

# *LIGO*

## *Project Status Update*

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*LIGO Laboratory Caltech*

Rencontres de Moriond

24 - 30 January 1999

Les Arcs, Savoie - France



# Overview

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- Observatories
- Detector
- Data Analysis
- Simulation

# Project Status

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- Project is within budget and close to schedule
- Facility construction is complete
- Vacuum Equipment delivered and accepted - both observatories
  - Need correction of some hardware problems [large aperture gate valves]
- Beamtubes accepted - both observatories
  - BT Bakeout 50% complete at Hanford
- Detector design complete
- Detector fabrication in full swing
  - Major procurement contracts all in place
  - Many items being delivered daily
- Detector installation at Hanford underway
- Data analysis systems and simulation systems being implemented to support “first light”.

# LIGO Livingston Observatory (LLO)

*LIGO has left its mark on the planet...*



# LIGO Livingston Observatory (LLO)

## *Technical highlights*

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- Preparation for bake out of the beam tubes is underway: installation of thermocouples is in progress
  - *Insulation and electrical installation work for bakeout work will begin in summer 1999 and finish in Q2 2000.*
- Computer network has been installed with T1 connection via LSU
- Installation activities at LLO lag LHO by approximately 6-9 months because of the sequential nature of many of the construction and installation activities.
- Schedule Overview
  - *1999 - detector installation activities, with vertex Michelson shakedown anticipated to occur before year end*
  - *2000 - commissioning activities continue - Fabry-Perot arms added to the interferometer by mid-year and shakedown of the apparatus continuing for the remainder of the year.*
  - *Peter Saulson - Syracuse University, will be Commissioning Team Leader at LLO during this year.*
  - *2001 - Engineering run, in coincidence with Hanford*
  - *2002 - Science run*



# LIGO Livingston Observatory (LLO)

## *Vacuum Equipment*

- Vacuum equipment all baked and accepted - meet LIGO specifications

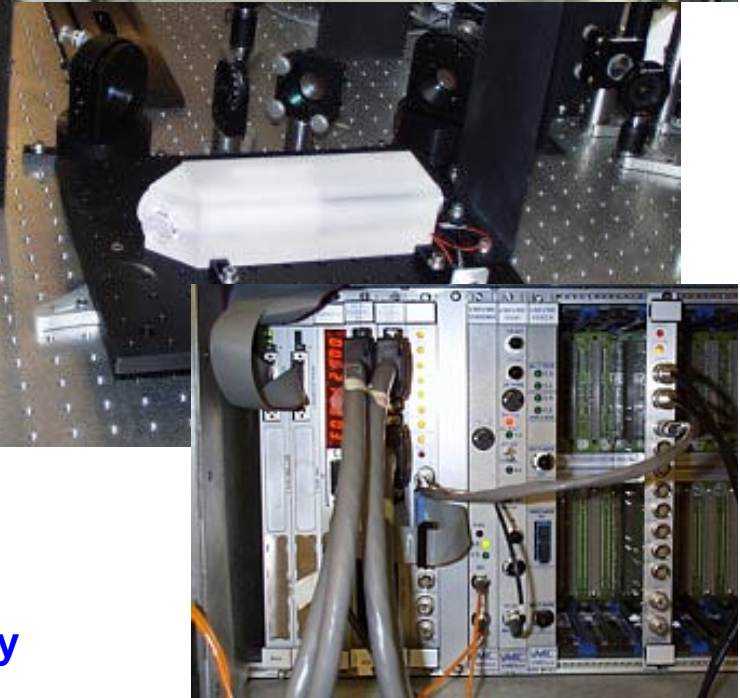
*>Need correction of large gate valve  
O-ring sticking problems*



# LIGO Hanford Observatory (LHO)

## *Technical highlights*

- Infrastructure complete - all contractors off- site
- >50% staffing; labs furnished & operational
- Science!
  - > 1<sup>st</sup> physics meetings [PAC & LSC]
  - > 1<sup>st</sup> student projects [4 REU students in '98]
- 2 BT modules baked, commissioned
- 1<sup>st</sup> 10W laser operational
- HAM Seismic System installation 75% complete
- BSC Seismic System installation initiated (pier surveys, etc.)
- Input Optics Suspensions 75% complete
- Input Optics insertion to begin 99.01.24
- 1<sup>st</sup> Core Optic [RM2K] suspension underway



# LIGO Hanford Observatory (LHO)

## *Beamtube Bakeout*

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- All equipment designed, built, operational.
- Y-arm completely baked at Hanford



- Proceeding to first half of X-arm



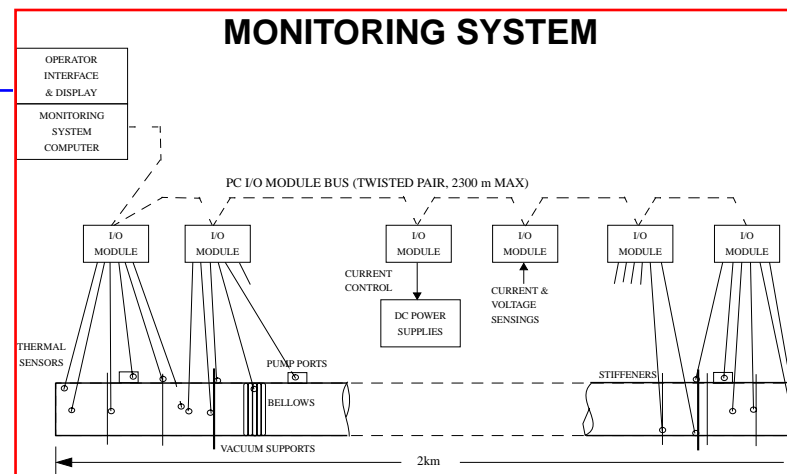
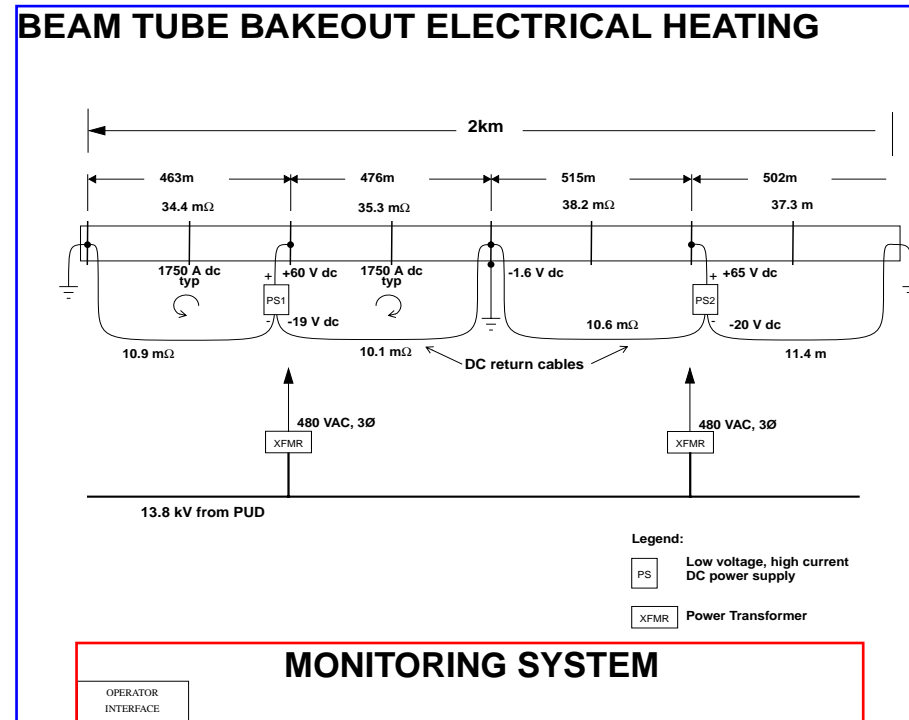
- Livingston in preparation for bake - insulation, instrumentation, etc.



# LIGO Hanford Observatory (LHO)

## Beamtube Bakeout

- BT bakeout uses ohmic [DC] heating of 304L SS BT wall
- ~1500 - 2000 A [depends of ambient conditions]
- ~ 600 sensors along 2km module
  - thermocouples
  - pressure
  - strain gauges
  - RGA
  - cryopump controllers



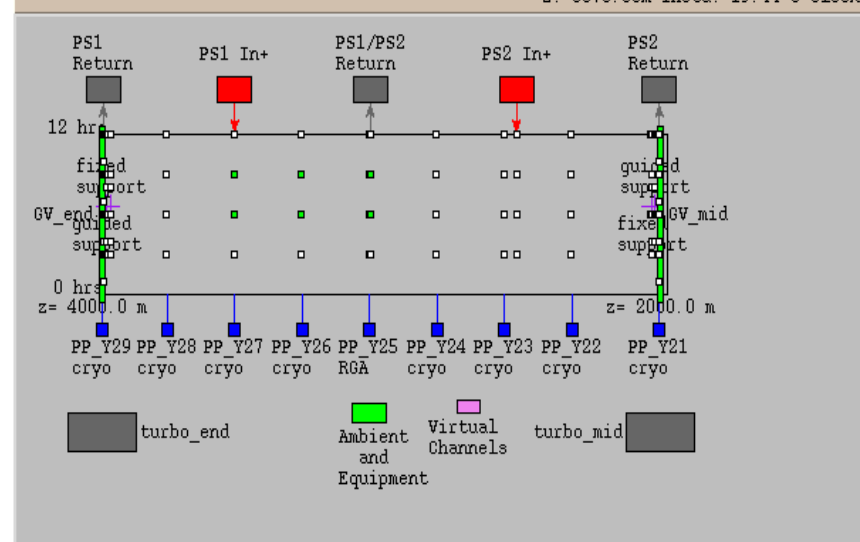
# LIGO Hanford Observatory (LHO)

## Beamtube Bakeout

- BT Bakeout database access via www browser
- Database ~ 400MB/module

Bakeout Data Retrieval Tclet

Unixtime	Date	Time	PS1 A CURR	VAL0 ILOW	SET VPOINT	VAL0	TEMP
905855400	09/15/98	10:30:00	6409.00	1775.00	155.00	479.00	479
905857200	09/15/98	11:00:00	6382.00	1775.00	155.00	481.00	481
905859000	09/15/98	11:30:00	6354.00	1775.00	155.00	481.00	480
905860800	09/15/98	12:00:00	6340.00	1775.00	155.00	481.00	481
905862600	09/15/98	12:30:00	6326.00	1775.00	155.00	480.00	480
905864400	09/15/98	13:00:00	6326.00	1775.00	155.00	479.00	479
905866200	09/15/98	13:30:00	6333.00	1775.00	155.00	481.00	481



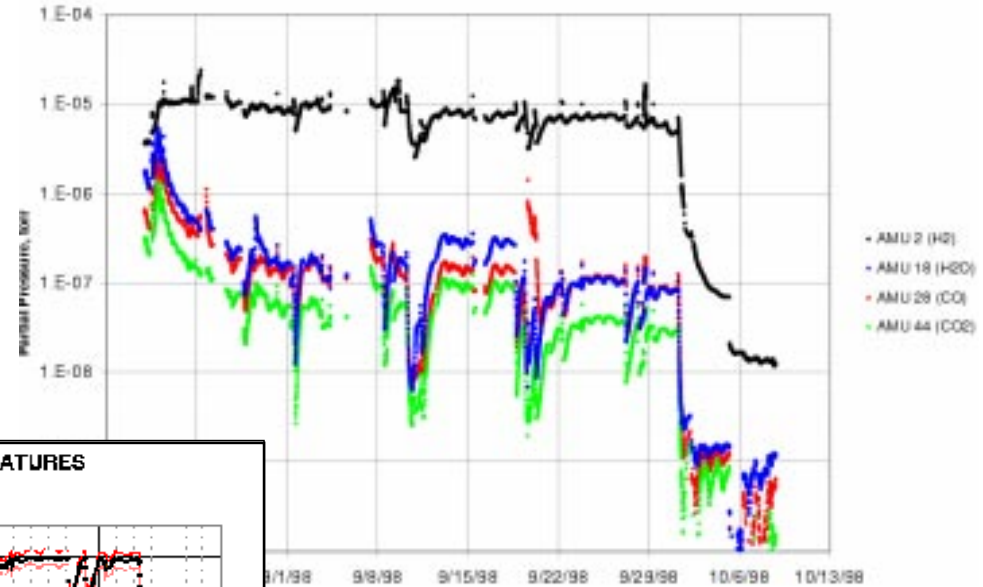
# LIGO Hanford Observatory (LHO)

## Beamtube Bakeout

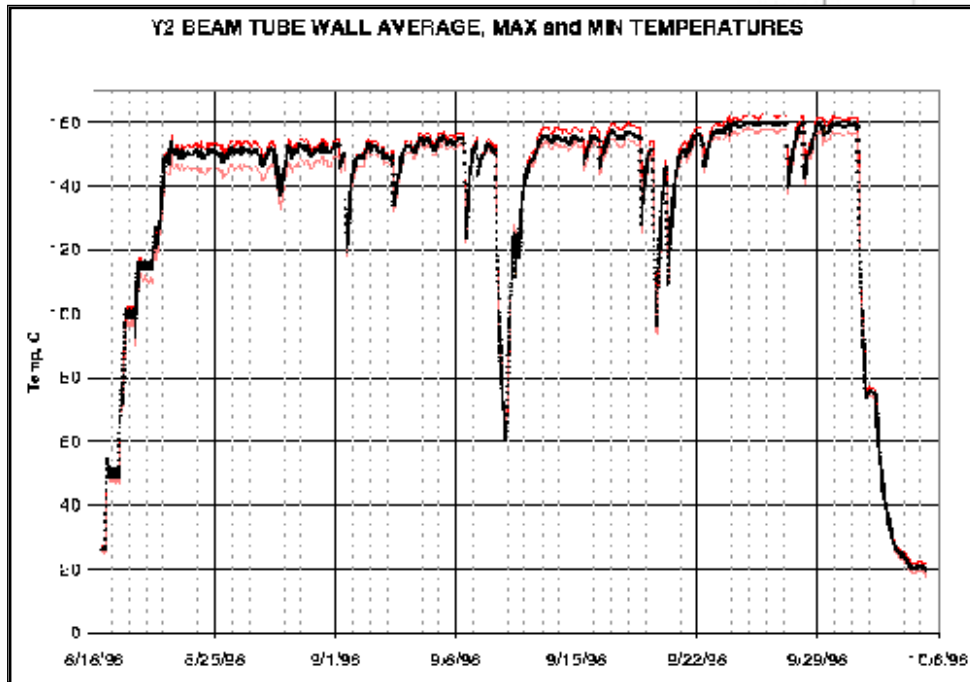
HY2 SELECTED PARTIAL PRESSURES DURING BAKEOUT

Y1 Hanford [ $Q < 1 \times 10^{-10}$  t-l/s]

Species	J @ 25C t-l/cm <sup>2</sup> /s	p[mid-tube] 23C, end pump only
H <sub>2</sub>	$6.3 \times 10^{-14}$	$3.6 \times 10^{-8}$
H <sub>2</sub> O	$< 2 \times 10^{-17}$	$< 1.4 \times 10^{-12}$
N <sub>2</sub>	$< 3 \times 10^{-19}$ [8C]	$< 5 \times 10^{-14}$ [8C]
CO <sub>2</sub>	$< 1.8 \times 10^{-18}$	$< 1 \times 10^{-12}$
H <sub>n</sub> C <sub>p</sub> O <sub>q</sub>	$< 8.5 \times 10^{-19}$	$< 5 \times 10^{-13}$



Y2 BEAM TUBE WALL AVERAGE, MAX and MIN TEMPERATURES



Y2 Hanford [ $Q < 2 \times 10^{-10}$  t-l/s]

Species	J @ 25C t-l/cm <sup>2</sup> /s	p[mid-tube] 23C, end pump only
H <sub>2</sub>	$4.8 \times 10^{-14}$	$3.4 \times 10^{-9}$
H <sub>2</sub> O	$< 4 \times 10^{-18}$	$< 1.9 \times 10^{-10}$
N <sub>2</sub>	$< 2 \times 10^{-18}$	$< 1 \times 10^{-13}$
CO <sub>2</sub>	$< 4 \times 10^{-18}$	$< 4 \times 10^{-13}$
H <sub>n</sub> C <sub>p</sub> O <sub>q</sub>	$< 1.5 \times 10^{-18}$	$< 6 \times 10^{-13}$

# Detector *Installation*

- **Sequence will be: LHO 2km -> LLO 4km -> LHO 4km**
- **Hanford Infrastructure:**
  - *all labs & shops set up*
  - *data networks up; fibre optic cabling complete*
  - *data racks positioned*
  - *cable trays installed*
  - *control complete*
  - *seismic piers surveyed & installed for both IFOs*
  - *some of Physical Environment Monitoring system [PEM] installed*
  - *data acquisition system kernel functioning*
  - *all vacuum feed-throughs for electrical signals installed, leak checked*
  - *all viewports [non-high quality] installed, leak checked*



# Detector *Installation*

- **2km IFO [Hanford]:**
  - Prestabilized laser installed, near completion of acceptance tests
  - 3 HAM seismic systems installed [MC and RM]
  - 1 HAM support table installed
  - 1st BSC SEI began 99.01.18
  - External input optics installation well underway
  - Vacuum installation of IO began 99.01.19
  - Small optics, RM and input telescope large mirror suspended, control electronics, cabling installed



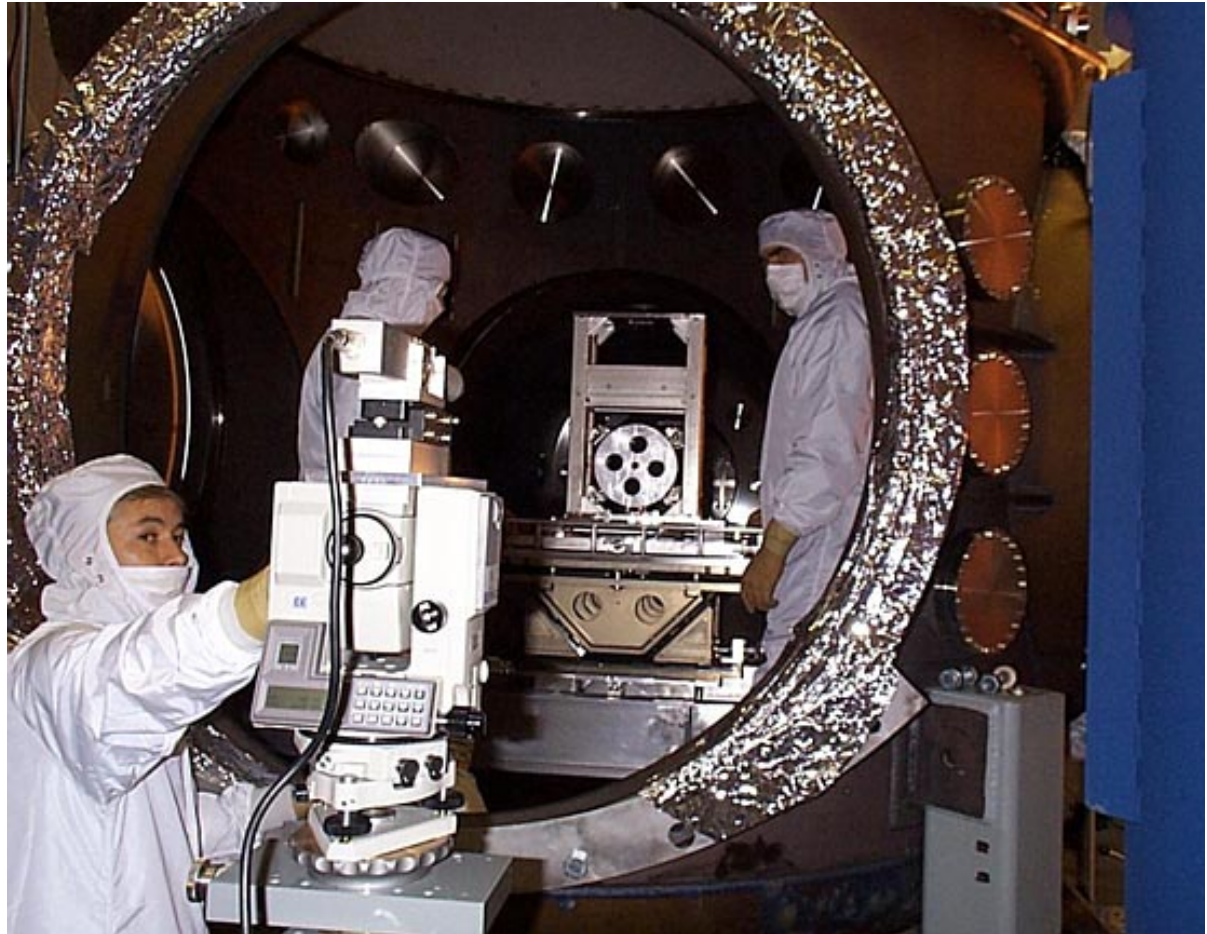
# Detector *Installation*

- **Livingston infrastructure:**

- Most lab & shop facilities set up
- all fiber optic cabling [down arms] installed
- some of PEM installed

- **4km Interferometer:**

- SEI installation activities ramp up 01/99
- PSL installation ramps up 03/99



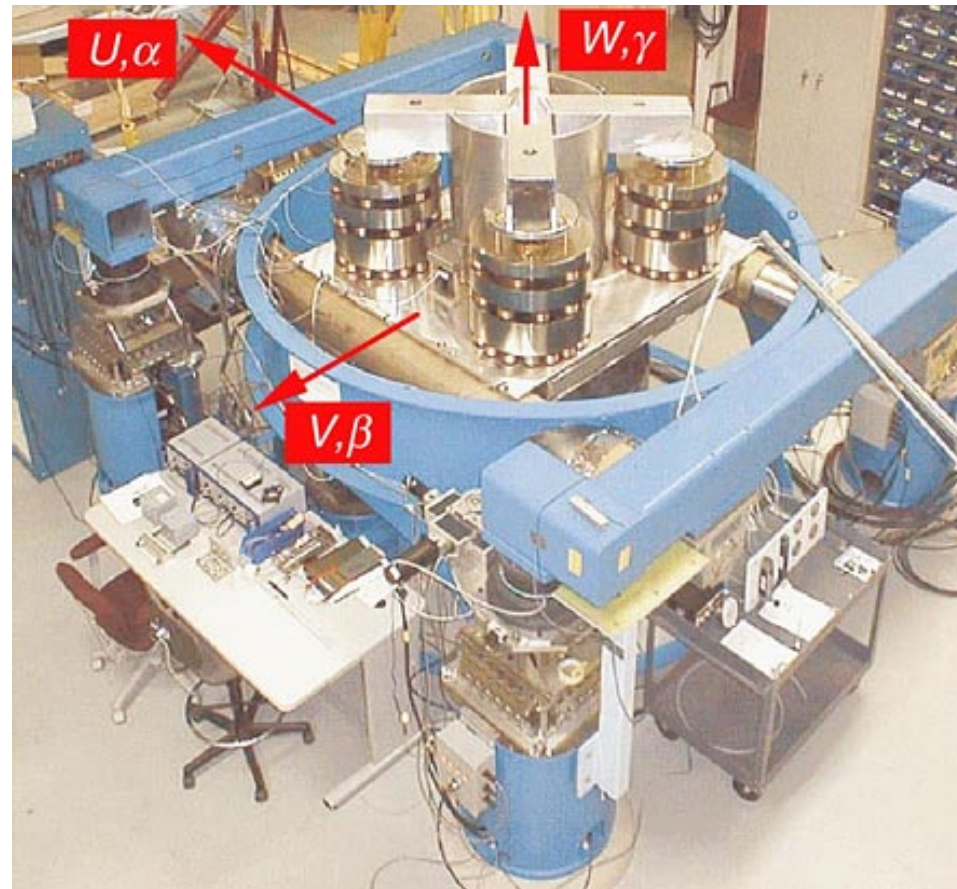
# Detector

## *Seismic/Suspension Systems*

- Design complete and all fabrication into production phase

- First article tests complete for SEI HAM and BSC - lessons learned factored back into production

- Passive isolation system meets LIGO I requirement

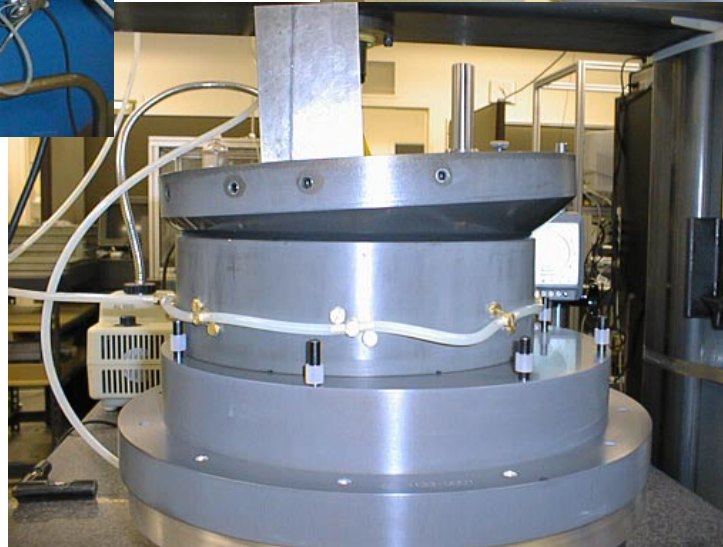
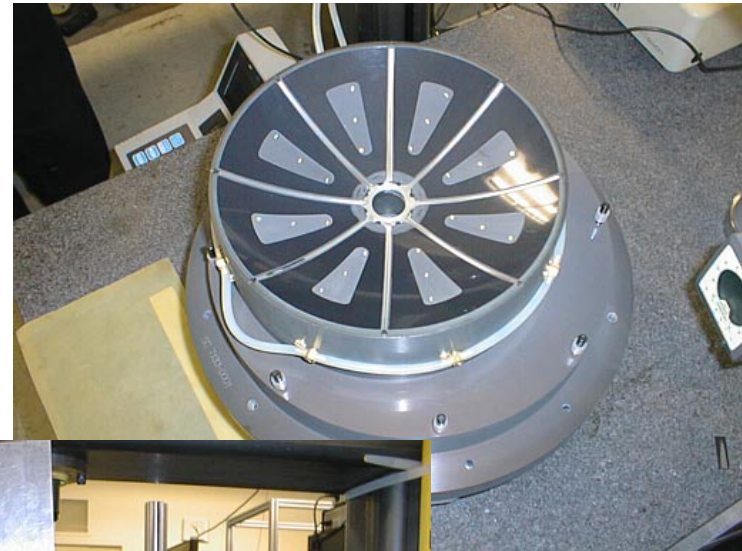
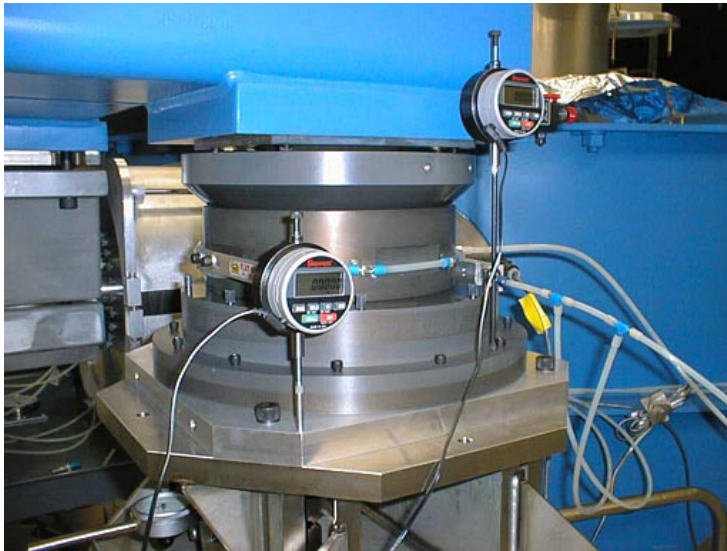


- First article tests of SUS complete
  - Isolation meets LIGO I requirement
- First large optics suspension installation and alignment in BSC completed successfully.

# Detector

## *Seismic/Suspension System*

Spherical air-bearing assembly for angular alignment of BSC SEI assemblies.





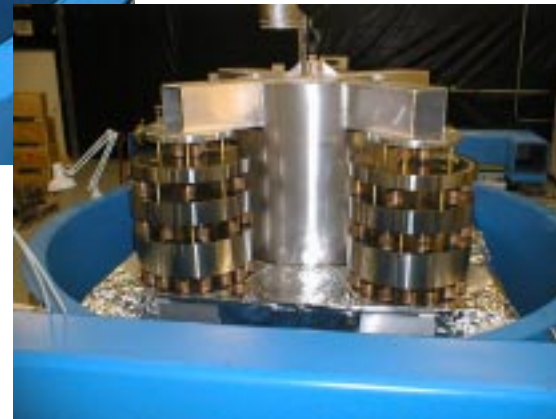
# Detector

## *Seismic/Suspension System*

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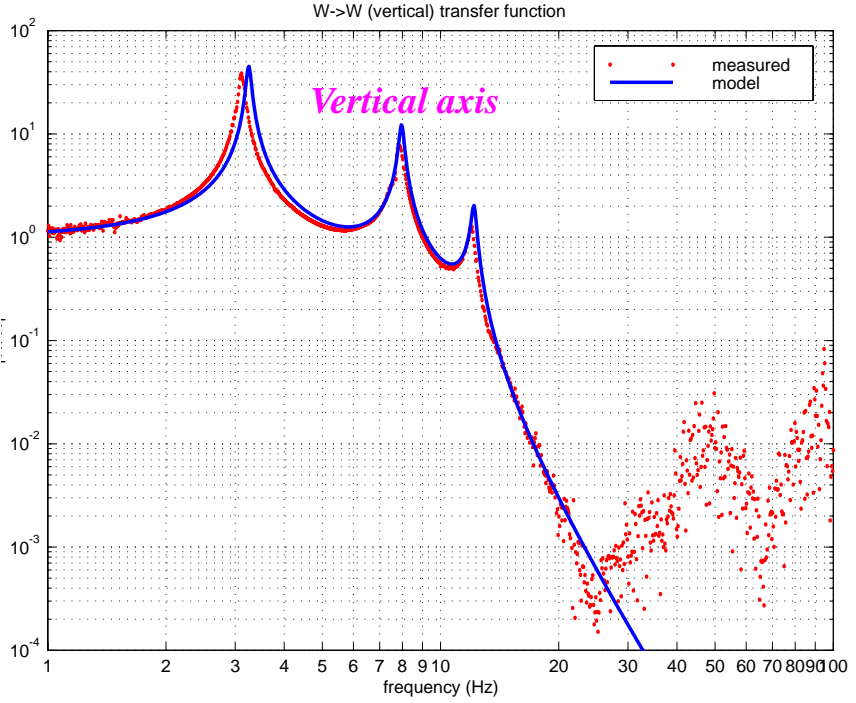
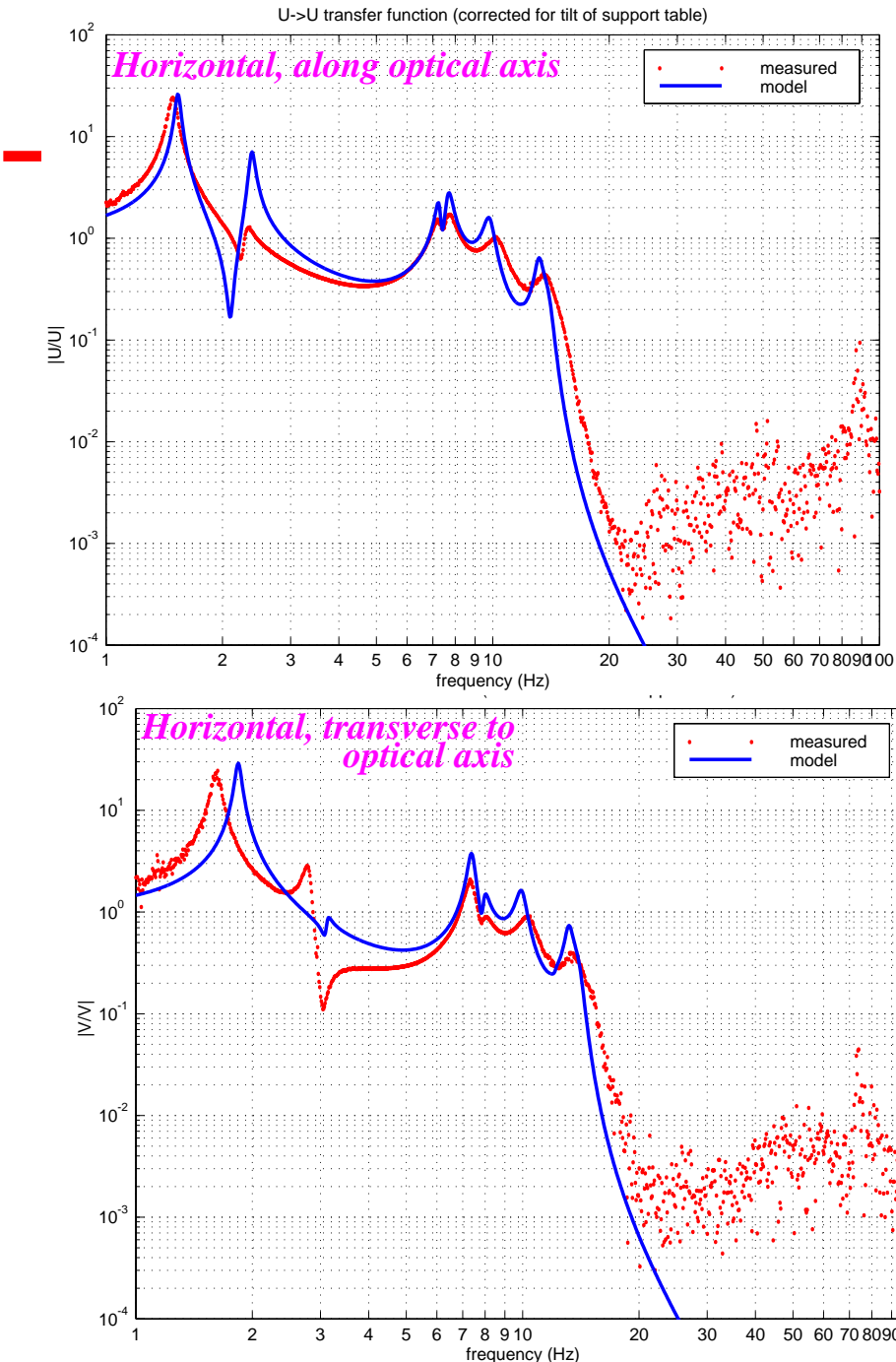


- **BSC seismic isolation system assembly inside mockup BSC shell for performance tests [HYTEC, Los Alamos, NM]**



# Detector SEI/SUS

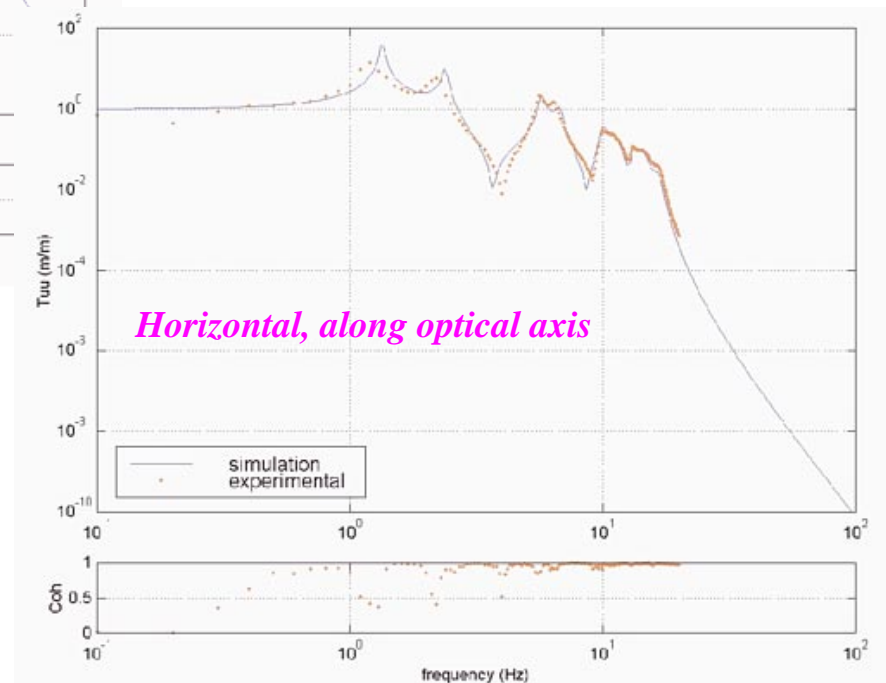
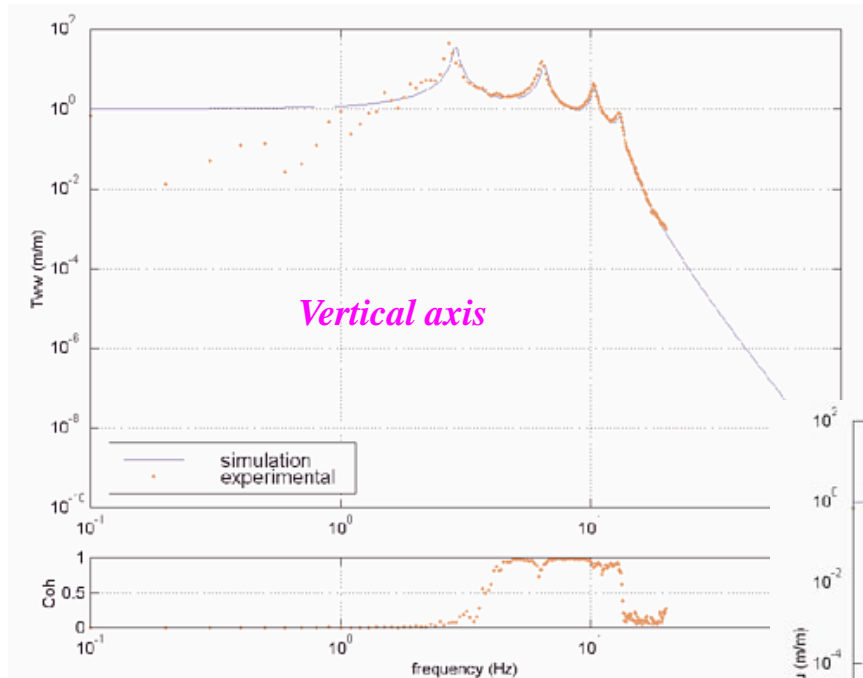
- HAM seismic isolation system transfer function tests at Hanford in first article
  - In air tests



# Detector

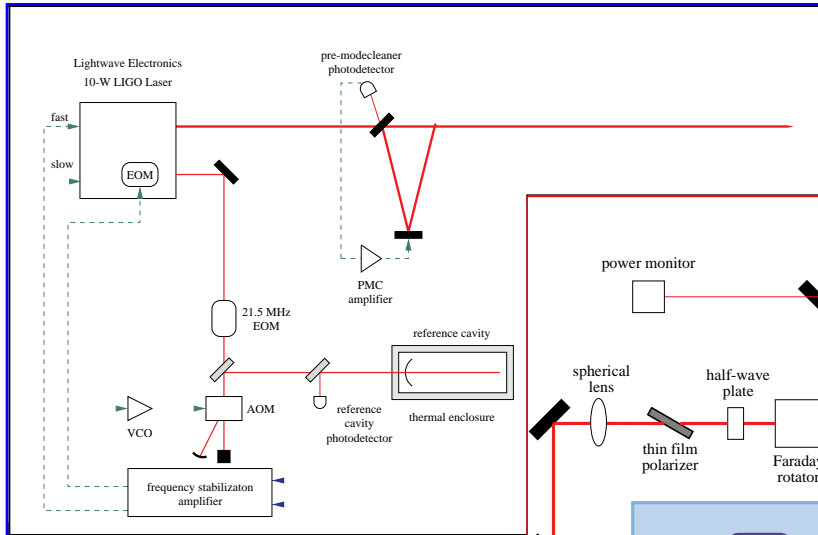
## Seismic/Suspension System

- BSC seismic isolation system transfer function tests at Los Alamos for first article
  - In air tests



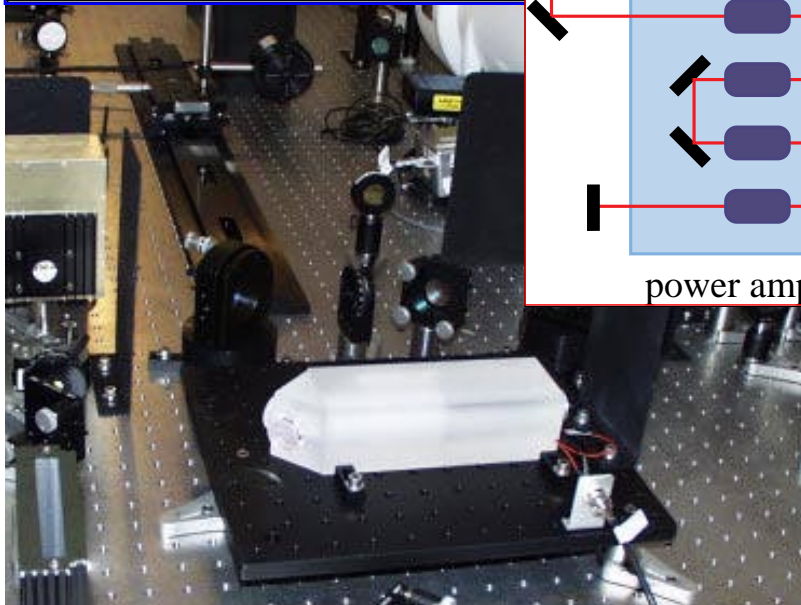
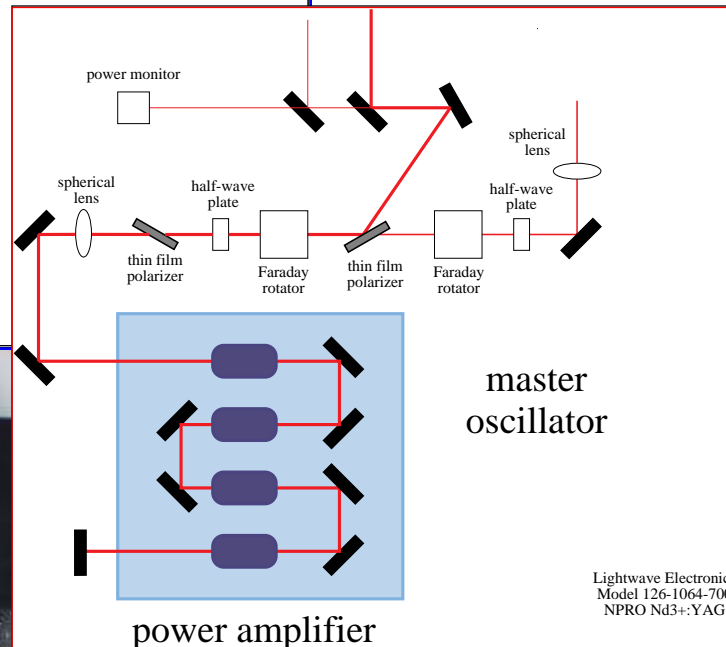
# Detector

## Prestabilized Laser [PSL]



- Tests at Caltech validated operation of all 4 control servos [fast/slow f, I, pre-MC]:

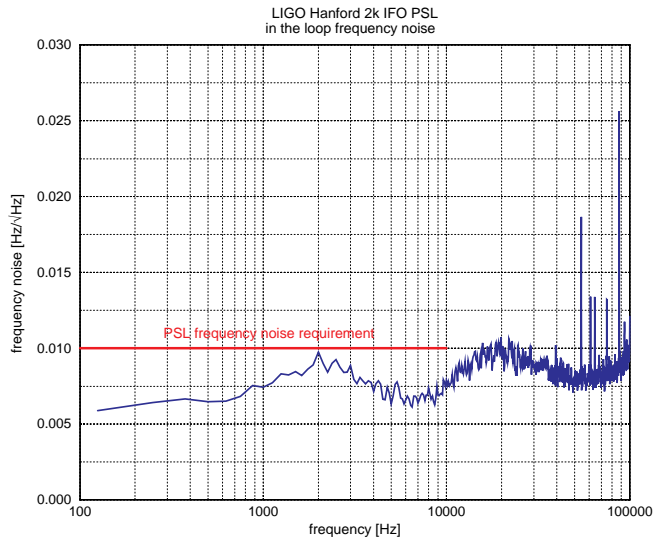
- Auto-lock acquisition of f-stabilization servo and pre-MC servo demonstrated
- Weekend tests ran until  $M=3.9$  earthquake caused loss-of-lock



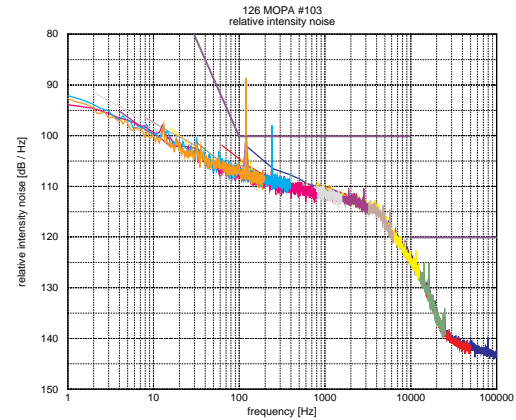
- 2km IFO PSL at Hanford stayed locked for 264 hrs before unknown event triggered a P.S. fault.

# Detector

## Prestabilized Laser [PSL]



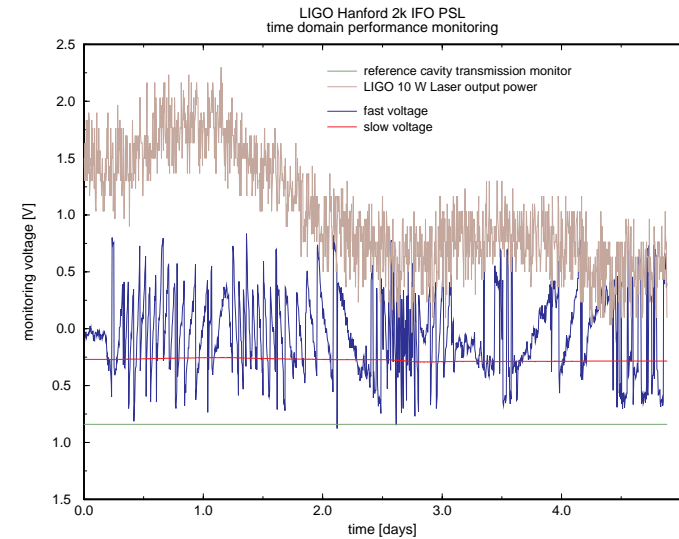
*In-loop error meets LIGO requirement*



*Free running 10W laser meets LIGO requirement*



*1m reference cavity*

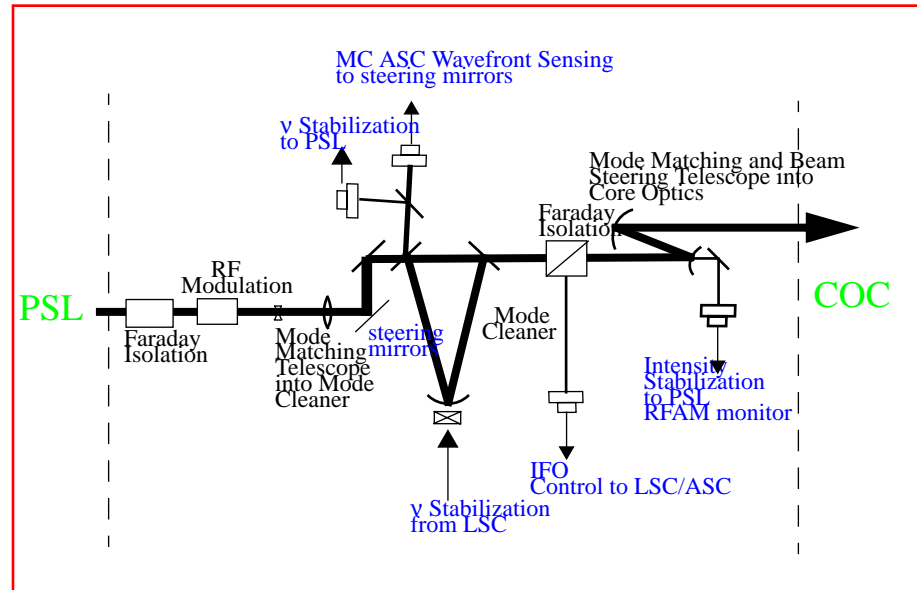


*1m mode cleaner [MC]*

# Detector

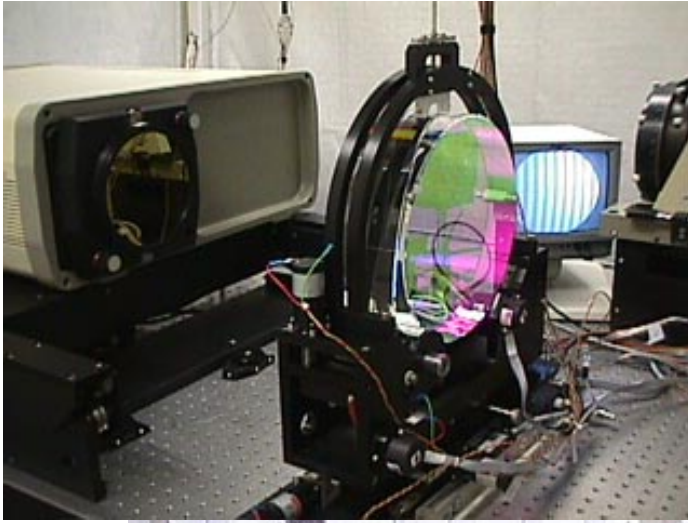
## Input Optics [IO]

- University of Florida responsible to LIGO for subsystem
- All optics for MC and telescope for 2km and 4km IFOs polished, coated
- Small optics suspensions [SOS] vacuum-prepped; all small optics prepared; final balancing, actuator installation underway
- External IO for 2km IFO complete
  - > *Beam quality characterization underway*
- Mode matching control [TEM<sub>20</sub>] uses wavefront sensing analogous to alignment control for TEM<sub>10,01</sub>
- Radius of curvature of last [large] telescope mirror 26.2m with 0.1% precision;
- Vacuum installation began 99.01.18.
- 2km IFO MC length, alignment control optics & electronics on site at Hanford
- End-to-end model for IO subsystem being built.



# Detector

## Core Optics [COC]



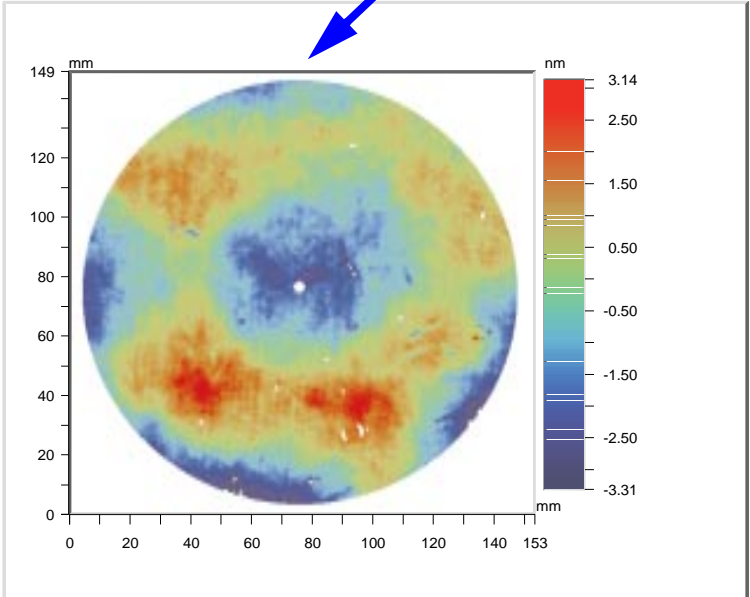
- 30/40 polished substrates received
  - material absorption meets LIGO requirement
- 20/40 substrates coated
  - balance complete by 99.04
- Optics cleaning procedures established
- In-house metrology @ 1064 nm in place, qualified, operating on coated optics
- 2km IFO RM surface measured after coating
  - LIGO requirements met\*
  - delivered to Hanford for installation

\* still trying to understand Caltech environment, long term drifts

# Detector Core Optics [COC]

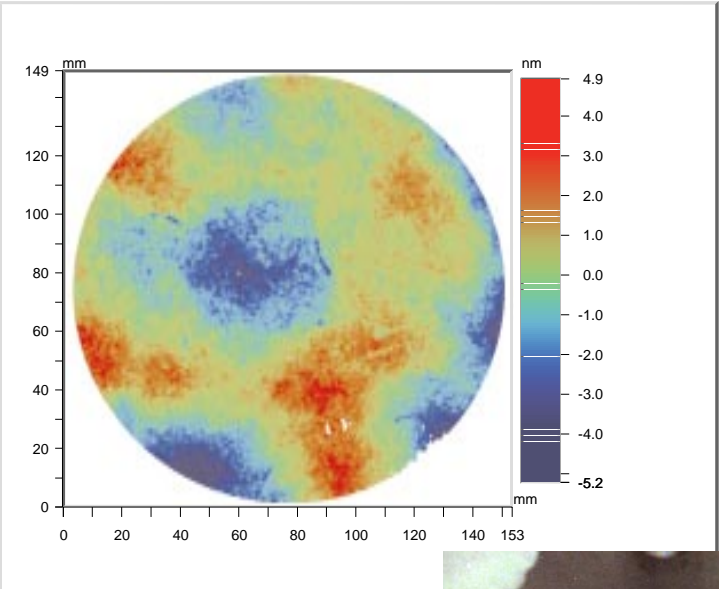
Caltech  
measurement

CSIRO  
measurement



Date: 11/16/1998  
Time: 16:39:59  
Wavelength: 1.064  $\mu\text{m}$   
Pupil: 100.0 %  
**PV: 6.4471 nm**  
**RMS: 1.1005 nm**  
Rad of curv: 570.70 km

X Center: 284.00  
Y Center: 240.00  
Radius: 267.72 pix  
Terms: Tilt Power Astig  
Filters: None  
Masks: 3.0 Sigma Mask



Date: 12/04/1998  
Time: 08:56:13  
Wavelength: 1.064  $\mu\text{m}$   
Pupil: 100.0 %  
**PV: 10.1607 nm**  
**RMS: 1.2981 nm**  
Rad of curv: 292.37 km

X Center: [unclear]  
Y Center: [unclear]  
Radius: [unclear]  
Terms: [unclear]  
Filters: [unclear]  
Masks: [unclear]

Zernike\_8[8]: -0.00143 wv  
Zer  
Zer

**Seidel Aberrations (8 Ter)**  
Coeff (per radius)

Tilt	0.0041 wv	
Power	0.0042 wv	0.001
Focus	0.0124 wv	
Astig	0.0008 wv	0.000
Coma	0.0038 wv	0.001
Sa3	-0.0086 wv	0.003

Title: AvCH2  
Note: - Cref\_av\_tft-45\_3de

**Zernike Coefficients:**  
Zernike\_3[3]: 0.00434 wv

Zernike\_8[1]: -0.01393  
Zernike\_8[2]: 0.01964  
Zernike\_8[3]: 0.00431  
Zernike\_8[4]: 0.00064  
Zernike\_8[5]: 0.00162  
Zernike\_8[6]: -0.00130  
Zernike\_8[7]: 0.00106  
Zernike\_8[8]: 0.00008



Detail of suspension  
wire stand-off



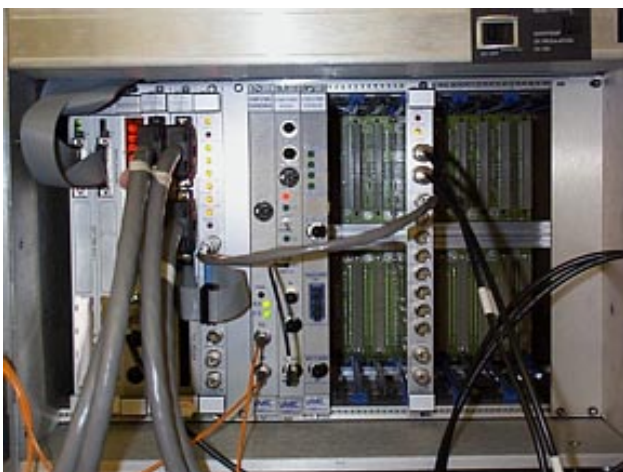


# Detector

## *Control and Data Systems [CDS]*

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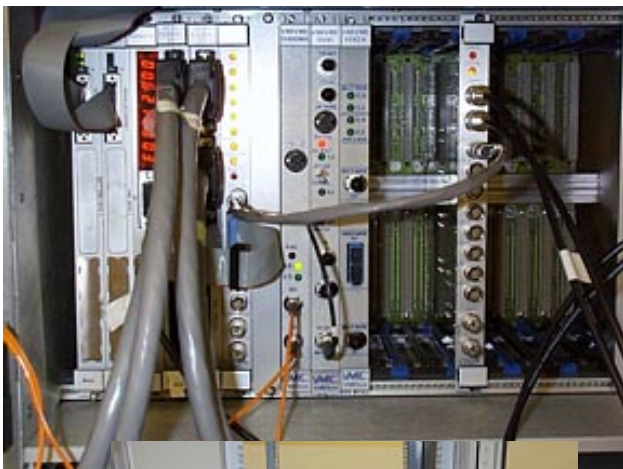
- **Vacuum Controls for VE complete, both observatories**
- **PSL Controls**
  - *Hanford 2km IFO installed & operational; awaiting connections to DAQ System*
- **SUS Controls**
  - *All hardware delivered & tested*
  - *Hanford test stand [for optics mounting/testing] installed; Livingston unit ready for installation [99.03]*
  - *Hanford 2km system installed & tested; awaiting further testing after optics are installed*
- **Alignment & Length Control [ASC/LSC]**
  - *Hanford 2km IFO IO system installation began 99.01.18*
  - *2km IFO ASC/LSC system under development; due at Hanford 99.03.*



# Detector

## Control and Data Systems [CDS]

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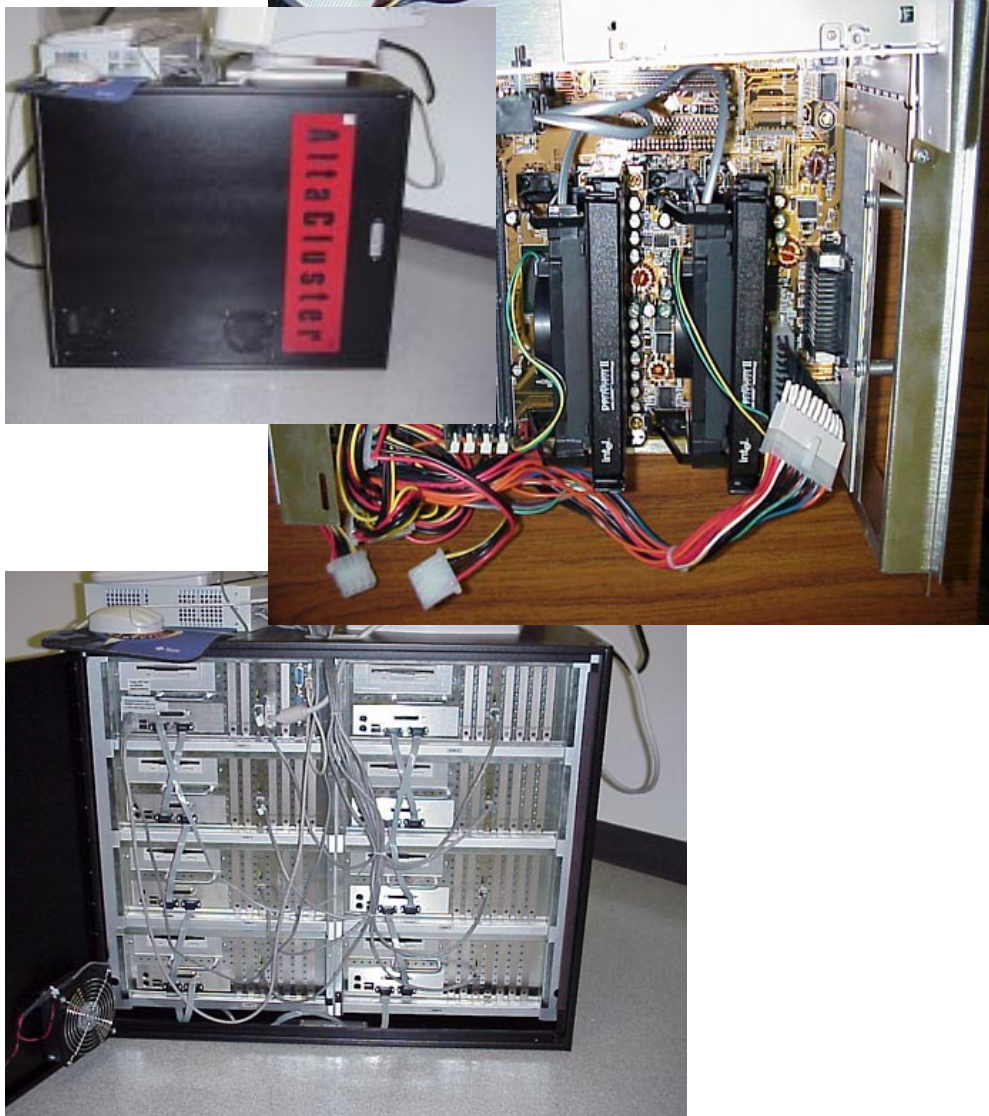


- **Data Acquisition System [DAQS]**

- *Hanford server and DAQS controller HW/SW installed, being tested*
- *Data Collection Units [DCU] field installation began 99.01.18*
- *Data framing SW operational [fast ethernet];*
  - ⌘ *Fixes required for reflective memory network [Sun multiprocessor bus problems in design] by 9.02.14*
- *Network Data Server [NDS] operational*
- *Data viewer, based on Motif/xmgr operational*
- *Interface module between NDS and GEO/Triana data viewer/analyzer operational - real-time data feed to Triana.*

# Data Analysis

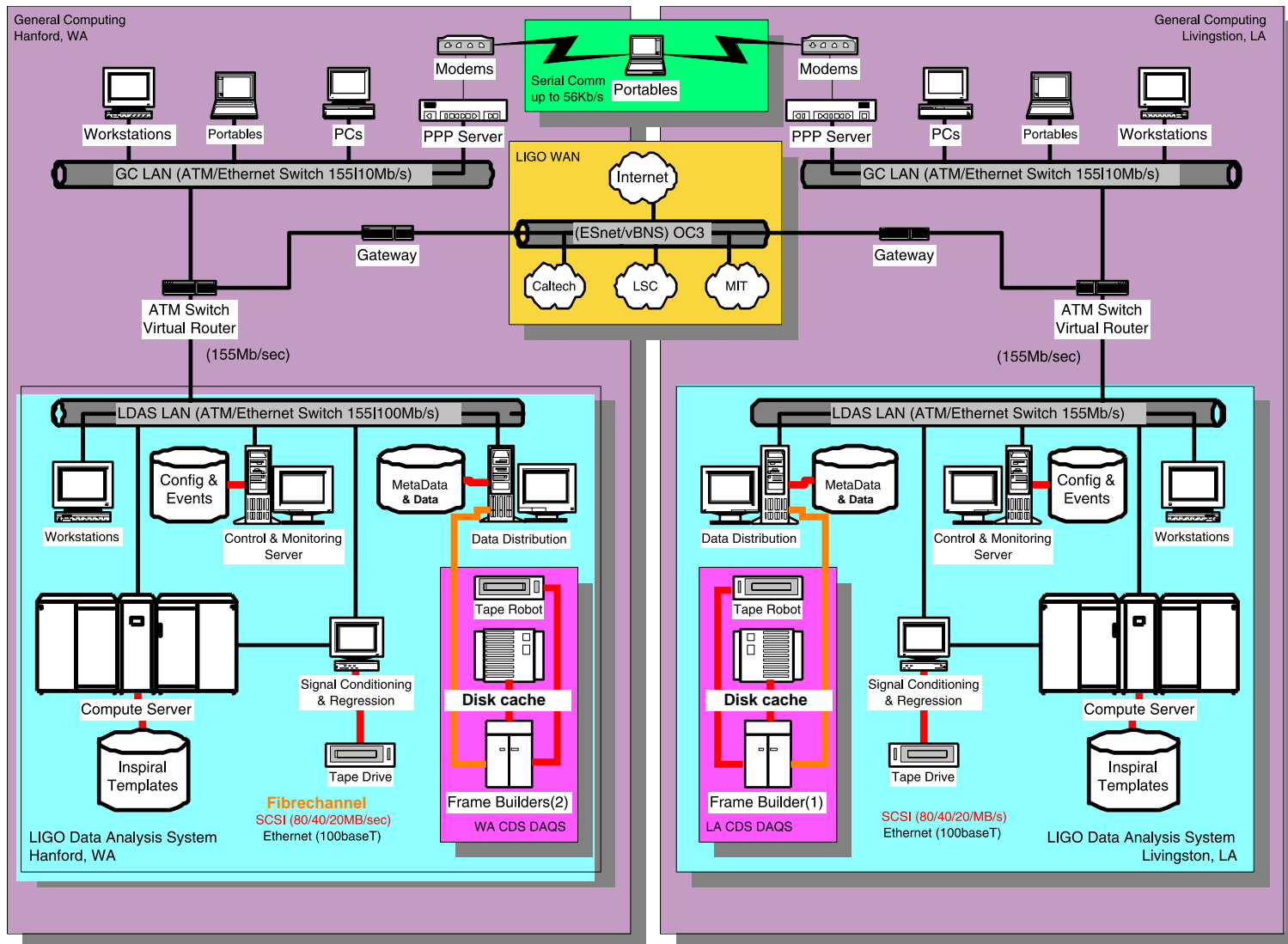
## LIGO Data Analysis System [LDAS]



- Design essentially complete
  - Design review 99.02.14
- Layered, modular design allows future extensions revisions of analysis flows as experience grows
- On-line systems dedicated to processing 100% of the GW channel
  - > *optimal filters*
  - > *transients*
  - > *frequency-time analyses*
  - > *end-to-end detector diagnostics*
  - > *data distribution to local and remote users*
- Off-line system dedicated to archiving data, distribution, computationally intensive [re] analysis of the GW channel

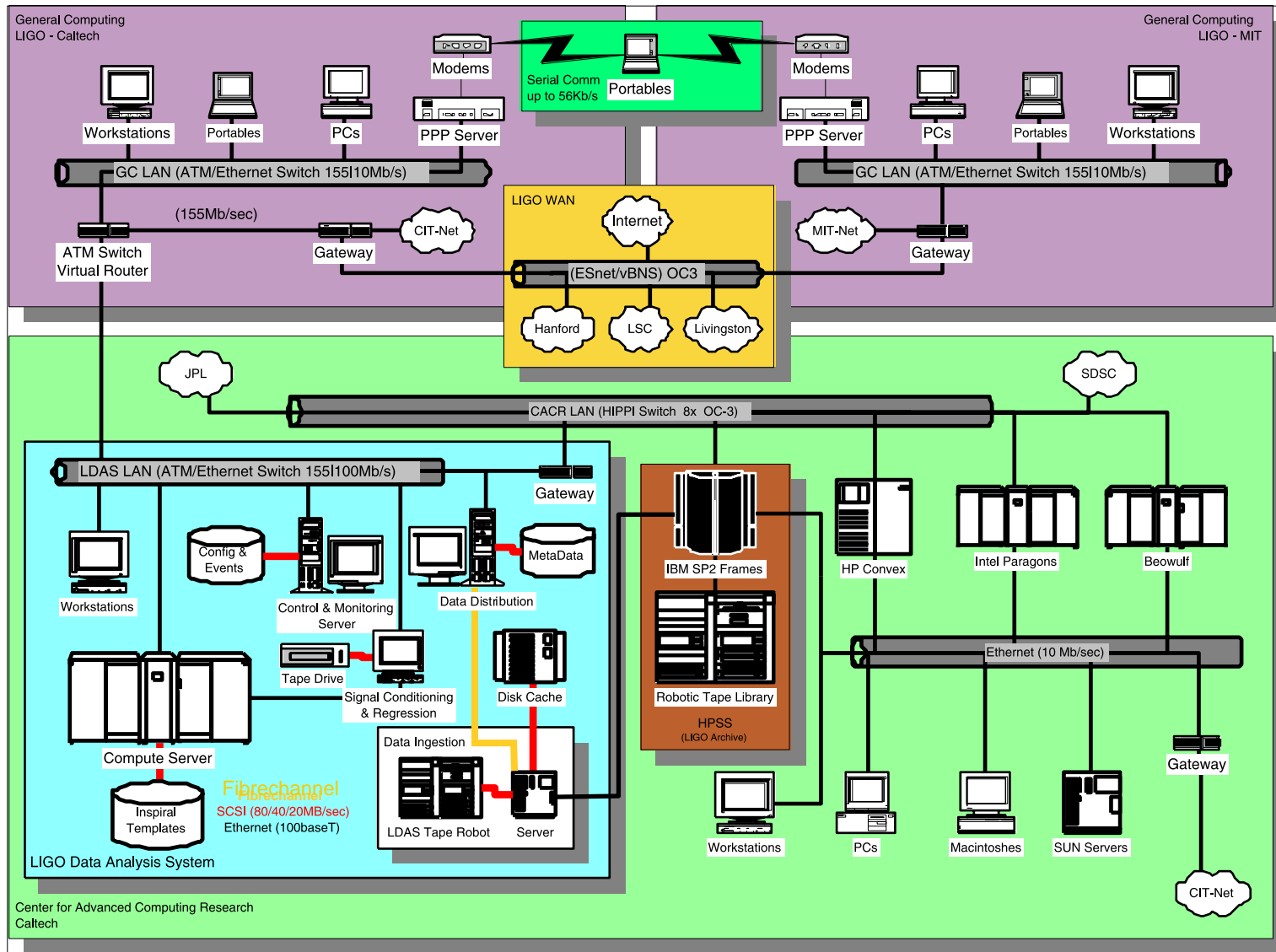
# Data Analysis

## On-line LDAS



# Data Analysis

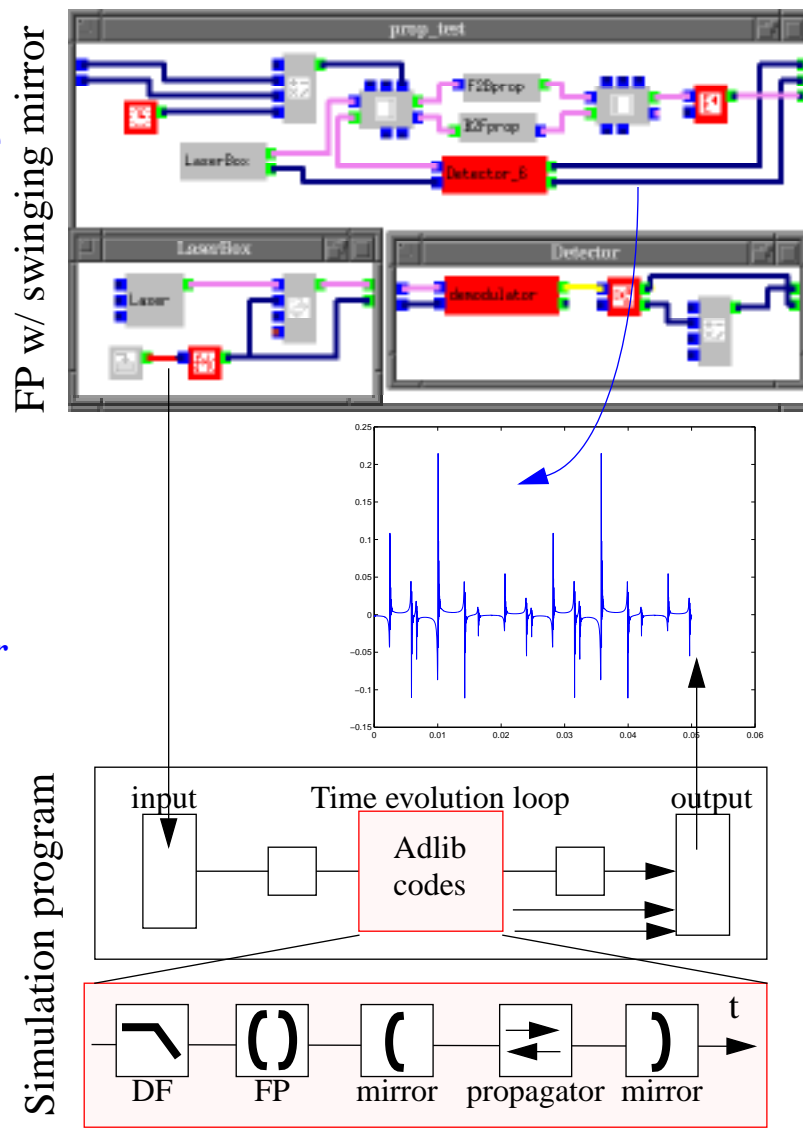
## Off-line LDAS



# Simulation

## LIGO End to End [E2E] modeling software - Overview

- Time domain simulation program for Laser Interferometers
  - Written in C++ with a modular architecture
  - Graphical User Interface to define the configurations and settings
- Functions:
  - Hardware Diagnostics
  - Future R&D and trade studies
  - Pseudo data production
- Features:
  - Field represented by Hermite-Gaussian - or time domain modal model
  - Mirror, lens and field propagators
  - Field modulators and demodulators
  - Digital Filters, saturation effects, logics
  - Modular mechanical structure simulation
  - Math functions
  - Software Spectrum Analyzer





# Summary

- Project within budget and on schedule!

## LIGO Installation Major Milestones

Milestone	Date	Comment
Vacuum Equipment Complete	1998.12.08	Both sites
BT Bakeout Complete	2000.02.21	Both sites
LHO 2km Start	1998.07.01	Begun
Power Recycled	1999.10.18	
Vertex Michelson complete		
LHO 2km IFO complete	2000.08.28	$h[f] < 10^{-20}$
LLO 4km Start	1999.06.01	
Power Recycled	2000.02.28	
Vertex Michelson complete		
LLO 4km IFO complete	2000.11.20	$h[f] < 10^{-20}$
LHO 4km Start	1998.07.01	Begun
Power Recycled	2000.03.20	
Vertex Michelson complete		
LHO 4km IFO complete	2000.10.16	$h[f] < 10^{-20}$
Design sensitivity	2001.11.05	$h[f] < 10^{-21}$
First science run	2002.01.01	3X operation