The Status of LIGO

LIGO Hanford Observatory

LIGO Livingston Observatory

Mark Coles

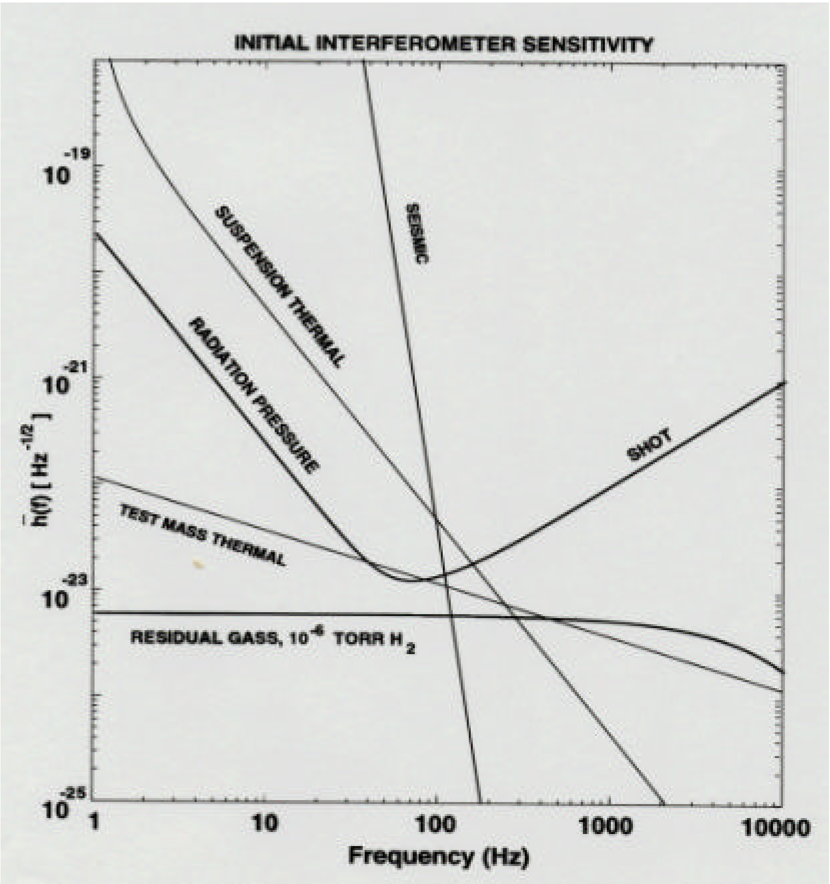
LIGO Livingston Observatory

Third Edoardo Amaldi Conference on Gravitational Waves

July 12 - 16, 1999

California Institute of Technology Pasadena, California, USA

Overview of LIGO



Design features:

•10 Watt Nd:YAG Laser - 1.06µ

•Power recycling

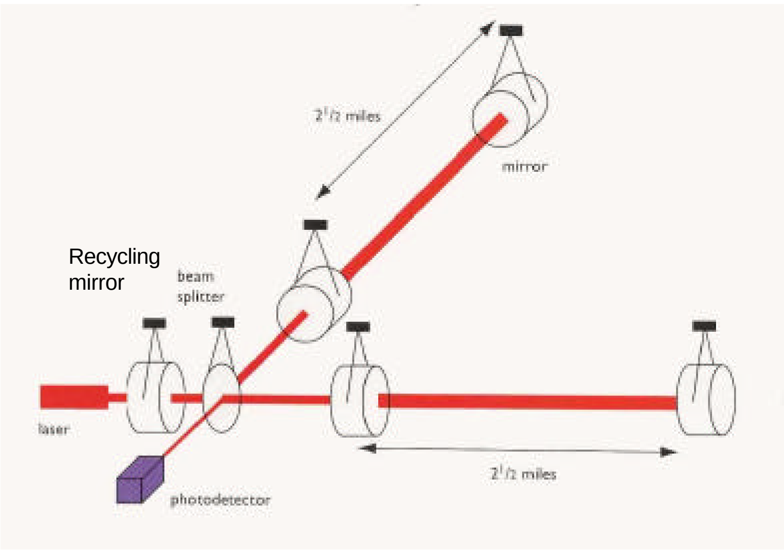
•***2 interferometers*** - each with 4km Fabry-Perot arms, at Hanford and Livingston

•***1 interferometer*** with 2km Fabry-Perot arms at Hanford *(shares same vacuum as 4 km interferometer)*

•Passive seismic isolation - 4 layers of damped springs

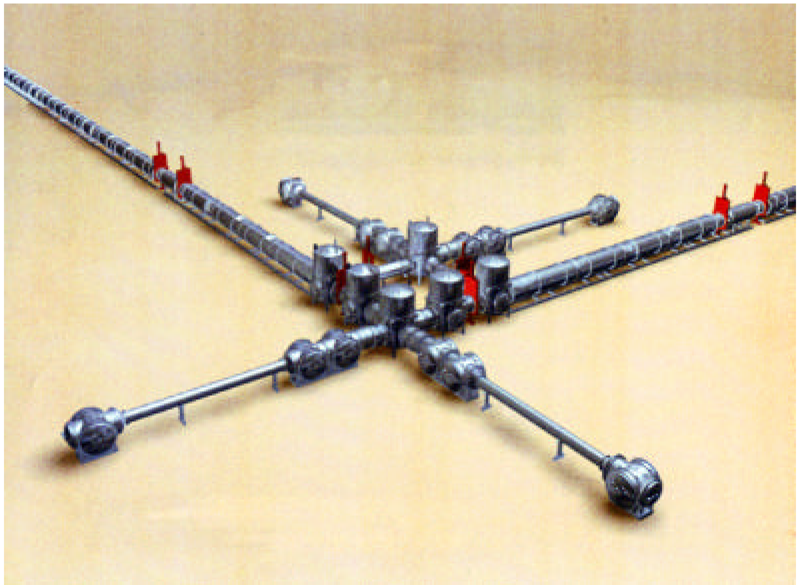
•Single pendulum suspension of test masses and beam splitter

Overview (ctd)



Optical configuration

Vacuum configuration at Hanford - 2 interferometers



Overview

- **construction project:**
  - ***will be completed this year (except for computer installation and beam tube bakeout at Livingston)***
  - ***on cost and schedule***
- **detector installation:**
  - **in progress**
  - ***close to schedule***
  - ***to be completed in 2000***
- **commissioning of interferometers**
  - ***follows installation***
- **first scientific data run**
  - ***begins 2002***

Topics presented:

- status of observatory facilities and infrastructure at Hanford (LHO) and Livingston (LLO)
- status of beam tubes, vacuum systems
- seismic isolation system
- pre-stabilized laser (PSL)
- optics
- data acquisition and control system (DAQ)
- data analysis

Facilities status

- facility construction is complete at both sites (with the exception of bakeout at LLO, now underway)
- both observatories have on-site support labs and shops
- data acquisition networks installed, fiber optic data links between corner, mid, and end stations installed
- data acquisition racks positioned and now being stuffed
- data collection software installed and operational at both sites

On-site preparation of in-vacuum components in vacuum bakeout oven

Vacuum equipment bakeout

- **all vacuum chambers surveyed into place, pumped down, leak checked, baked out**

Vacuum Performance Results for Large Vacuum Chamber Volumes

Livingston data:

PARTIAL PRESSURE FOR STATION BASELINE (torr)				
AMU	*Left End Station*	*Right End Station*	*Vertex*	***Goals***
2	5.80E-09	5.20E-09	3.70E-09	**5.00E-09**
16	3.30E-11	4.00E-11	4.30E-11	**2.00E-10**
18	1.80E-11	9.90E-10	6.50E-11	**5.00E-09**
28	6.00E-10	8.00E-10	1.10E-09	**1.00E-09**
44	8.50E-12	2.10E-11	3.00E-11	**2.00E-10**
all others	7.70E-11	7.40E-10	1.10E-10	**1.90E-09**
TOTAL PRESSURE FOR STATION BASELINE (torr)				
Max total pressure	6.54E-09	7.79E-09	5.05E-09	**2.00E-08**
Max pressure excl H_2, H_20	7.19E-10	1.60E-09	1.28E-09	**3.00E-09**

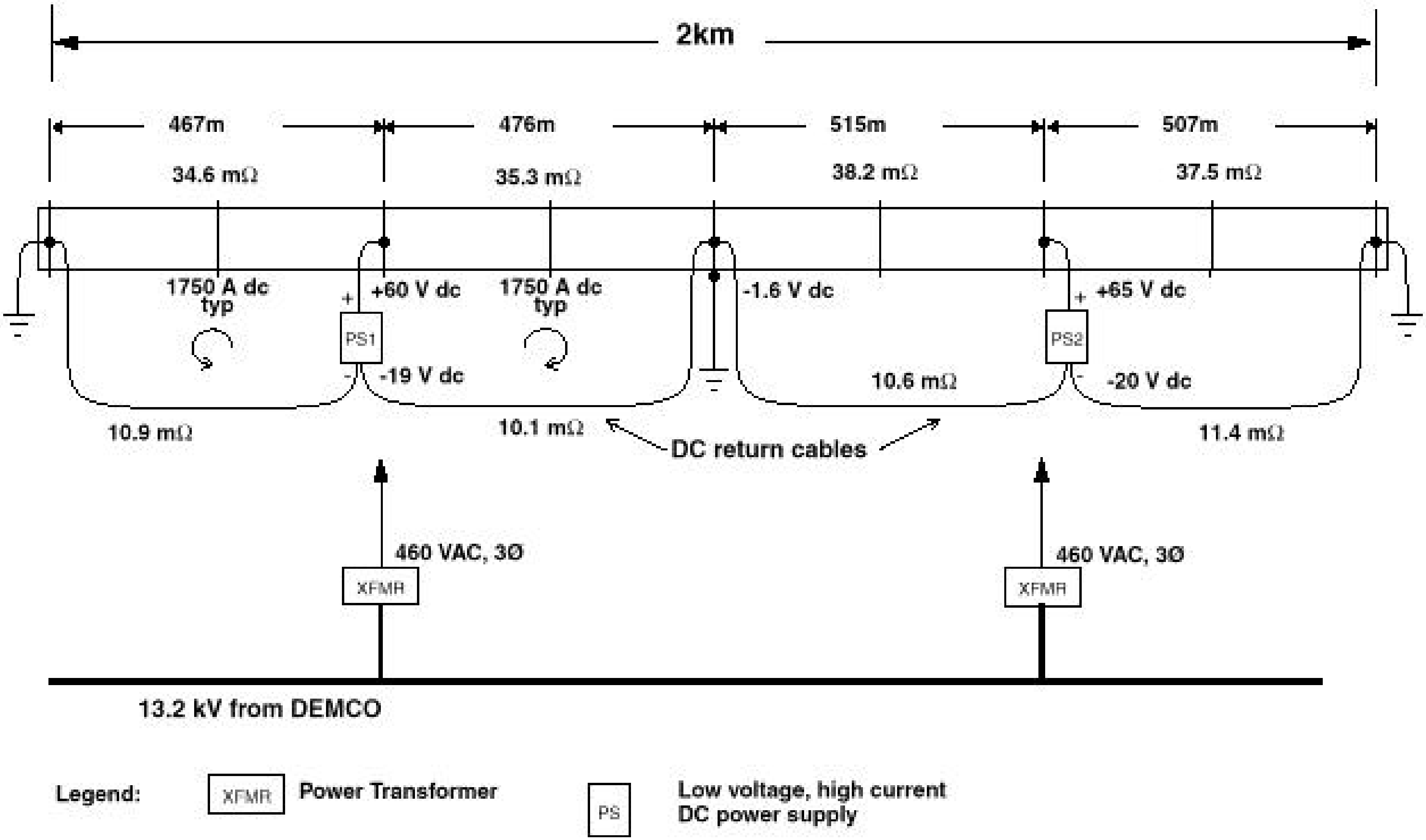
Primary and secondary acceptance criteria

Data satisfies acceptance requirements

Beam Tube Bakeout

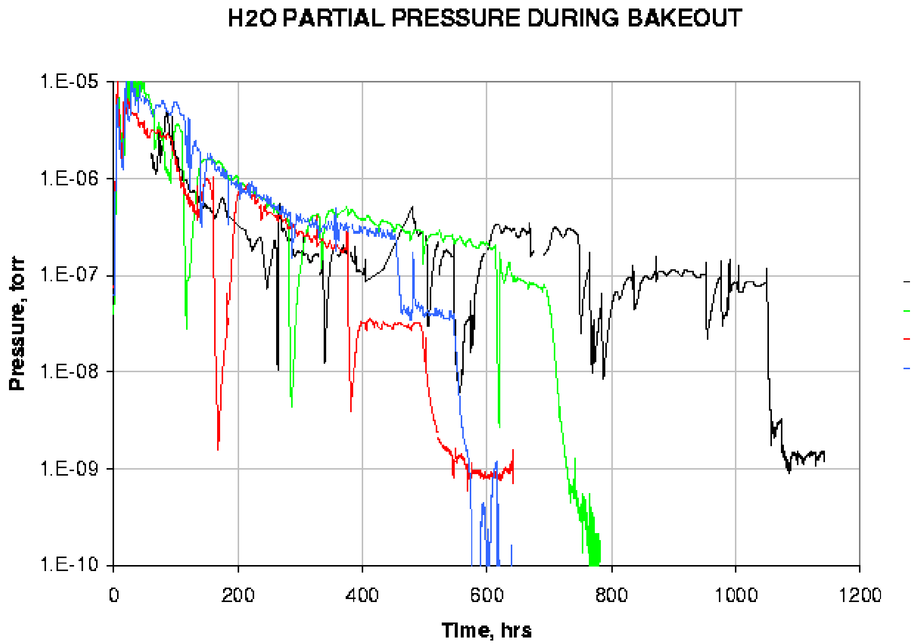
- BT is baked out in 2km sections using resistive heating of 3 mm 304L SS
  - heating current ~1500 - 2000 A (depends of ambient conditions - wind, temperature)
  - ~ 600 sensors mounted along each 2km module to monitor activity and ensure uniform heating:
    - thermocouples, pressure transducers, strain gauges, RGA, cryopump controllers
- Hanford bakeout of 4 beam tube modules complete
- results of each bake meet or exceed LIGO goals for advanced IFOs
- bakes became more efficient and results more sensitive as we learned
  - *higher temperature bakeout (168C vs 150C) required shorter duration to achieve pressure goal*
- equipment shipped to Livingston, setup in progress, will be completed in about one year

Electrical Layout for Beam Tube Bakeout

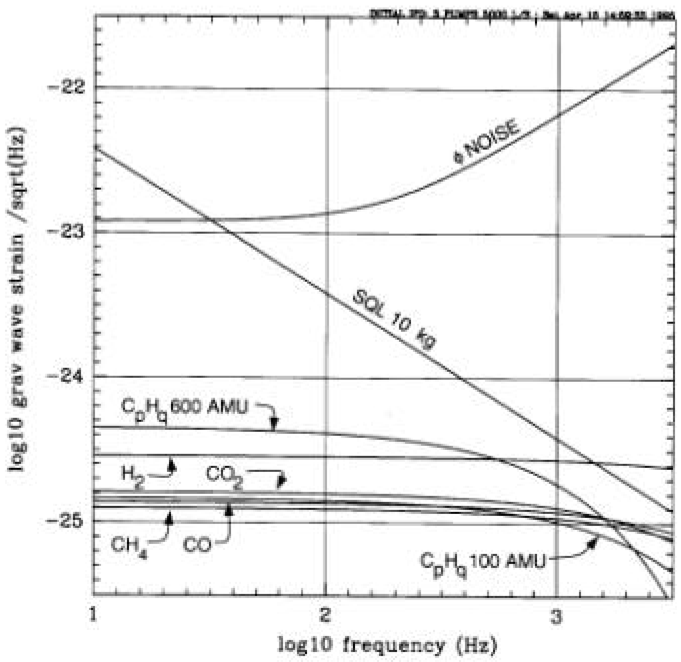


All 8 km of beam tube insulated at each site in preparation for beam tube bake out

LIGO Hanford beam tube bakeout results

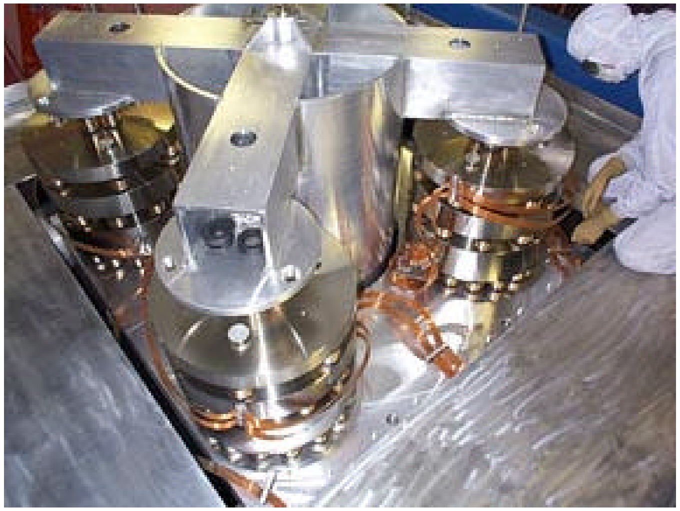


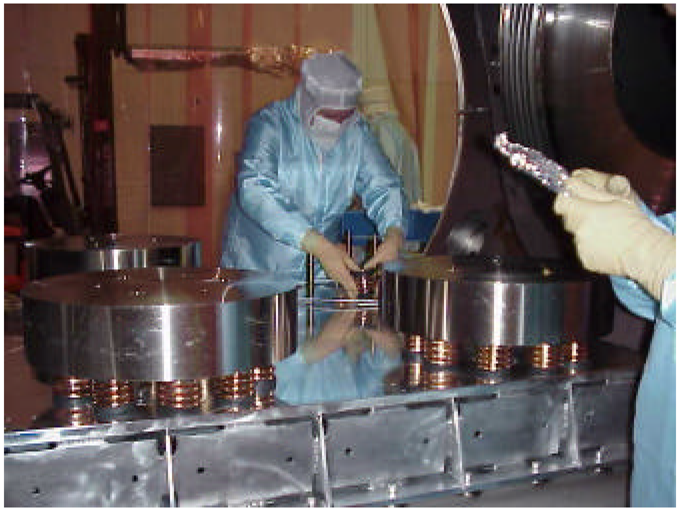
Residual gas contribution to noise budget



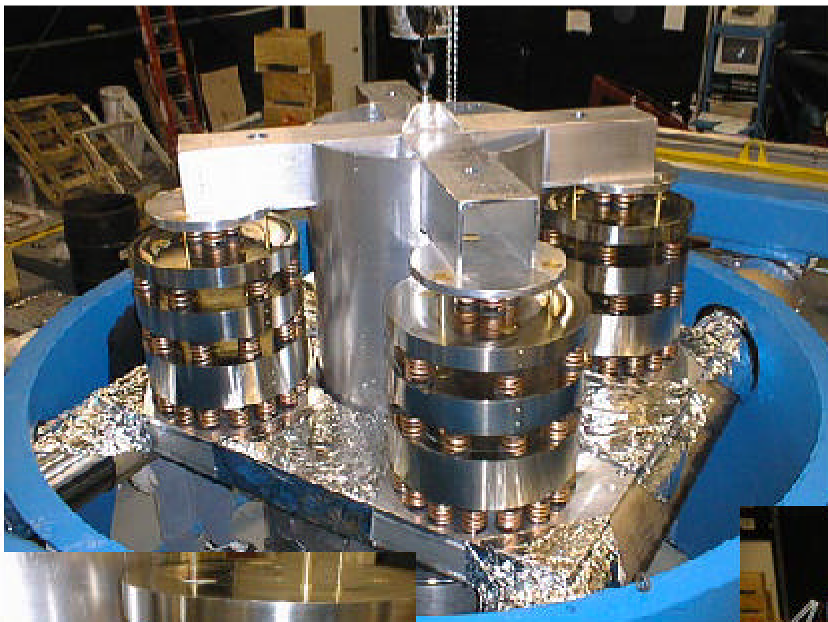
Seismic isolation system

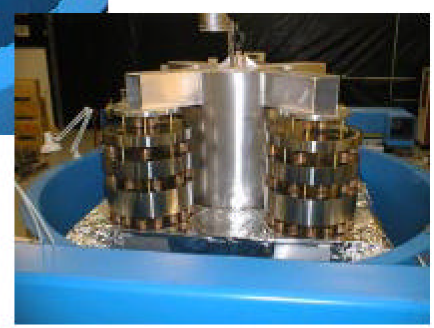
- provides passive isolation of suspended optics from ground motion
- maintains the total motion of test masses within the control range of suspension actuators
- test masses and beam splitter suspensions are mounted on 4 layer sandwiches of springs and steel
- support optics mounted on 3 layer sandwiches
- helical springs are internally damped so that Q < ~5





Performance testing of BSC prototype seismic isolation system





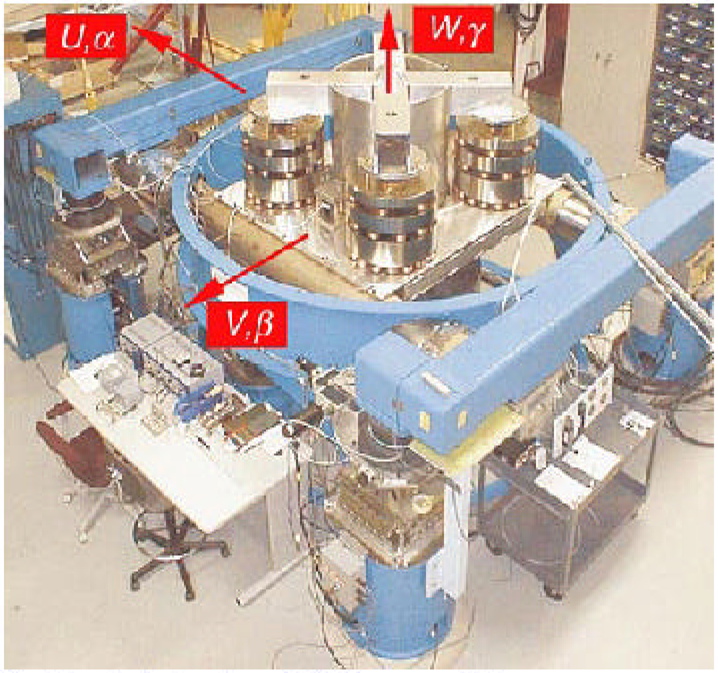
- BSC seismic isolation system assembly inside mockup BSC shell for performance tests [HYTEC, Los Alamos, NM]

BSC Prototype Seismic Isolation System:

Transfer Function Measurements

- 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

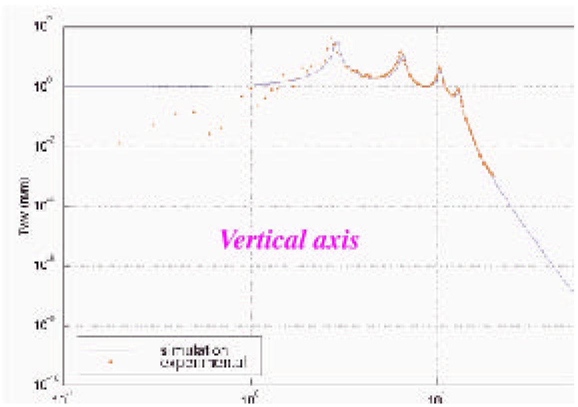
First article HAM tests at LHO

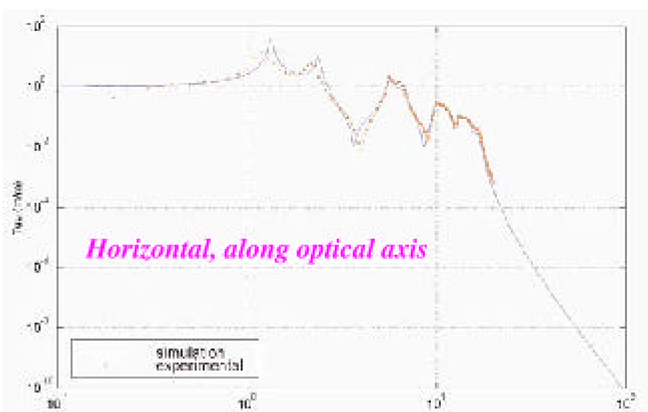


BSC prototype tests at Hytec

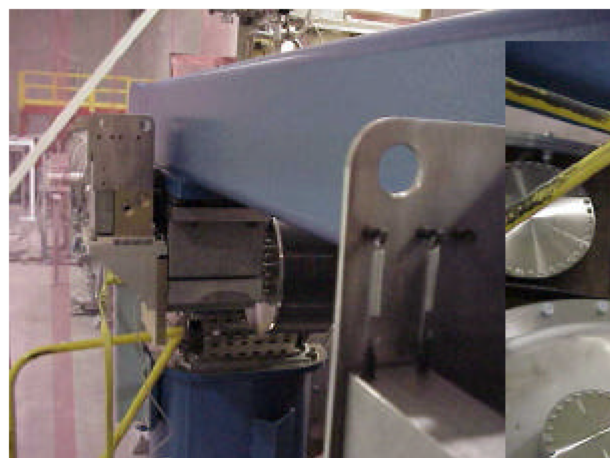
- First article tests of SUS complete
  - Isolation meets LIGO I requirement
- First large optics suspension installation and alignment in BSC completed successfully.

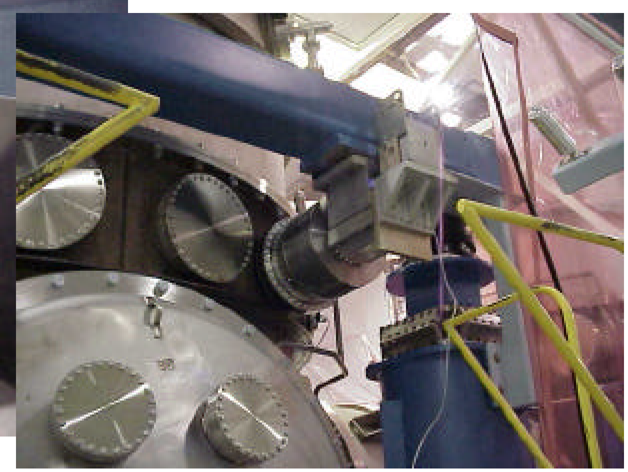
Tests of BSC prototype seismic isolation system



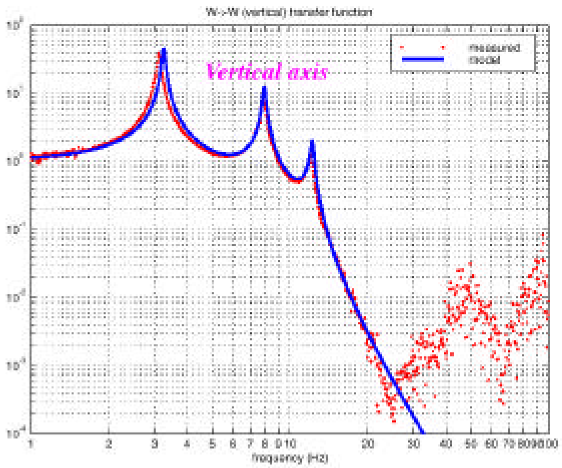


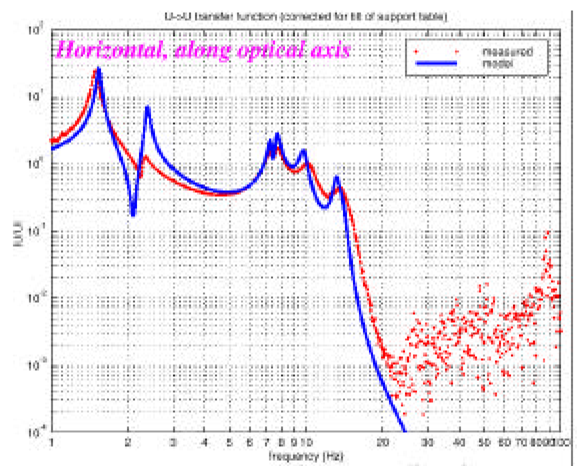
- **Initial measurements of BSC isolation transfer function made in air at Hytec.**
- **Measurements in vacuum underway at LLO**

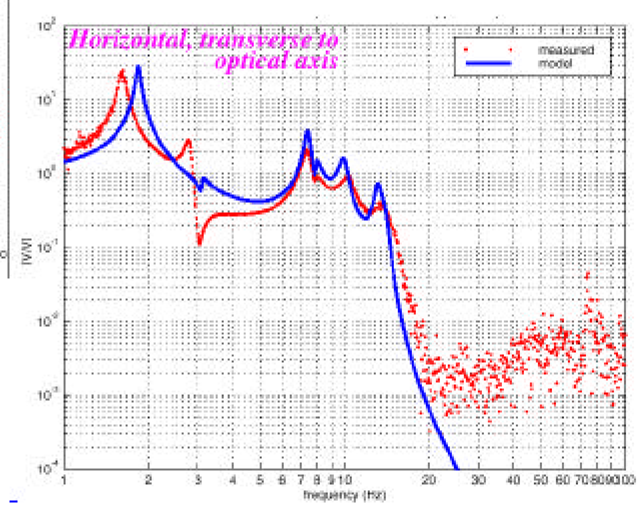




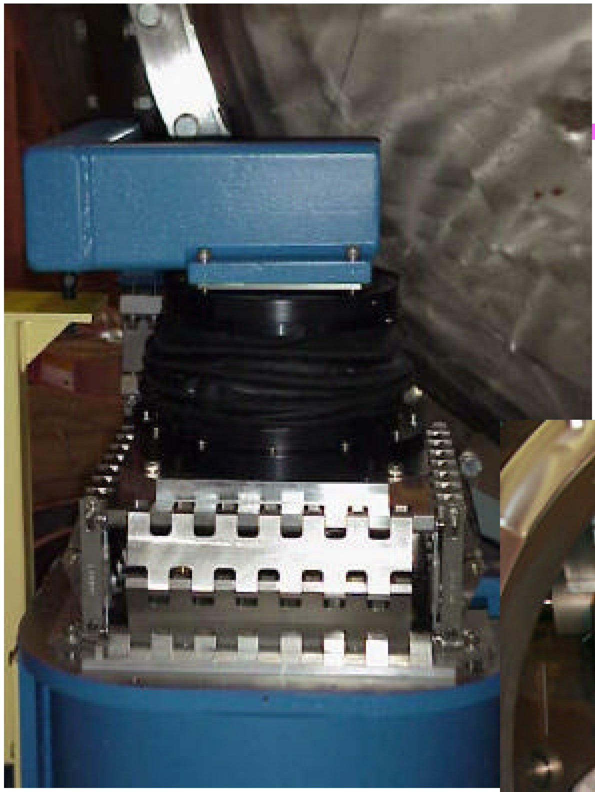
HAM seismic isolation system tests measured in air at LHO

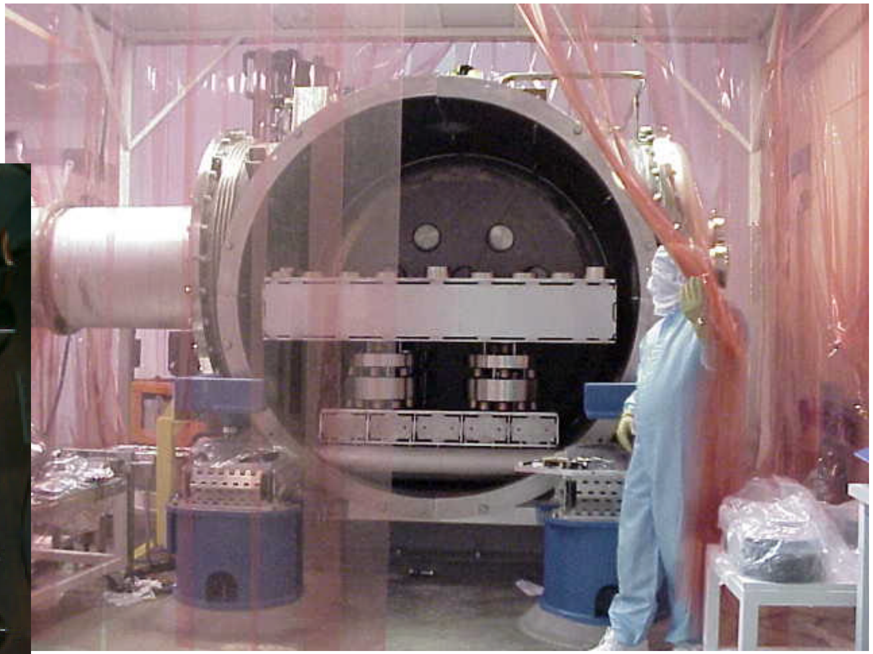






Installation of seismic isolation systems in progress at both sites



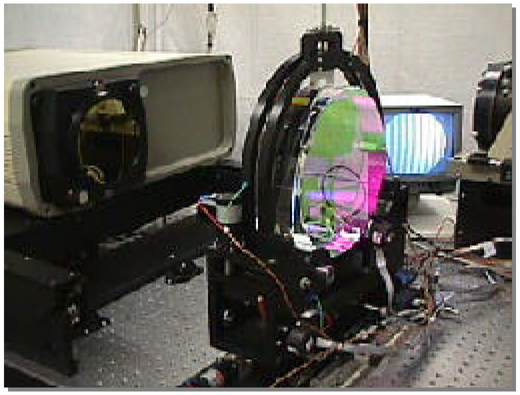


Seismic support piers and control racks installed in Livingston

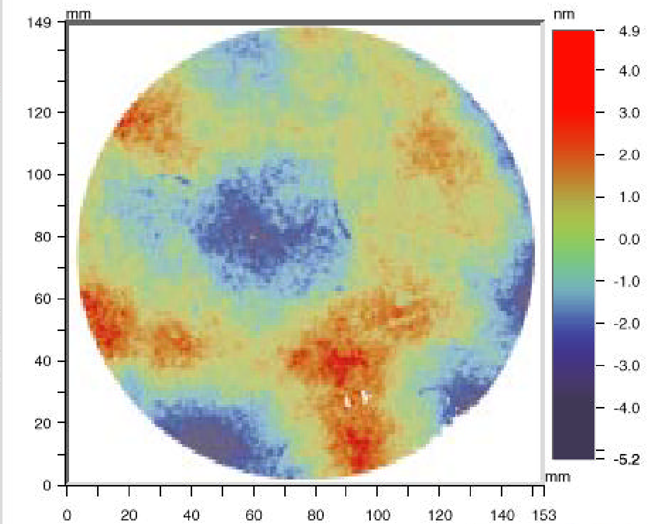
first BSC seismic stack complete at LLO

Optics status

- all substrates polished and coated
- optics cleaning procedures established
- in-house metrology lab set up at Caltech
- external measurements at CSIRO compare well with in-house measurements



Caltech measurement



Title: AvCH2
Note: - Cref_av_tft-45_3de

Zernike Coefficient
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

Date: 12/04/1998
Time: 08:56:13
Wavelength: 1.064 um
Pupil: 100.0 %
PV: 10.1607 nm
RMS: 1.2981 nm
Rad of curv: 292.37 km

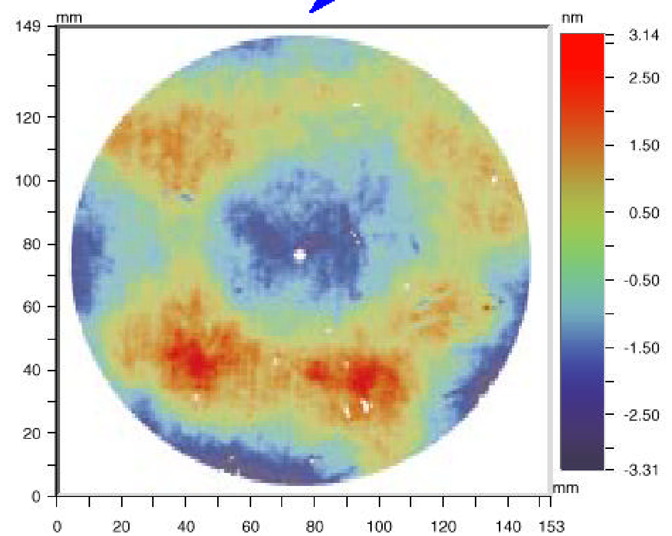
X Cente
Y Cente
Radius
Terms:
Filters:
Masks:

Zernike_8[8]: -0.00143 wv

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

CSIRO measurement



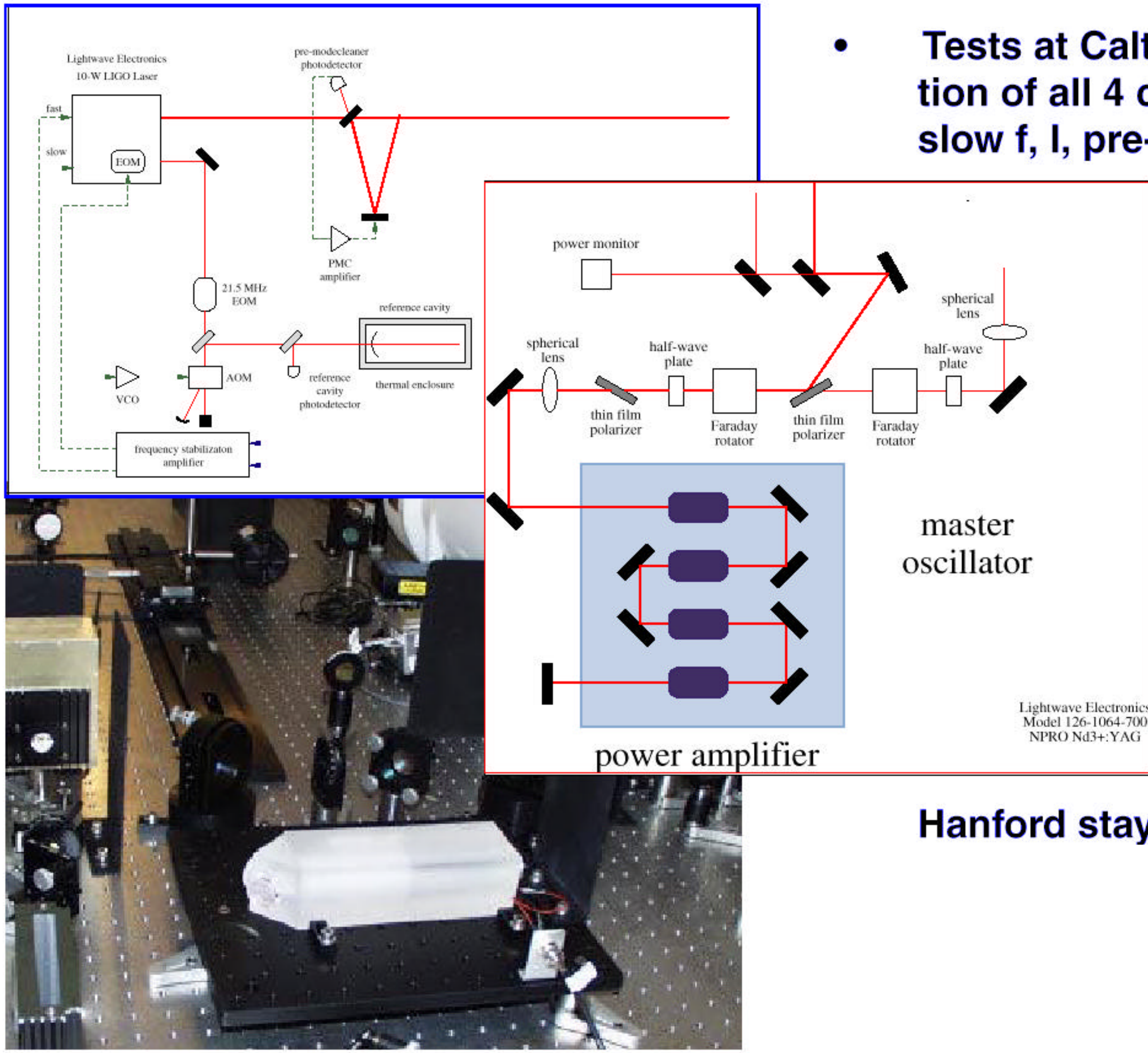
Date: 11/16/1998
Time: 16:39:59
Wavelength: 1.064 um
Pupil: 100.0 %
PV: 6.4471 nm
RMS: 1.1005 nm
Rad of curv: 570.70 km

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

Detail of suspension wire stand-off

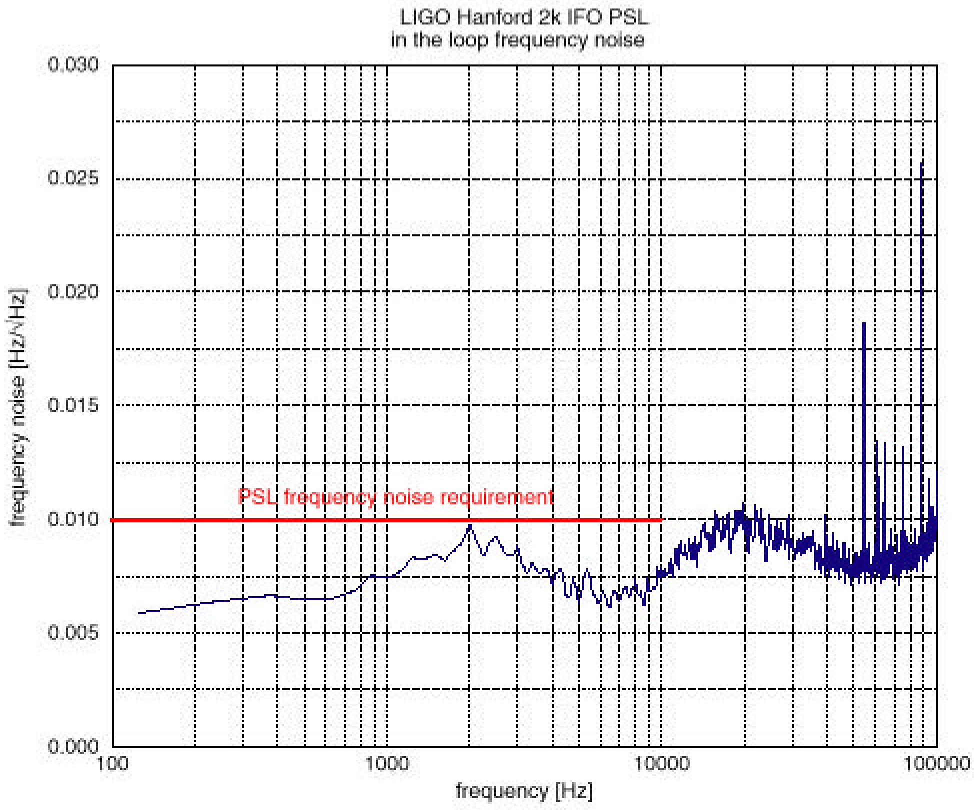
Laser status

- Wavelength = 1.06μ,
- output power > 8W in TEM_{00} mode
- frequency noise: $\delta\nu(f) < 10^{-2}$ $Hz/Hz^{1/2}$, 40Hz<f<10KHz
- intensity noise: $\delta I(f)/I < 10^{-6}/Hz^{1/2}$, 40 Hz<f<10 KHz
- 5 delivered out of 10 ordered
- 1 each installed at LHO and LLO
  – frequency and intensity control servos being implement



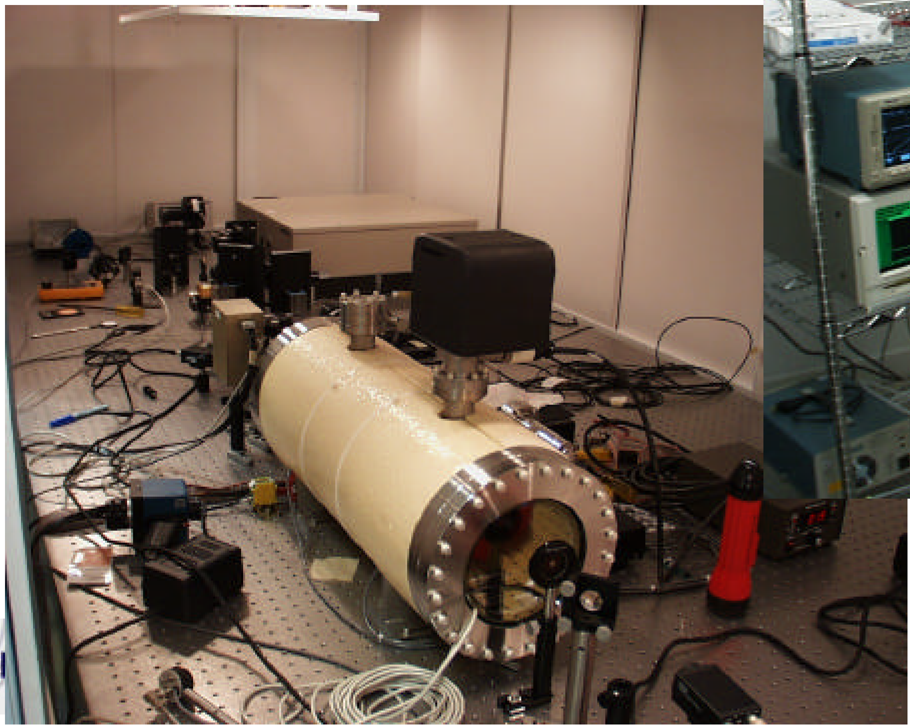
- **Tests at Caltech validated operation of all 4 control servos [fast/ slow f, I, pre-MC]:**
  - ***Auto-lock acquisition of f-stabilization servo and pre-MC servo demonstrated***
- **2km IFO PSL at Hanford stayed locked for 264 hrs**

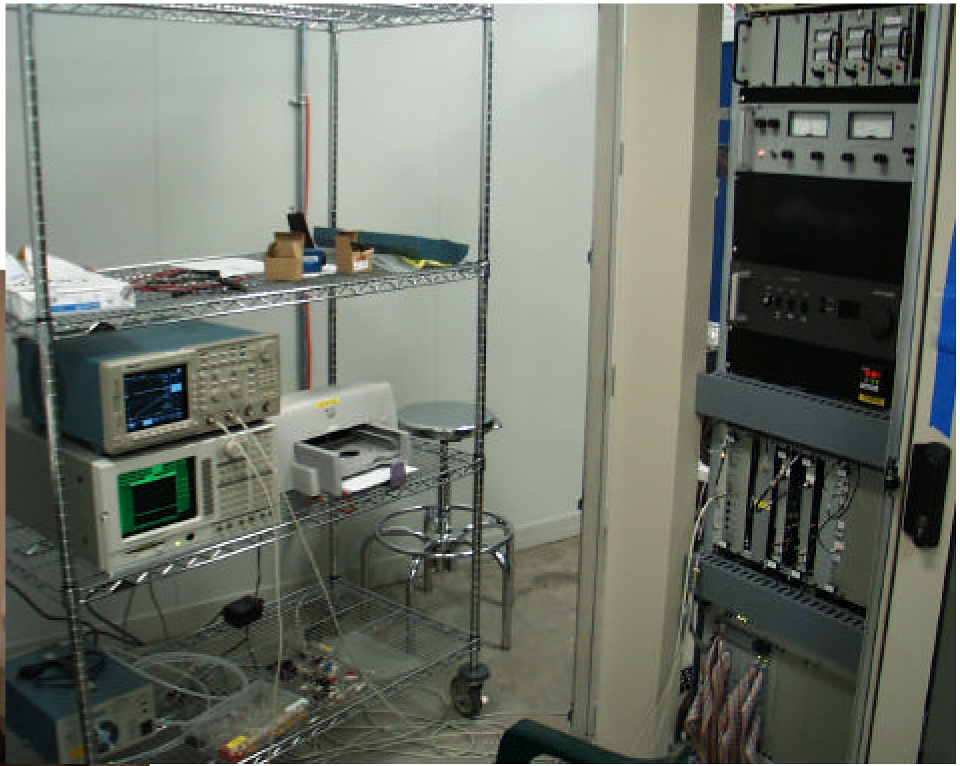
Pre-stabilized laser frequency noise meets LIGO requirements



Pre-stabilized laser installation at Livingston

Pre-stabilized laser (with reference cavity in foreground) during installation





PSL control electronics

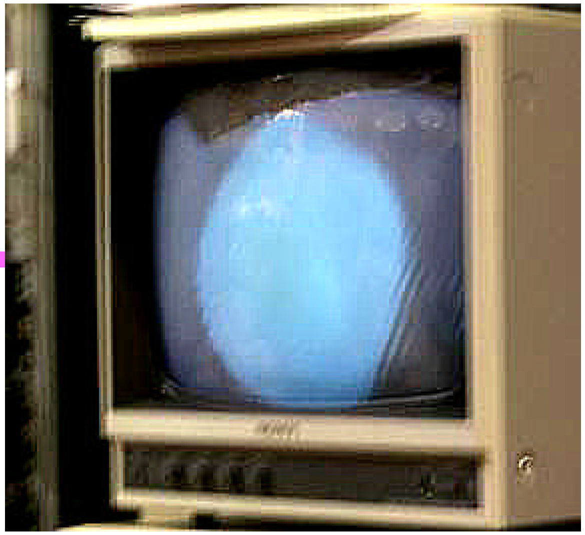
Mode cleaner

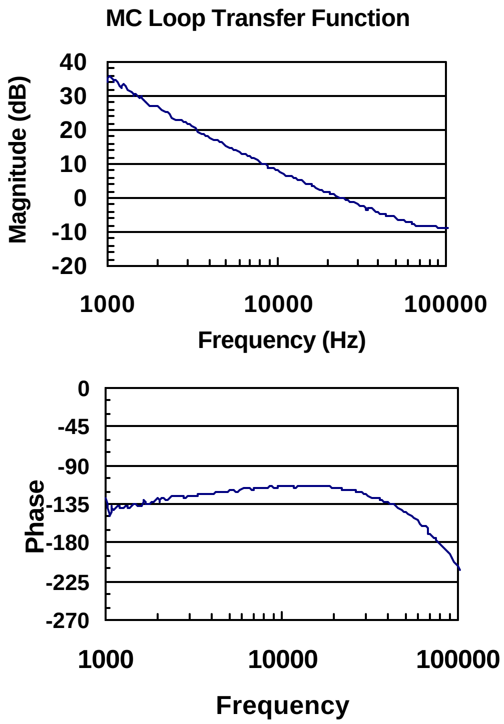
- 15 meters long
- resonant for carrier and side-bands
- provides frequency and spatial stabilization of input light
- active frequency stabilization thru feedback to PSL
- passive spatial stabilization (at all frequencies) and passive frequency stabilization above cavity pole
- mode cleaner frequency noise (limited by mirror thermal vibration):
    - $< 10^{-4}$ Hz/Hz$^{1/2}$ at 100 Hz
    - $< 10^{-5}$ Hz/Hz$^{1/2}$ at 10 KHz

Mode cleaner installation at LHO

LHO 2 KM Interferometer Mode Cleaner Lock

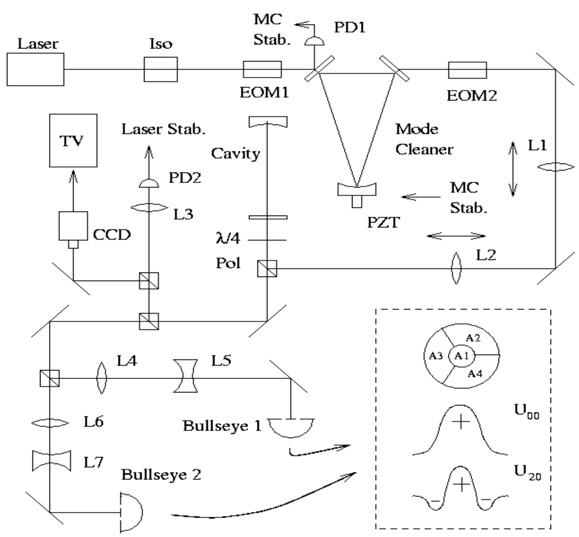
- Demonstrates successful integration of PSL controls and suspension servo controls
- aligned and preliminary lock achieved in air
- mode cleaner stably locked in vacuum:
  - interferometer resonant side bands transmitted through mode cleaner
  - mode cleaner length measured
  - measurements of cross couplings between pitch, yaw, and position and diagonalization of the sensing matrices performed
  - preliminary measurements of mode cleaner length servo loop transfer functions



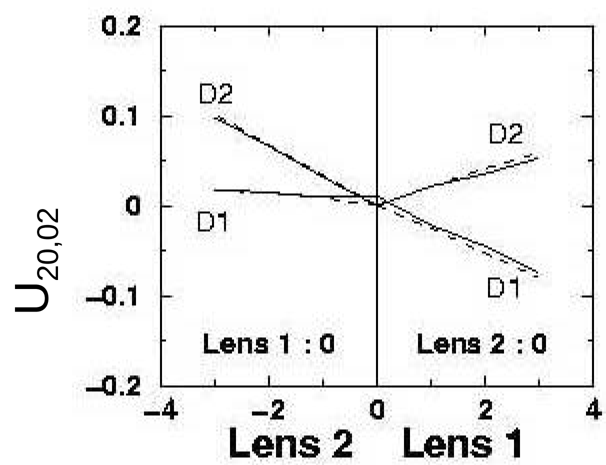


LIGO Mode Matching Diagnostics

- Desire accurate measurement of mode matching into arm cavities
- Heterodyne technique similar to wavefront alignment sensing system, but for higher order modes: $U'(r,z)=CU_{00}(r,z)+\epsilon U_{20,02}(r,z)$;
- "Bull's eye" photo-diode used to detect 2,0 modes



Lens position (mm)



Schematic of prototype measurement

U_{00} = Gaussian mode and $U_{20,02}$ are higher order cylindrical modes,

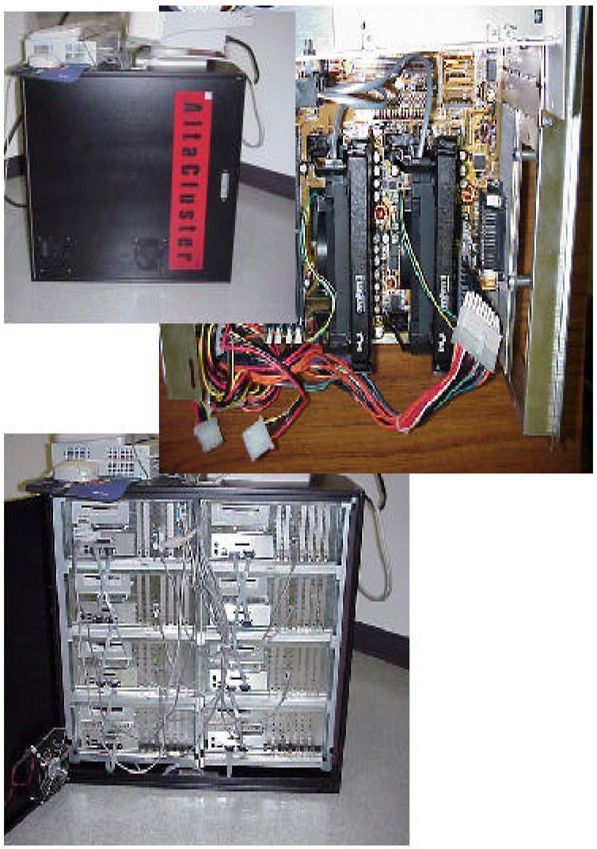
ε=complex coupling coefficient

D1, D2 are waist position and size

Data acquisition and control system status

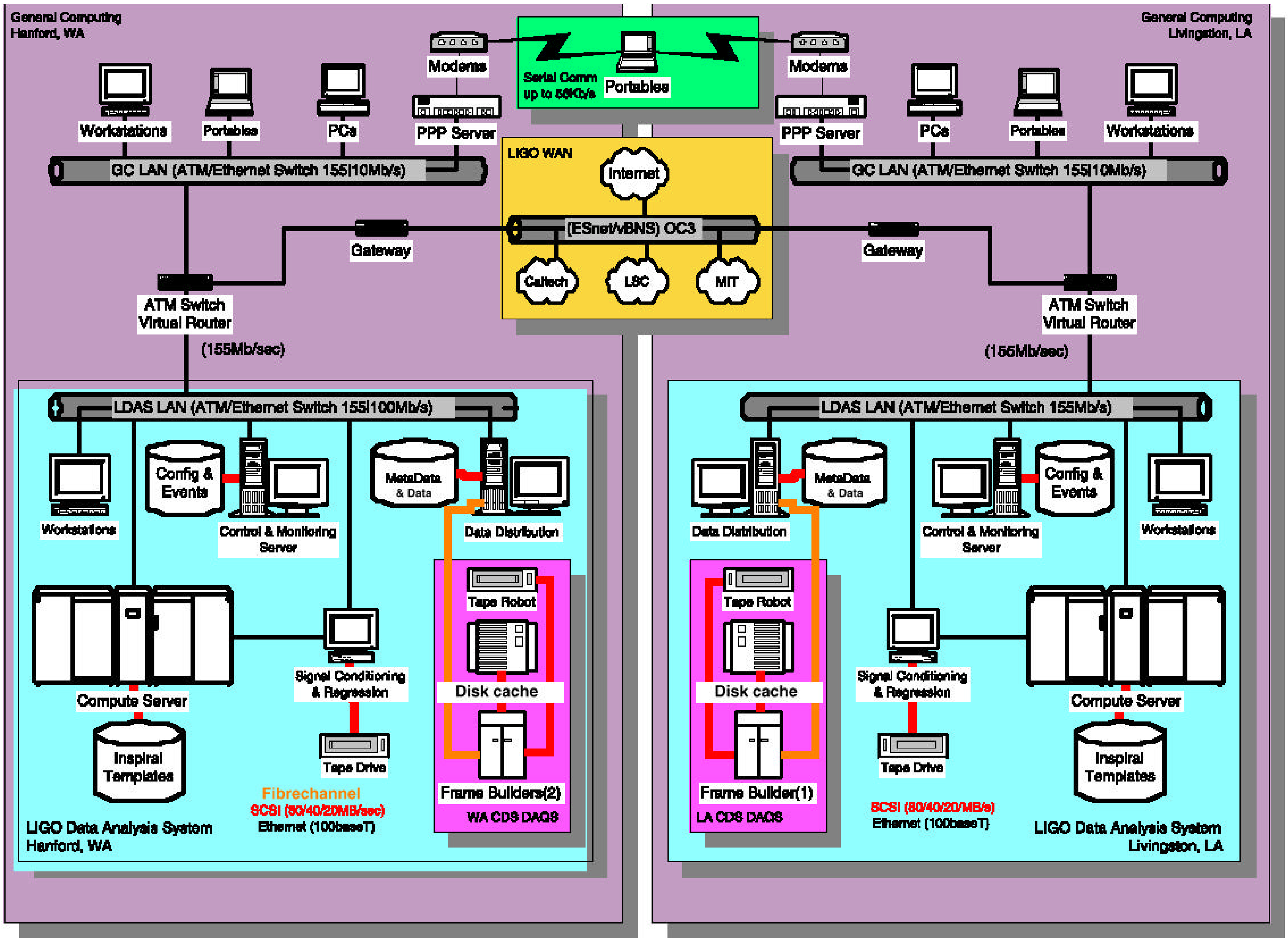
- **vacuum controls** installed at both sites
- **pre-stabilized laser controls** installed at both sites
- **environmental monitoring system** - installation of hardware and software in progress
- **suspension control system** installed and operating in Hanford, begins in August at LHO
- **alignment and length sensing** (for mode cleaner) control system installation underway at LHO, not yet started at LLO
- **preparing suspension system, length, and alignment servo controls** for one arm test at LHO in August

LIGO Data Analysis System

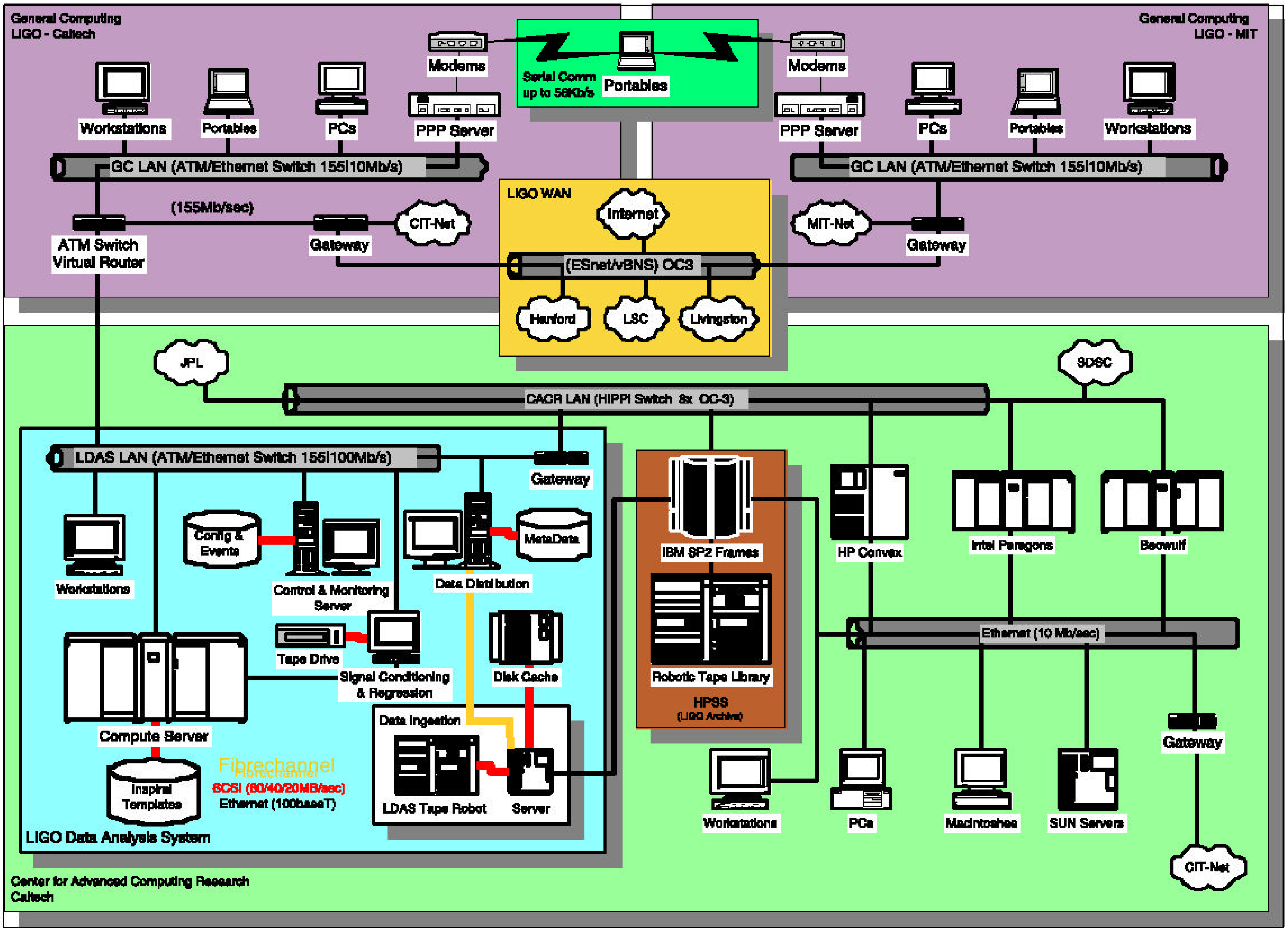


- **on-line systems dedicated to processing 100% of the GW channel**
- **design is now complete**
  - Layered, modular design allows future extensions and revisions of analysis flows as experience grows
    - *optimal filters*
    - *transients*
    - *frequency- time analyses*
    - *end- to- end detector diagnostics*
  - data distribution to local and remote users
- **off-line system dedicated to archiving data, distribution,computationally intensive re-analysis of the GW channel**

On-site data analysis system design



Off-site data analysis system design



Simulation and Modelling

- **End-to-end model is complete and has been released for use to build up LIGO model elements:**
  - PSL:
    - time domain model of laser complete, validation with hardware in progress at LHO
  - Input optics:
    - modelling of detailed components in progress
  - Suspensions+seismic isolation:
    - simple suspended optic + fiber model being implemented for LIGO main optics.
    - Measured stack transfer functions used to estimate filtered ground motion (more detailed physical model of stack planned with support from Univ of Pisa
  - Servo controls
    - digital representations of LIGO control loops (gains, poles, zeroes) being implemented
- **Plan to have sufficient simulation capability in place to support single arm studies getting underway at LHO**
- **Efficiency improvements in model being investigated:**
  - parallelization, coding efficiency

Schedule

LIGO Hanford:

• tests of laser and mode cleaner	summer/fall 1999
• "first light" down one arm	fall 1999
• complete installation/commissioning of 2K and 4K IFO's	2000

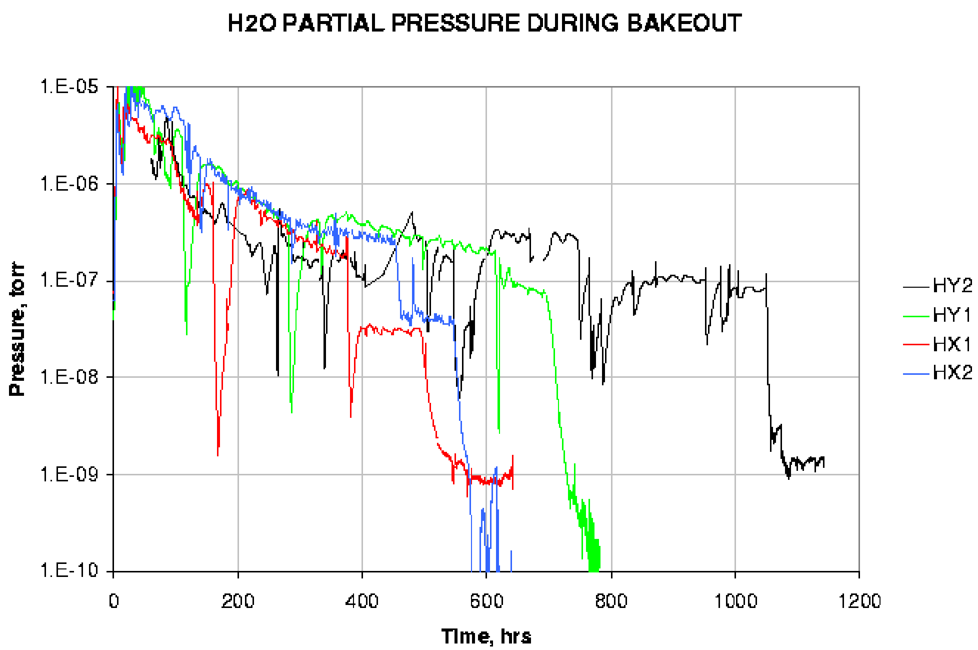
LIGO Livingston:

• complete installation and commissioning of 4K IFO	2000

Simultaneous operation:

• "Engineering run" at reduced strain sensitivity	12/2000
• first coincidences by 2001	
• improve reliability and sensitivity	during 2001
• first "Scientific Data run"	2002
– planned for 2 years @ 50% efficiency at $h \sim 10^{-21}$	

LIGO Hanford beam tube bakeout results



- **HX1:** 200-375 hrs, at 168 C (150 C afterwards for intercomparison)
- H_2O hangs at 1e-9 torr during cooldown because we (deliberately) left the bake jackets at the RGA inlet hot
- **HX2:** 100-450 hrs, at 168 C (150 C afterwards for intercomparison) held hot longer because data taken early in bake had higher pressures
- **HY1:** 300-600 hrs, at 160 C (150 C afterwards for intercomparison)
- **HY2:** 150 C throughout except for several down periods due to PS breaker failures or pump failures. 600-750 hrs, 2 pumps (either side of RGA) off system for repair.

Beam Tube Bakeout Results

	Outgassing Rate corrected to 23 °C torr liters/sec/cm^2 (All except H_2 are upper limits)					
molecule	Goal*	HY2	HY1	HX1	HX2	
H_2	4.7	4.8	6.3	5.2	4.6	$\times 10^{-14}$
CH_4	48000	< 900	< 220	< 8.8	< 95	$\times 10^{-20}$
H_2O	1500	< 4	< 20	< 1.8	< 0.8	$\times 10^{-18}$
CO	650	< 14	< 9	< 5.7	< 2	$\times 10^{-18}$
CO_2	2200	< 40	< 18	< 2.9	< 8.5	$\times 10^{-19}$
$NO+C_2H_6$	7000	< 2	< 14	< 6.6	< 1.0	$\times 10^{-19}$
$H_nC_pO_q$	50–2†	< 15	< 8.5	< 5.3	< 0.4	$\times 10^{-19}$

air leak	1000	< 20	< 10	< 3.5	< 16	$\times 10^{-11}$ torr liter/sec

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

†Goal for hydrocarbons depends on weight of parent molecule; range given corresponds with 100–300 AMU

5/24/99 wea