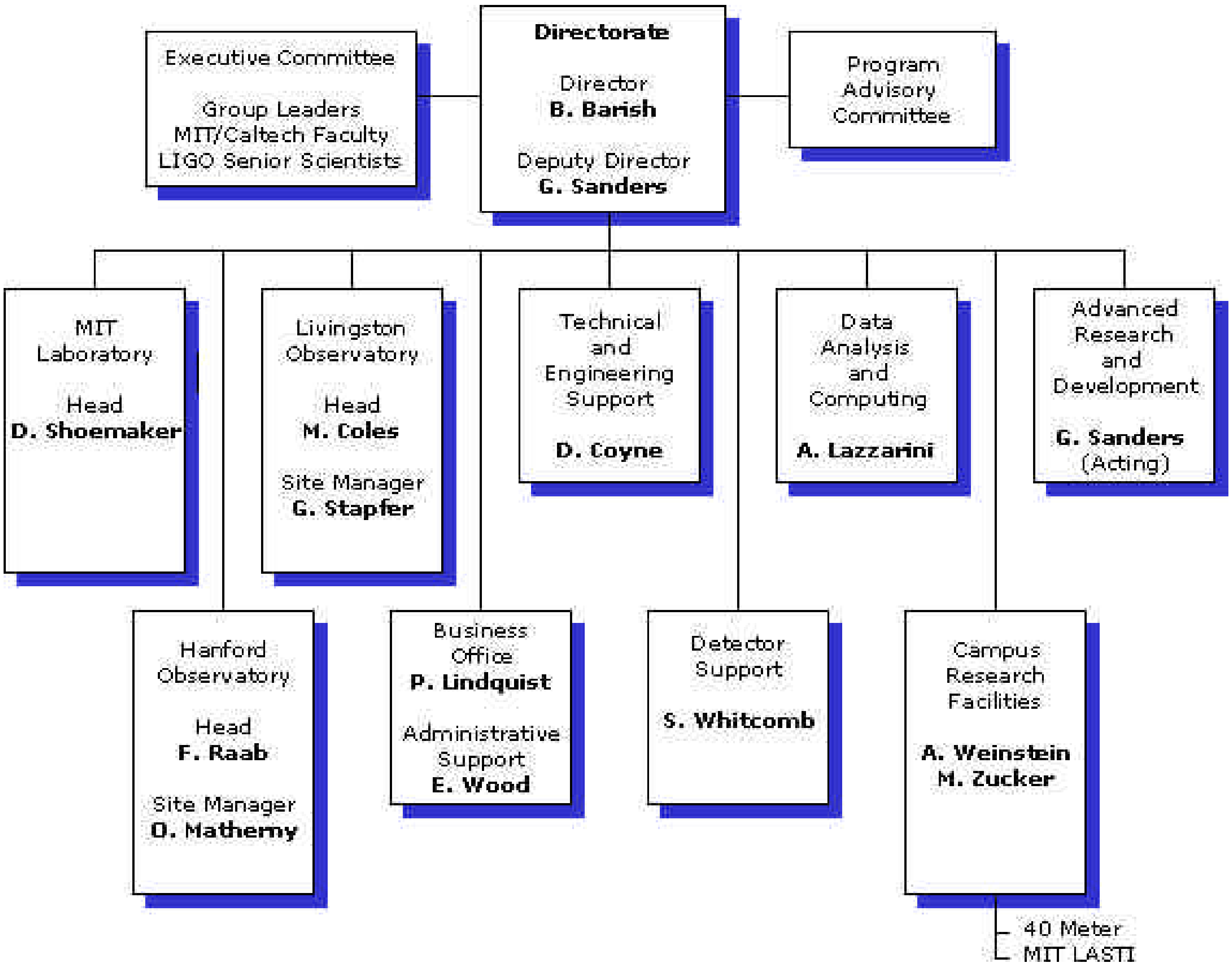
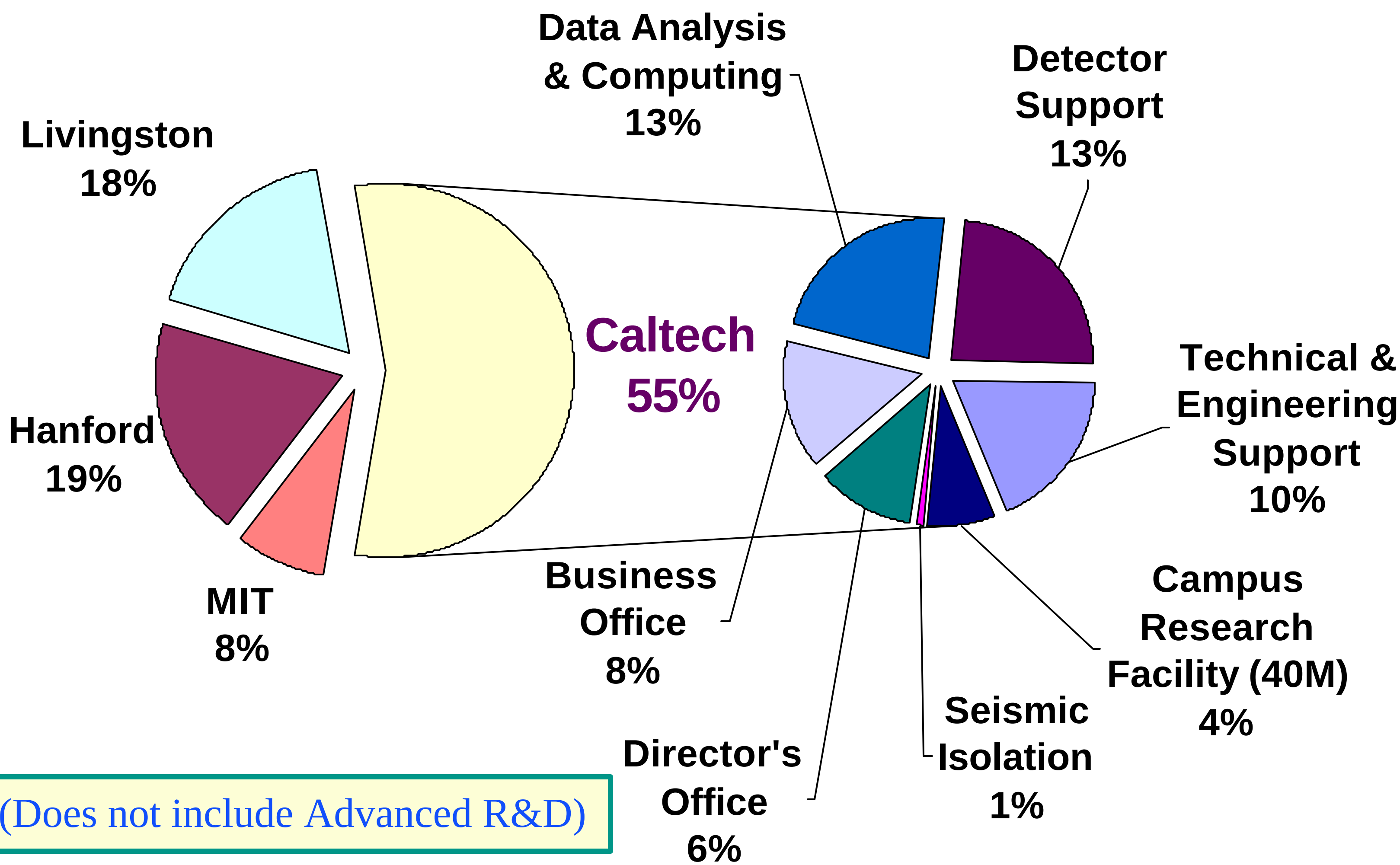
Construction Project (Construction, R&D) — **Operations** (Operations, Advanced R&D)

LIGO Laboratory Organization

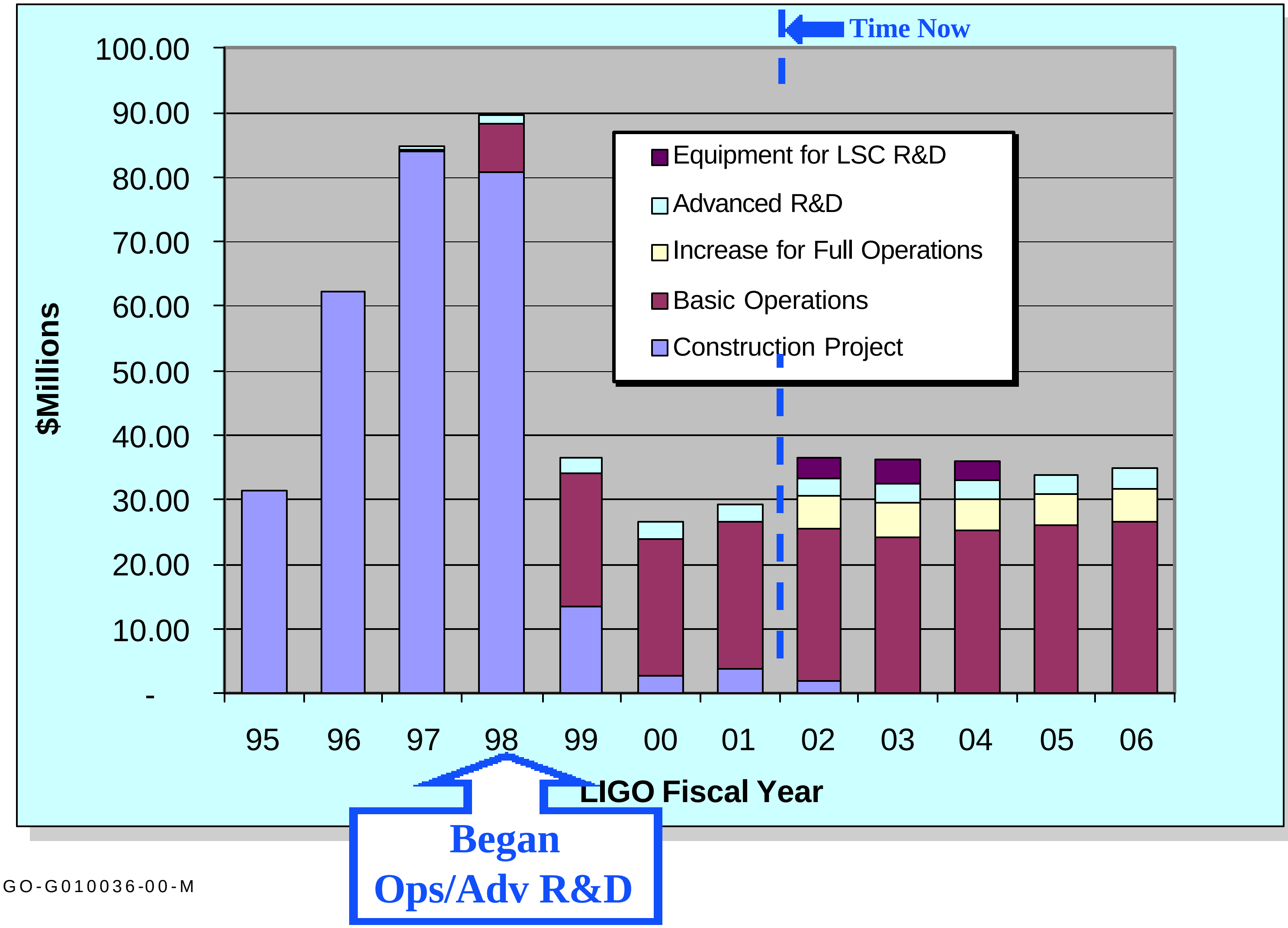


FY 2000 Expenses



(Does not include Advanced R&D)

Funding History and Request



LIGO
funding request

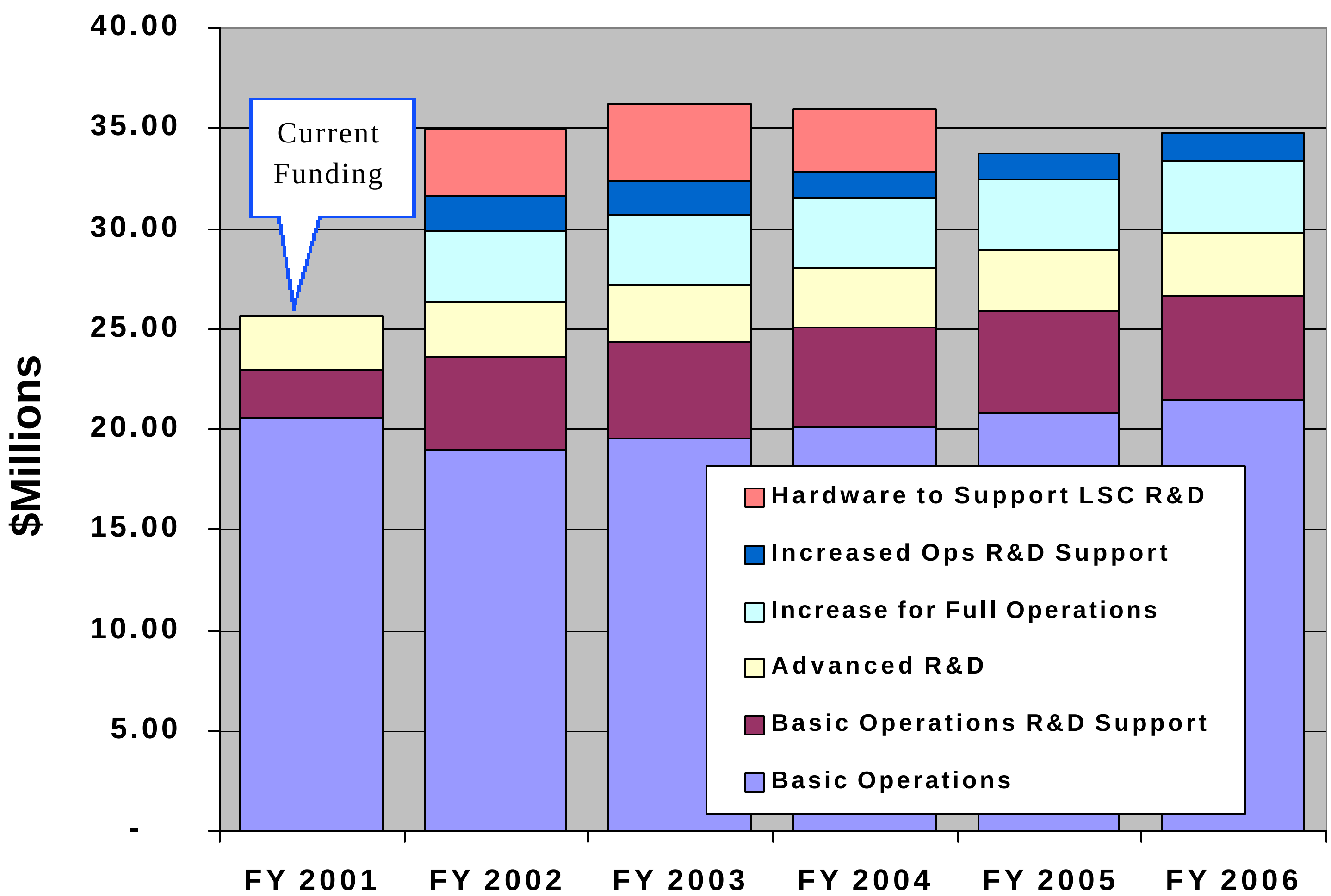
	FY 2001 ($M)	FY 2002 ($M)	FY 2003 ($M)	FY 2004 ($M)	FY 2005 ($M)	FY 2006 ($M)	Total 2002-6 ($M)
Currently funded Operations	22.92	23.63	24.32	25.05	25.87	26.65	125.52
Increase for Full Operations		**5.21**	**5.20**	**4.79**	**4.86**	**4.95**	**25.01**
Advanced R&D	2.70	2.77	2.86	2.95	3.04	3.13	14.76
R&D Equipment for LSC Research		**3.30**	**3.84**	**3.14**			**10.28**

FY 2001 currently funded Operations ($19.1M for ten months) is normalized to 12 months and provided for comparison only and is not included in totals.

Increase for Full Operations

Budget Category		Increase	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006
Basic Operations							
	*	CDS Hardware Maintenance	513,800	502,434	517,507	533,032	549,023
	*	LDAS Maintenance	1,378,728	1,378,728	1,322,235	1,303,163	1,303,163
		Outreach	249,848	257,343	265,063	273,015	281,206
	*	Site Operations	558,485	575,240	592,497	610,272	628,580
		Telecommunications / Networking	540,500	542,200	542,200	539,500	539,500
		Staff for Site LSC Support	254,678	262,318	270,187	278,293	286,642
Basic Operations Totals			**3,496,039**	**3,518,263**	**3,509,689**	**3,537,275**	**3,588,114**
Operations Support of Advanced R&D							
		Seismic Development	506,300	434,574			
	*	Engineering Staff	920,868	948,494	976,949	1,006,257	1,036,445
		Simulation & Modeling Staff	282,485	293,949	305,614	317,772	330,617
R&D Total			**1,709,652**	**1,677,017**	**1,282,562**	**1,324,029**	**1,367,062**
Grand Total			**5,205,691**	**5,195,280**	**4,792,252**	**4,861,304**	**4,955,176**

* Need recognized by NSF panel



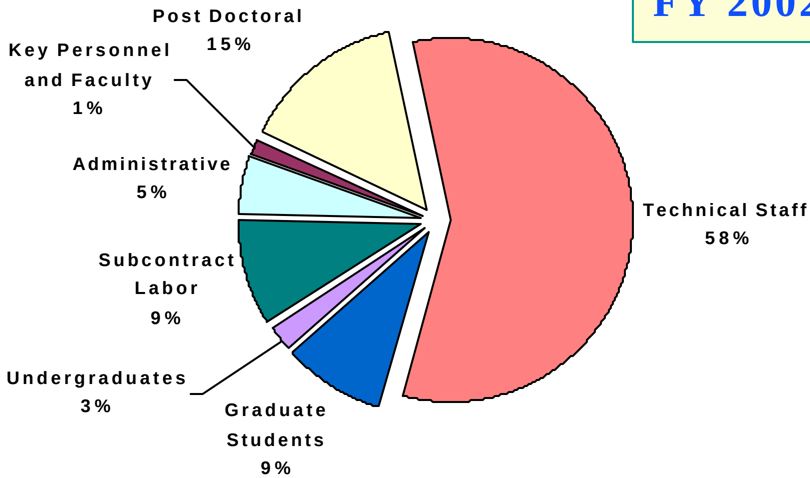
FY 2001 funding normalized to 12 months shown for comparison

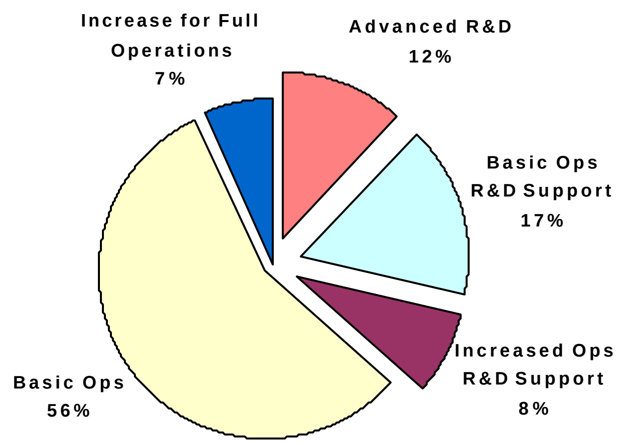
Staffing

Category	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006
Key Personnel / Faculty	2.6	2.6	2.6	2.6	2.6
Post Doctoral	27.0	27.0	26.0	26.0	26.0
Technical Staff	104.7	105.7	101.7	102.7	102.7
Graduate Students	18.0	17.0	17.5	17.5	17.5
Undergraduate	4.9	4.9	4.9	4.9	4.9
Subcontract Labor	17.0	17.0	17.0	16.0	16.0
Administrative	9.9	9.9	9.9	9.9	9.9
Grand Total	**184.1**	**184.1**	**179.6**	**179.6**	**179.6**

Numbers shown Are Full Time Equivalent Employees (FTEs) actually charged

FY 2002





LIGO
civil construction

LIGO (Washington)

LIGO (Louisiana)

LIGO

vacuum chambers

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 !!

LIGO Facilities

beam tube enclosure

- minimal enclosure
- reinforced concrete
- no services

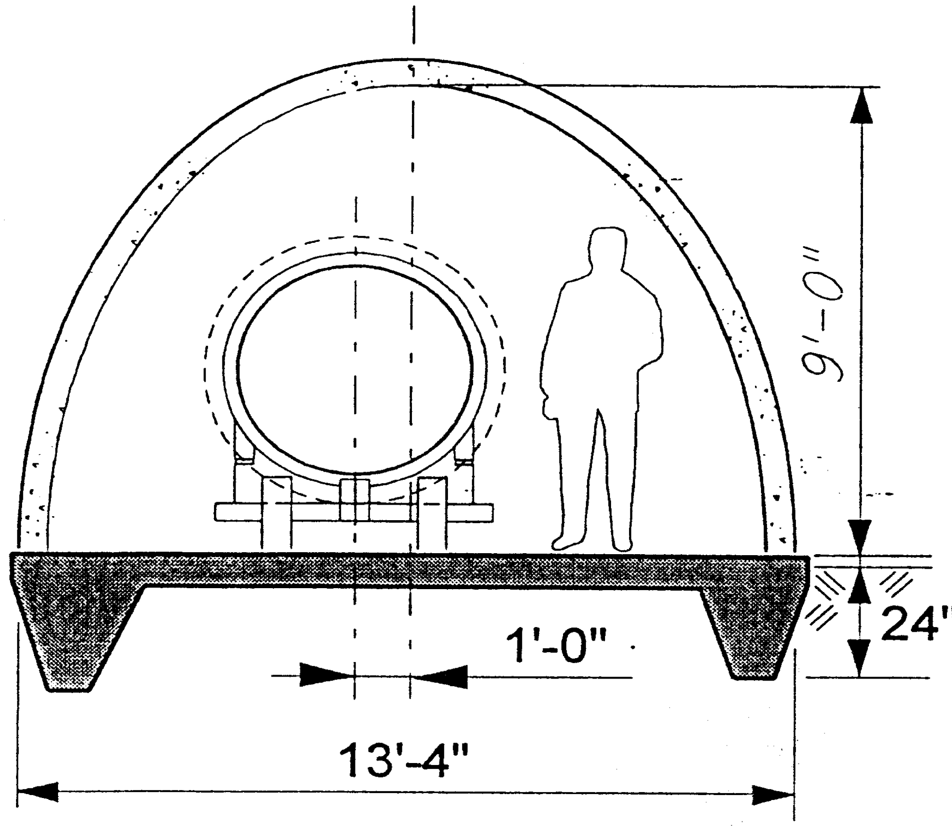
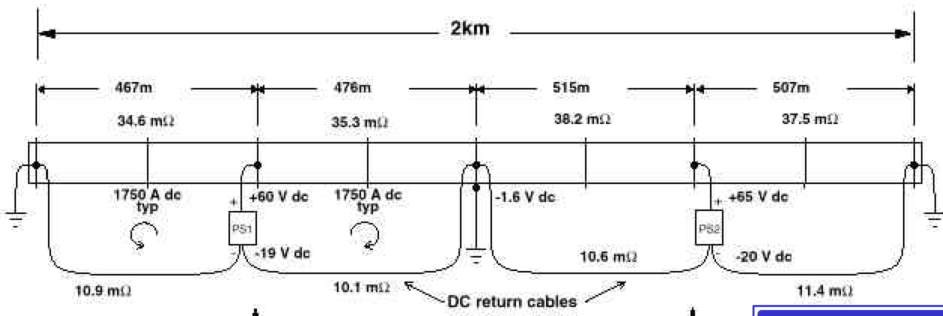


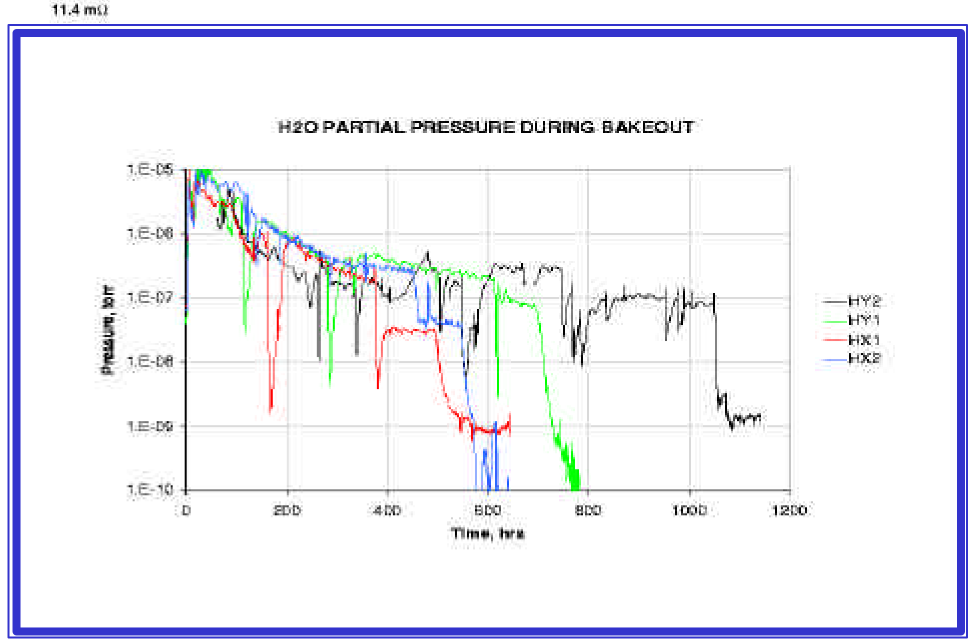
Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

Beam Tube

bakeout

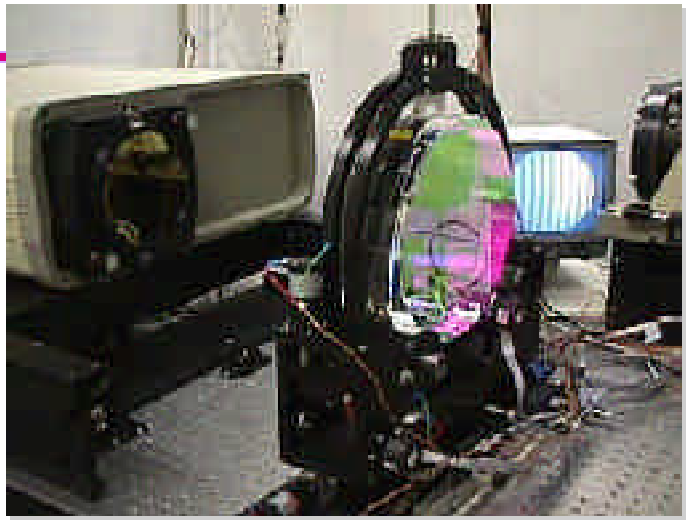


- I = 2000 amps for ~ 1 month
- no leaks !!
- final vacuum at level where it is not source of limiting noise (even future detectors)



Core Optics

fused silica



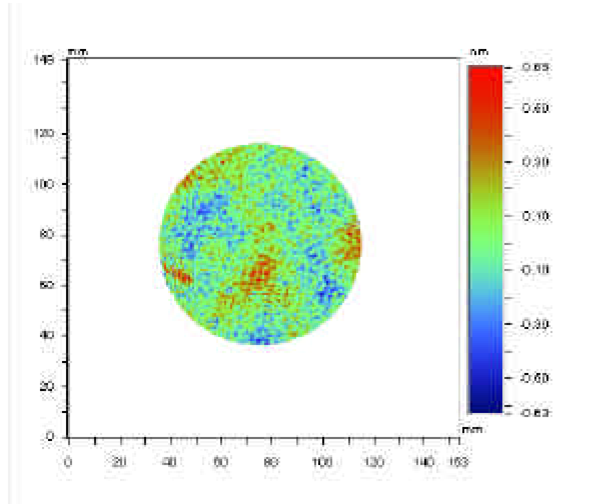
LIGO requirements

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

LIGO measurements

- central 80 mm of 4ITM06 (Hanford 4K)
- rms = 0.16 nm
- optic far exceeds specification.

Surface figure = λ / 6000



Date: 10/17/2000
Time: 09:26:37
Wavelength: 1.064 um
Pupil: 100.0 %
PV: 1.2818 nm
RMS: 0.1620 nm
Rad of curv: 14.053 km

X Center: 283.00
Y Center: 244.00
Radius: 150.00 pix
Terms: Tilt Power Astig
Filters: None
Masks: Analysis 4.0 Sigma Masks
Ref Sub:
Averages:

Core Optics

installation and alignment

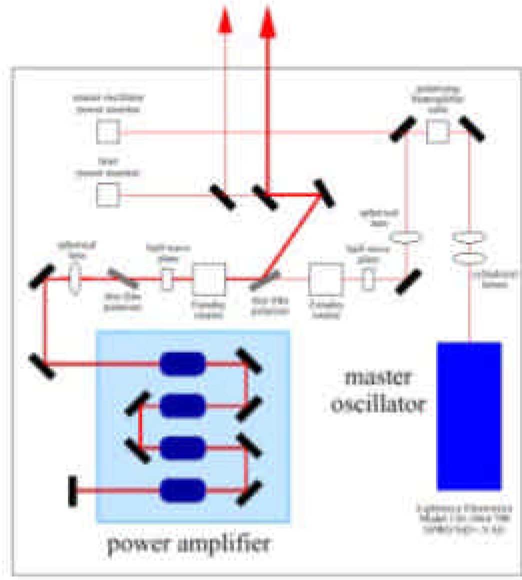
Commissioning
configurations

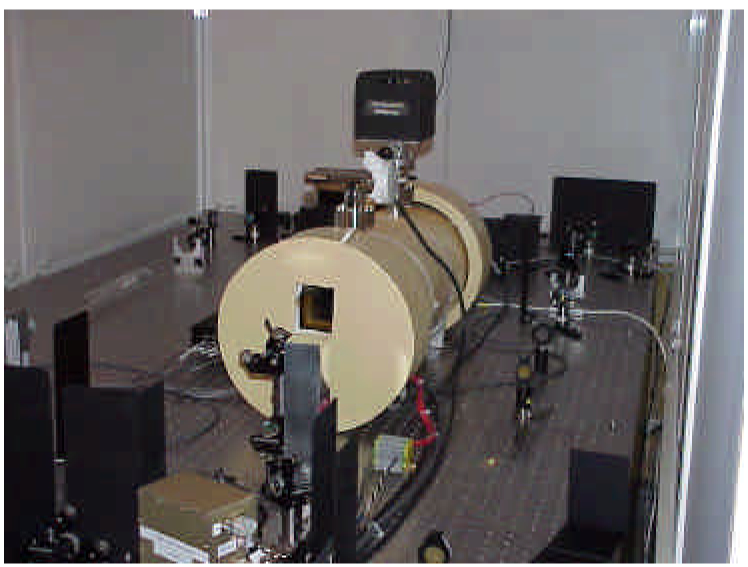
- Mode cleaner and Pre-Stabilized Laser
- 2km one-arm cavity
- short Michelson interferometer studies

- Lock entire 2km Michelson Fabry-Perot interferometer with Power Recycling (Hanford)
  - » **First lock – Oct 00**
  - » **Robust locking – Jan 01**
- Lock one 4km arm (Livingston)
  - » **First single long arm – Jan 01**

LIGO
laser

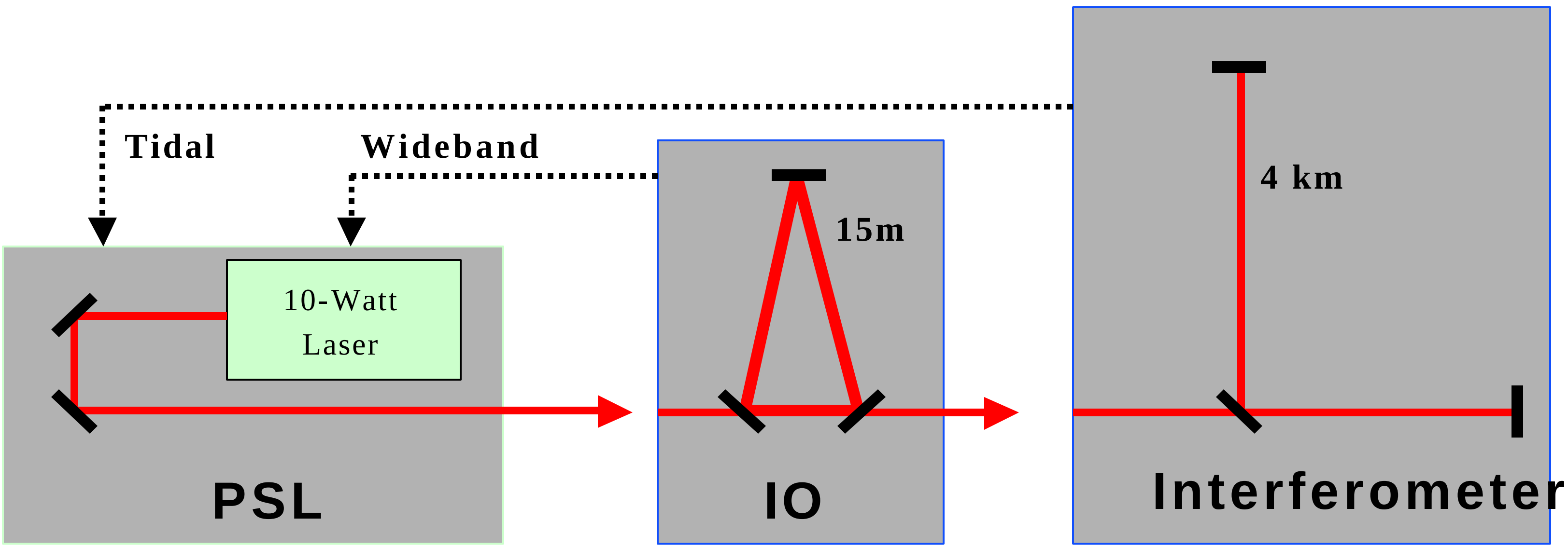
- **Nd:YAG**
- **1.064 μm**
- **Output power > 8W in TEM00 mode**





Laser *stabilization*

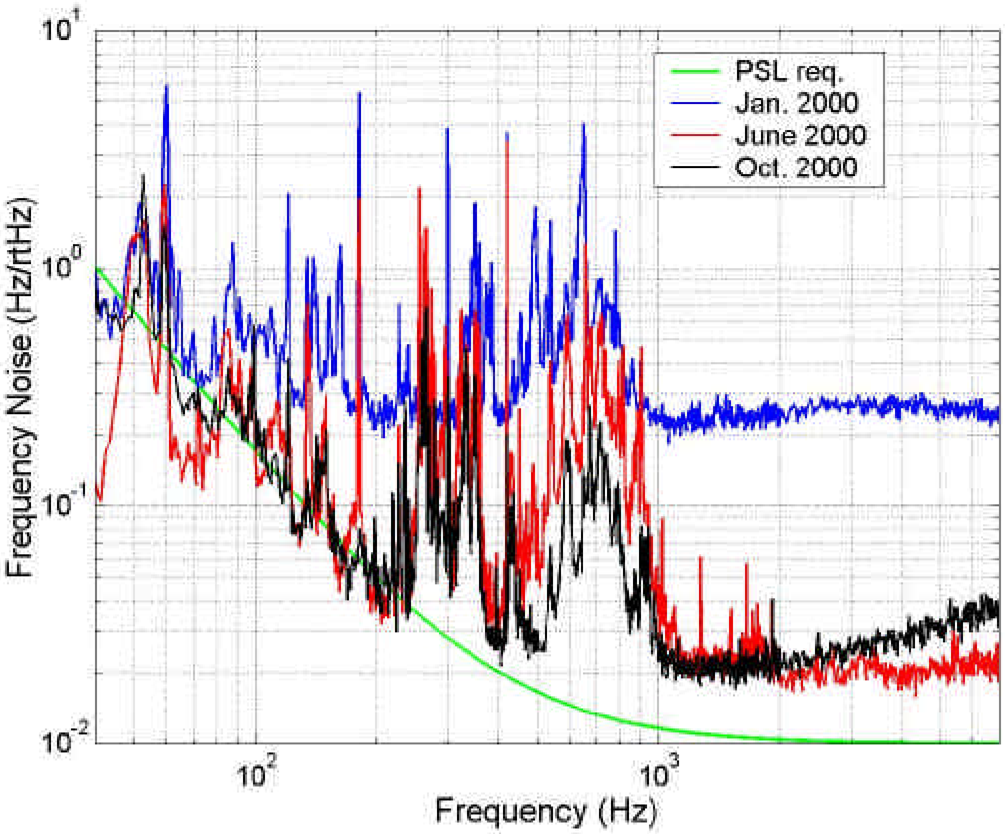
- **Deliver pre-stabilized laser light to the 15-m mode cleaner**
  - Frequency fluctuations
  - In-band power fluctuations
  - Power fluctuations at 25 MHz
- **Provide actuator inputs for further stabilization**
  - Wideband
  - Tidal



10^{-1} Hz/Hz$^{1/2}$ 10^{-4} Hz/ Hz$^{1/2}$ 10^{-7} Hz/ Hz$^{1/2}$

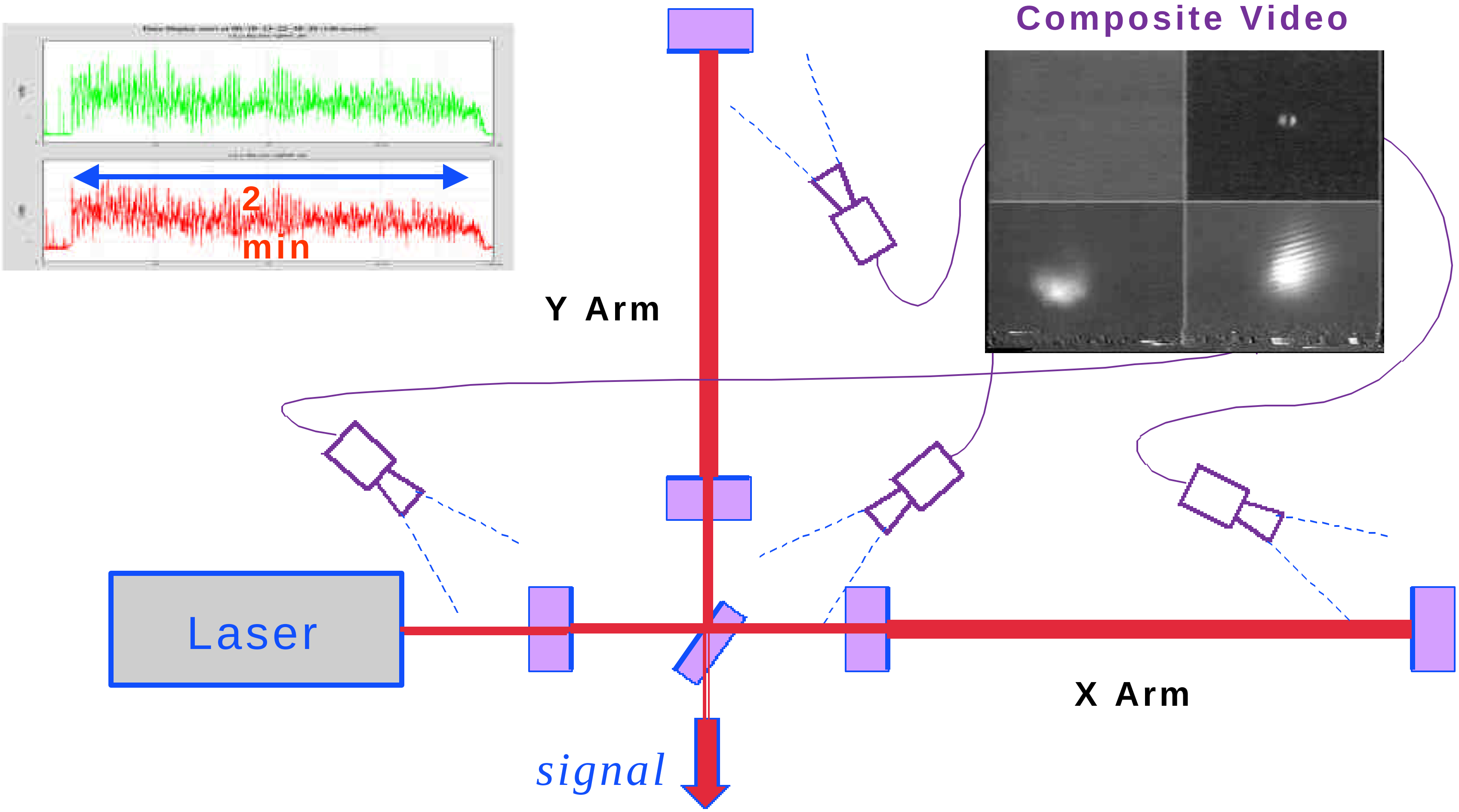
Pre-stabilized Laser

performance



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

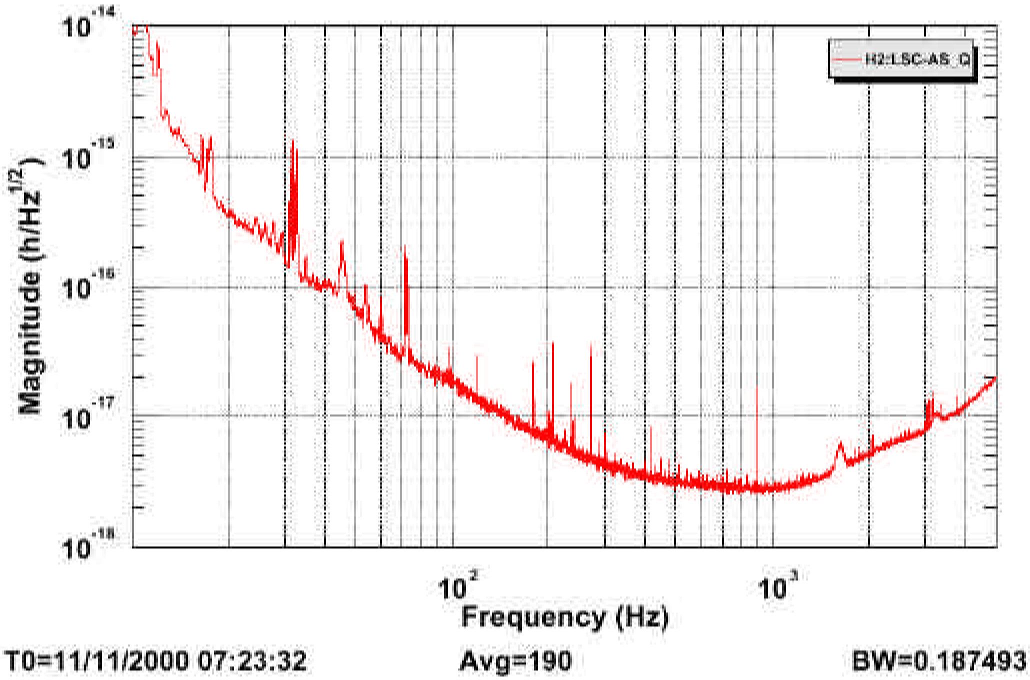
LIGO
first lock



Strain Sensitivity

Nov 2000

2-km Hanford Interferometer



- operating as a Michelson with Fabry-Perot arms
- reduced input laser power on the beam splitter (about 3 mW)
- without recycling
- noise level is a factor of 10^4-10^5 above the final specification
- sources of excess noise are under investigation

Significant Events

Hanford 2km interferometer	➢ Single arm test complete ➢ installation complete ➢ interferometer locked ➢ robust locking	6/00 8/00 10/00 1/01
Livingston 4km interferometer	➢ Input Optics completed ➢ interferometer installed ➢ short Michelson locked ➢ interferometer locked	7/00 10/00 1/01 3/01
Coincidence Engineering Run Hanford 2km& Livingston 4km	➢ Initiate (Upper Limit Run) ➢ Complete Engineering Runs	9/01 7/02
Hanford 4km interferometer	➢ All in-vacuum seismic installed ➢ interferometer installed ➢ interferometer locked	1/00 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

steps prior to science run

- **commissioning interferometer**
  - » **robust locking**
  - » **three interferometers**
  - » **sensitivity**
  - » **duty cycle**

- **interleave engineering runs (LSC)**
  - » **implement and test acquisition and analysis tools**
  - » **characterization and diagnostics studies**
  - » **reduced data sets**
  - » **merging data streams**
  - » **upper limits**

LIGO Scientific Collaboration
LSC

- **The LIGO Laboratory**
  - » **MIT, Caltech, LHO and LLO groups operating as one integrated organization.**
  - » **maintains the fiduciary responsibility for LIGO and is responsible for operations and improvements.**

- **The LIGO Scientific Collaboration**
  - » **The underlying principle in the organization is to present “equal scientific opportunity” to all collaborators.**
    - – **LSC has developed its own governance, elects its own leadership, and sets its own agenda.**
    - – **The LSC has an elected spokesman, has an executive committee, collaboration council and several working groups in different research areas and generally operates independently of the LIGO Laboratory management..**
    - – **The scientific research of the LIGO Laboratory staff is carried out through the LSC.**

LIGO Scientific Collaboration

LSC

- **LIGO is available to all interested researchers through participation in the LSC, an open organization.**
  - » **a research group defines a research program with the LIGO Laboratory through the creation of a Memorandum of Understanding (MOU) and relevant attachments**
  - » **When the group is accepted into the LSC it becomes a full scientific partner in LIGO**

LIGO Scientific Collaboration

Member Institutions

LSC Membership

35 institutions > 350 collaborators

University of Adelaide ACIGA	LIGO Livingston LIGOLA
Australian National University ACIGA	LIGO Hanford LIGOWA
California State Dominquez Hills	Louisiana State University
Caltech LIGO	Louisiana Tech University
Caltech Experimental Gravitation CEGG	MIT LIGO
Caltech Theory CART	Max Planck (Garching) GEO
University of Cardiff GEO	Max Planck (Potsdam) GEO
Carleton College	University of Michigan
Cornell University	Moscow State University
University of Florida @ Gainesville	NAOJ - TAMA
Glasgow University GEO	University of Oregon
University of Hannover GEO	Pennsylvania State University Exp
Harvard-Smithsonian	Pennsylvania State University Theory
India-IUCAA	Southern University
IAP Nizhny Novgorod	Stanford University
Iowa State University	University of Texas@Brownsville
Joint Institute of Laboratory Astrophysics	University of Western Australia ACIGA
	University of Wisconsin@Milwaukee

International

India, Russia, Germany, U.K, Japan and Australia.

The international partners are involved in all aspects of the LIGO research program.

GWIC

Gravitational Wave International Committee

Science in LIGO I

LSC data analysis

- **Compact binary inspiral:** *"chirps"*
  - » NS-NS waveforms are well described
  - » BH-BH need better waveforms
  - » search technique: matched templates
- **Supernovae / GRBs:** *"bursts"*
  - » burst search algorithms – excess power; time-freq patterns
  - » burst signals - coincidence with signals in E&M radiation
  - » prompt alarm (~ 1 hr) with ν detectors [SNEWS]
- **Pulsars in our galaxy:** *"periodic"*
  - » search for observed neutron stars (freq., doppler shift)
  - » all sky search (computing challenge)
  - » r-modes
- **Cosmological Signals** *"stochastic background"*

Inspiral Sources

LSC Upper Limit Group

Inspiral Sources   Co-chair   P Brady, G Gonzalez

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Data & Computing Group

engineering & science runs

» **Simulation & Modeling:**
  - detector support
  - data analysis

» **Data Management**
  - movement of large volumes of data
  - archive

» **Data Analysis**
  - pipeline analyses running
  - participation in analysis teams

» **Software**
  - maintenance/improvements/enhancements

» **LSC support**

» **LIGO Lab IT support**

LIGO I Science Run

Data Analysis Model

- Astrophysical searches : follow plan in the LSC Data Analysis White Paper – http://www.ligo.caltech.edu/LIGO_web/lsc/lsc.html
  - » organized around teams as in near-term upper limit studies
  - » open to all LSC members contributing to LIGO I
- LDAS resources to be shared among the teams
- LSC institutional resources used by individuals
- Longer term
  - » distributed computing LIGO/LSC Tier 2 centers – GriPhyN
  - » LSC open to researchers wanting access to LIGO data

LIGO I

science run

- **Strategy**
  - » initiate science run when good coincidence data can be reliably taken and straightforward sensitivity improvements have been implemented (~ 7/02)
  - » interleave periods of science running with periods of sensitivity improvements

- **Goals**
  - » obtain 1 year of integrated data at $h \sim 10^{-21}$
    - – searches in coincidence with astronomical observations (eg. supernovae, gamma ray bursts)
    - – searches for known sources (eg. neutron stars)
    - – stand alone searches for compact binary coalescence, periodic sources, burst sources, stochastic background and unknown sources at $h \sim 10^{-21}$ sensitivities
  - » Exploit science at $h \sim 10^{-21}$ before initiating 'advanced' LIGO upgrades

LIGO Science

physics schedule

- **LIGO I (~2002-2006)**
  - LIGO I Collaboration of LSC
  - obtain data for one year of live time at $h \sim 10^{-21}$ (by 2005)
  - one extra year for special running or coincidences with Virgo

- **Advanced LIGO (implement ~2006+)**
  - broad LSC participation in R&D, design and implementation
  - design sensitivity $h \sim 10^{-22}$ (or better)
  - 2.5 hr will exceed <u>all</u> LIGO I (rate increase $\propto$ sensitivity cubed)

- **'Facility Limited' Detectors (> 2010 +)**
  - new optical configurations, new vacuum chambers, cryogenic, QND, etc
  - sensitivity $h \sim 10^{-23}$

LIGO
Outreach and Education

REU, teacher training, student researchers, minority programs, public lectures and educational materials