Laboratory Update

LIGO Hanford Observatory [LHO]

LIGO Livingston Observatory [LLO]

Albert Lazzarini

LIGO Laboratory, Caltech

2ND TAMA Workshop on Gravitational Wave Detection

October 19 - 22, 1999

Tokyo, Japan

Overview

- construction project:
  - *complete (except for beam tube bakeout at Livingston)*
  - *within budget and on schedule*
- detector installation:
  - *in progress at both observatories*
  - *close to schedule*
  - *will be completed in 2000*
- commissioning of interferometers
  - *follows installation for period of ~ 1 year*
- first astrophysical data run
  - *planned for 2002*

Outline

- Status of observatory facilities and infrastructure at Hanford (LHO) and Livingston (LLO)
- Status of beam tube bakeout
- Status of detector subsystem installation
  - *Laser*
  - *Input Optics*
  - *Core optics*
  - *Seismic systems & suspension systems*
  - *Data acquisition and control system (DAQ)*
- Simulation environment & Data Analysis System

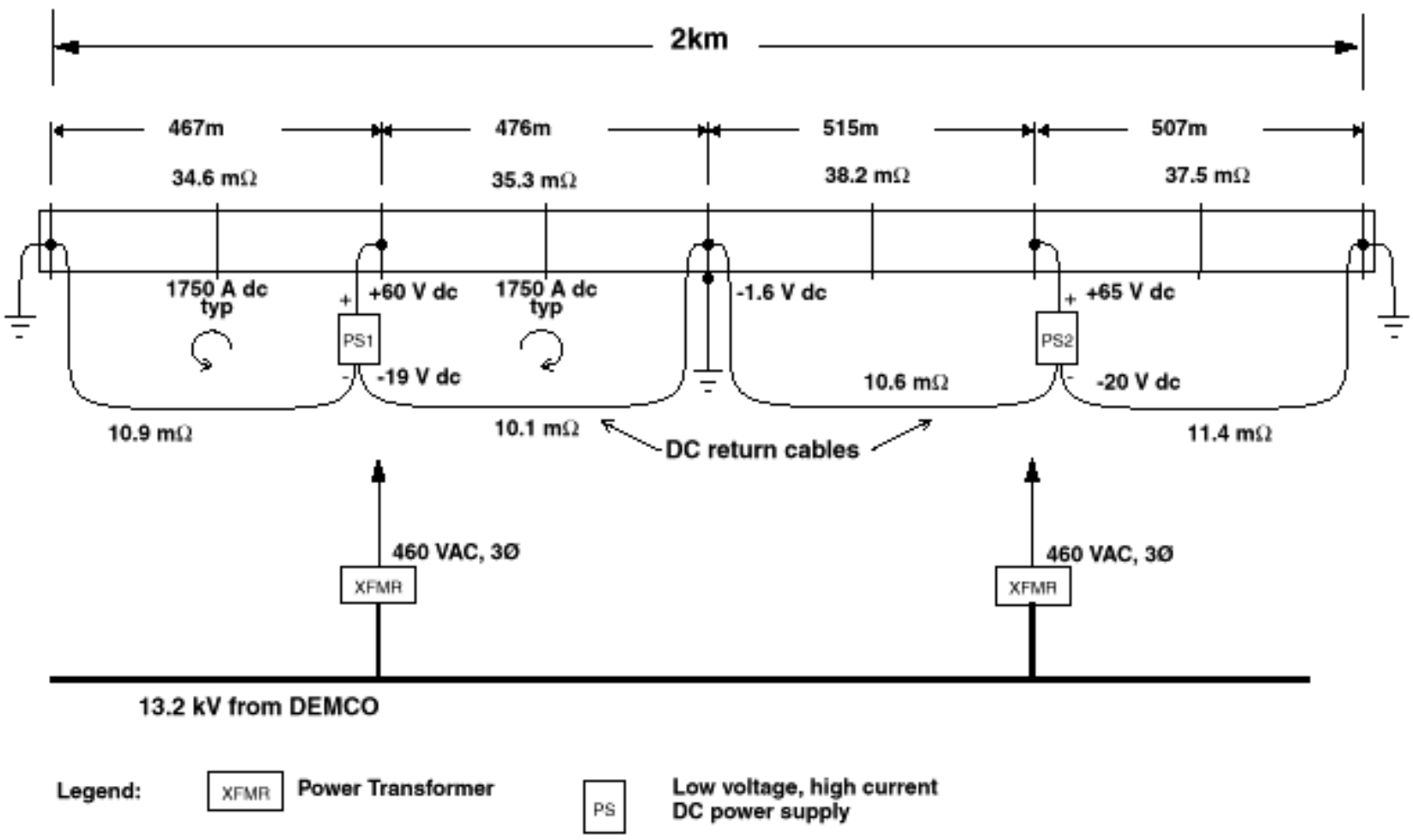
Facilities status

- facility construction is complete at both sites
  - *All vacuum equipment, beam tubes*
  - *All civil construction*
  - *Bakeout of beam tubes now underway at LLO; X-2 complete; X-1 starts by 11/99*
- 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

Beam Tube [BT] Bakeout

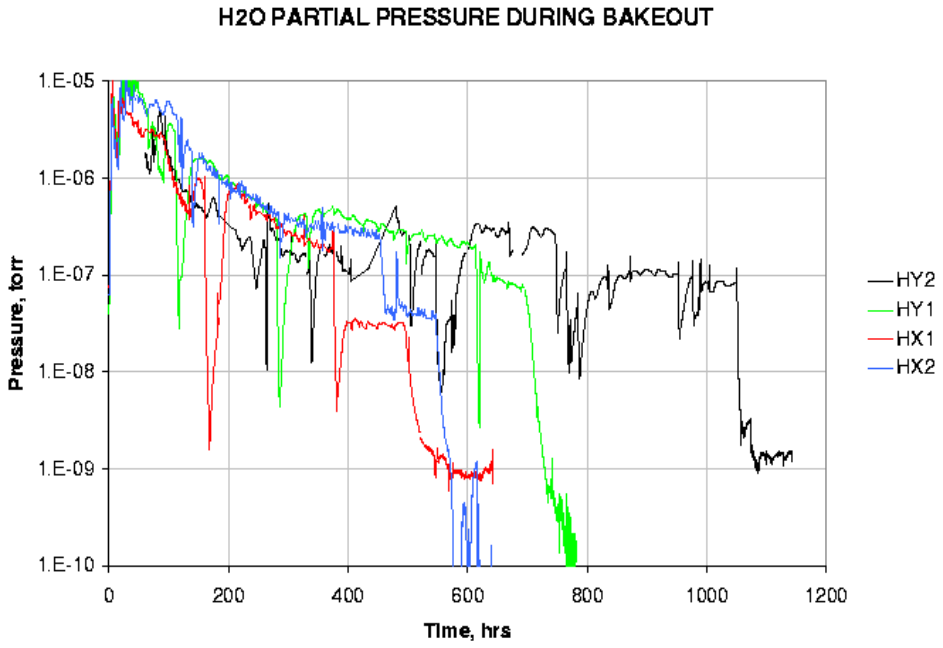
- BT is baked in 2km sections using Ohmic heating of 3 mm 304L SS
  - *heating current ~1500 - 2000 A (depends of ambient conditions - wind, temperature)*
  - *~ 600 sensors mounted along each 2km module to monitor activity and ensure uniform heating:*
    - thermocouples, pressure transducers, strain gauges, RGA, cryopump controllers
- Hanford bakeout of 4 beam tube modules complete [8 km total]
- Results of each bake meet or exceed LIGO goals for *advanced LIGO interferometers*
- Bakes became more efficient and results more sensitive as we learned
  - *higher temperature bakeout (168C vs. 150C) requires shorter duration to achieve pressure goal*
- Bake equipment move from LHO to LLO took 3 months to complete
  - ***1ST of 4 modules at LLO complete [9/99];***
  - ***Bakeout will be completed in ~1 year***

Electrical Layout for Beam Tube Bakeout

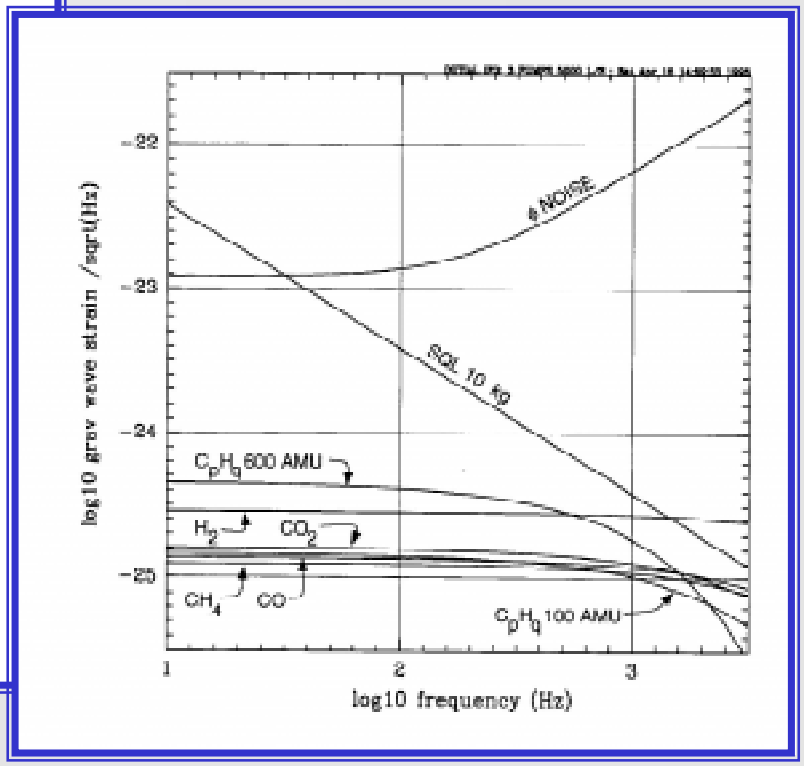


Total of 16 km of beam tube insulated!

Hanford beam tube bakeout results



Residual gas contribution to noise budget



Post-bake Residual Gas Assays

Beam Tube Bakeout Results[a]

NOTE: All results except for H_2 are upper limits

		Hanford				Livingston	
Species	Goal[b]	HY2	HY1	HX1	HX2	LX2	
H_2	4.7	4.8	6.3	5.2	4.6	4.3	x 10^{-14} torr liters/sec/cm^2
CH_4	48000	< 900	< 220	< 8.8	< 95	< 40	x 10^{-20} torr liters/sec/cm^2
H_2O	1500	< 4	< 20	< 1.8	< 0.8	< 10	x 10^{-18} torr liters/sec/cm^2
CO	650	< 14	< 9	< 5.7	< 2	< 5	x 10^{-18} torr liters/sec/cm^2
CO_2	2200	< 40	< 18	< 2.9	< 8.5	< 8	x 10^{-19} torr liters/sec/cm^2
$NO+C_2H_6$	7000	< 2	< 14	< 6.6	< 1.0	< 1.1	x 10^{-19} torr liters/sec/cm^2
$H_nC_pO_q$	50-2[c]	< 15	< 8.5	< 5.3	< 0.4	< 4.3	x 10^{-19} torr liters/sec/cm^2
air leak	1000	< 20	< 10	< 3.5	< 16	< 7	x 10^{-11} torr liter/sec

[a] *Outgassing results correct to 23 C*

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

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

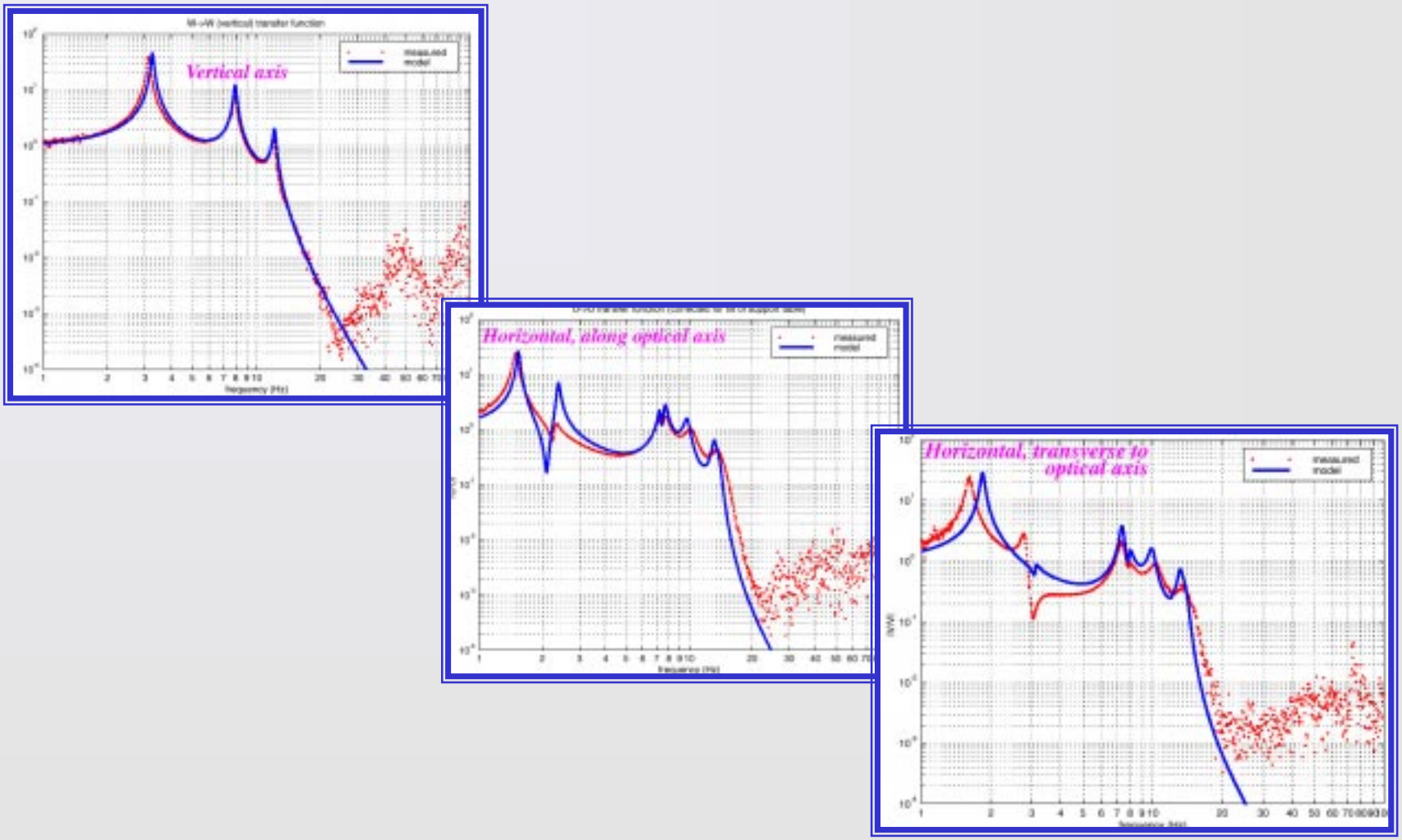
Detector: Seismic Isolation Systems

- LHO:
  - *All 2km chambers, except X-mid station complete*
  - *Coarse actuation systems validated*
  - *Work started on 4km interferometer*
  - *Problem with fluorel seat on bases of metal springs:*
    - H_2O outgassing load too large for LN_2 pumps
    - *Do not want to risk contaminating BT subsystem*
    - Need to pre-bake seats & control exposure to ambient air (< 8 days total after insertion)
    - Requires replacement of previously installed seats -- requires re-alignment of large optics
    - Rework at LHO to be complete by end of 11/99

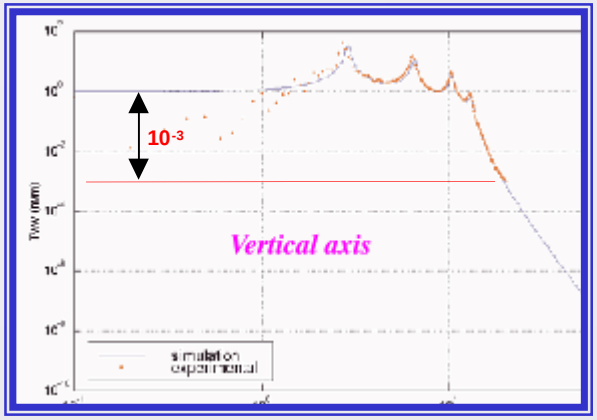
Detector: Seismic Isolation Systems

- LLO:
  - *All HAMs complete, 3 of 5 BSCs*
    - Still to-do: BS and X-end
  - *Coarse actuation servo electronics installation in November*
  - *In vacuo test of seismic isolation systems completed to validate and extend previous in-air results*
  - *Fluorel seat replacement required*
  - *Lessons learned @ LHO permit faster progress*

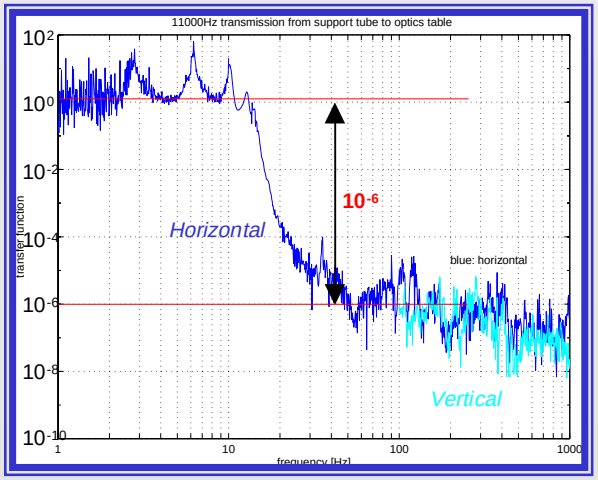
HAM seismic isolation system tests measured in air at LHO



Tests of BSC prototype seismic isolation system

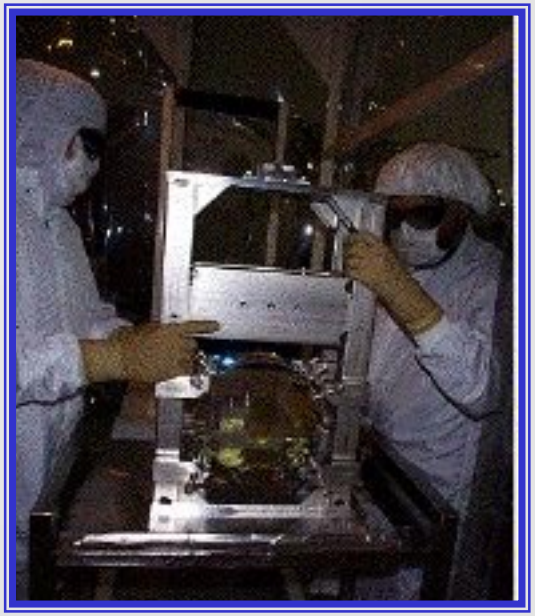


- Initial measurements of BSC isolation transfer function made in air at Hytec.
- Measurements in vacuum completed at LLO



Detector: Suspension Systems

- LHO:
  - *2km - All large optics, except X-mid installed & aligned once*
    - Several issues identified & resolved:
      - Sensor/actuator heads shorted - required re-work & retrofits
      - Magnet/standoff assys. on 3 large optics failed, needed re-work, changes to procedures.
      - No further problems encountered
    - Realignment needed after fluorel seat baking & replacement
- LLO:
  - *IO assembly begun*
    - Suspension electronics test in optics lab; controllers for IO installed
    - MMT3 suspended
    - RM mirror assy. begun

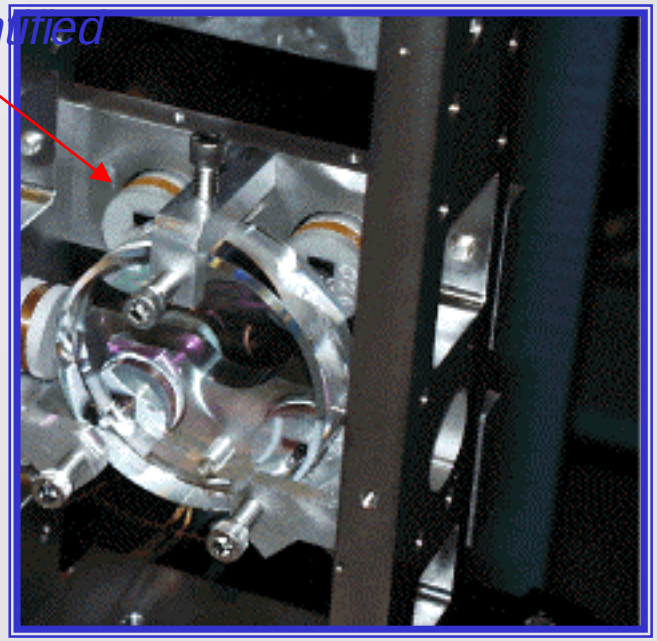


Detector: Input Optics

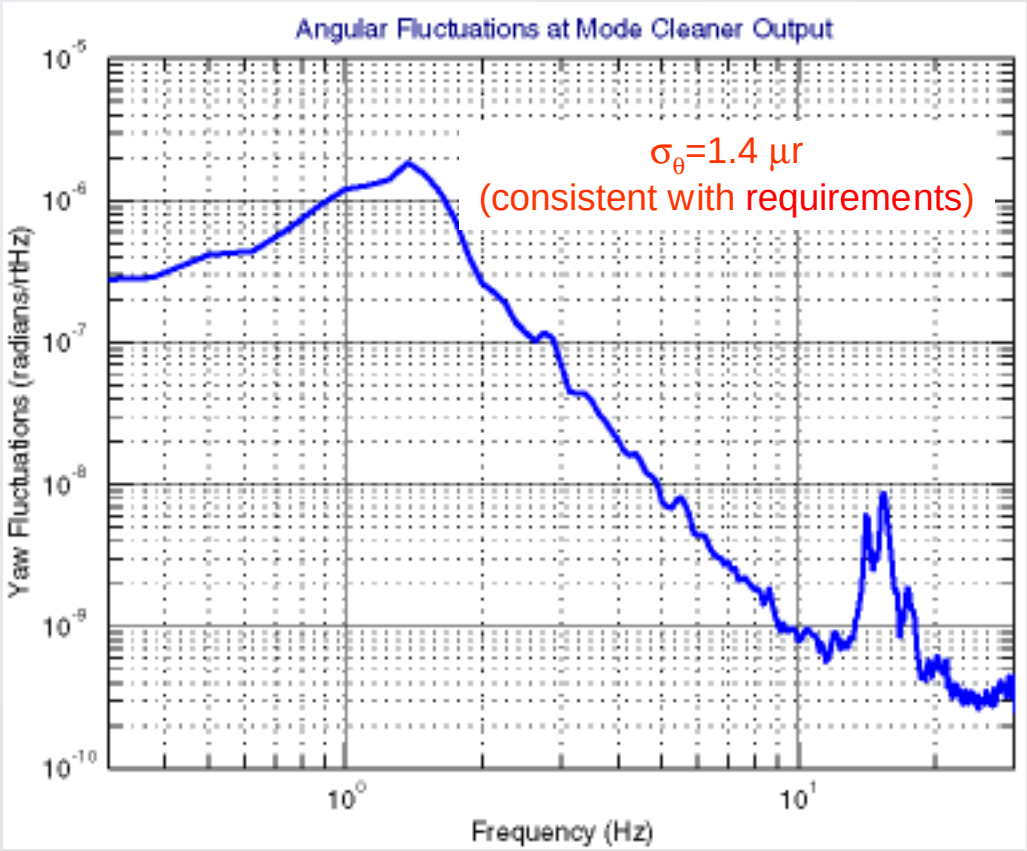
- LHO 2km Interferometer:
  - *IO installation complete, characterization under way.*
  - *Mode cleaner (15 m) locks for 12+ hours at a time*
  - *Cavity length : 15251 mm*
  - *Linewidth: 6.26 kHz*
  - *Finesse : 1550*
  - *Scatter+absorption+transmission as expected*
    - few 10s of ppm
  - *Length & frequency control servos operate as expected*
  - *Small optics suspension/servos now being characterized*

Detector: Input Optics

- LHO 2km Interferometer:
  - *Uncovered local alignment/damping system (OSEM) issue*
    - DC-coupled sensors have spectral overlap with PSL high power laser
    - Scatter from resonant build up [expected] leads to conflicting sensor signal, affecting alignment stability, local damping
    - *Short term (masks) solution identified*
    - Long term correction planned (change sensor wavelength, bandpass optical filter, etc.)
- LO:
  - *Installation has started*
    - assembling and suspending small optics

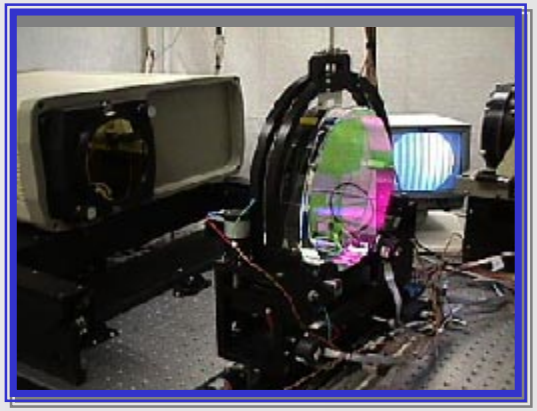


15 m Mode Cleaner Angular Fluctuations

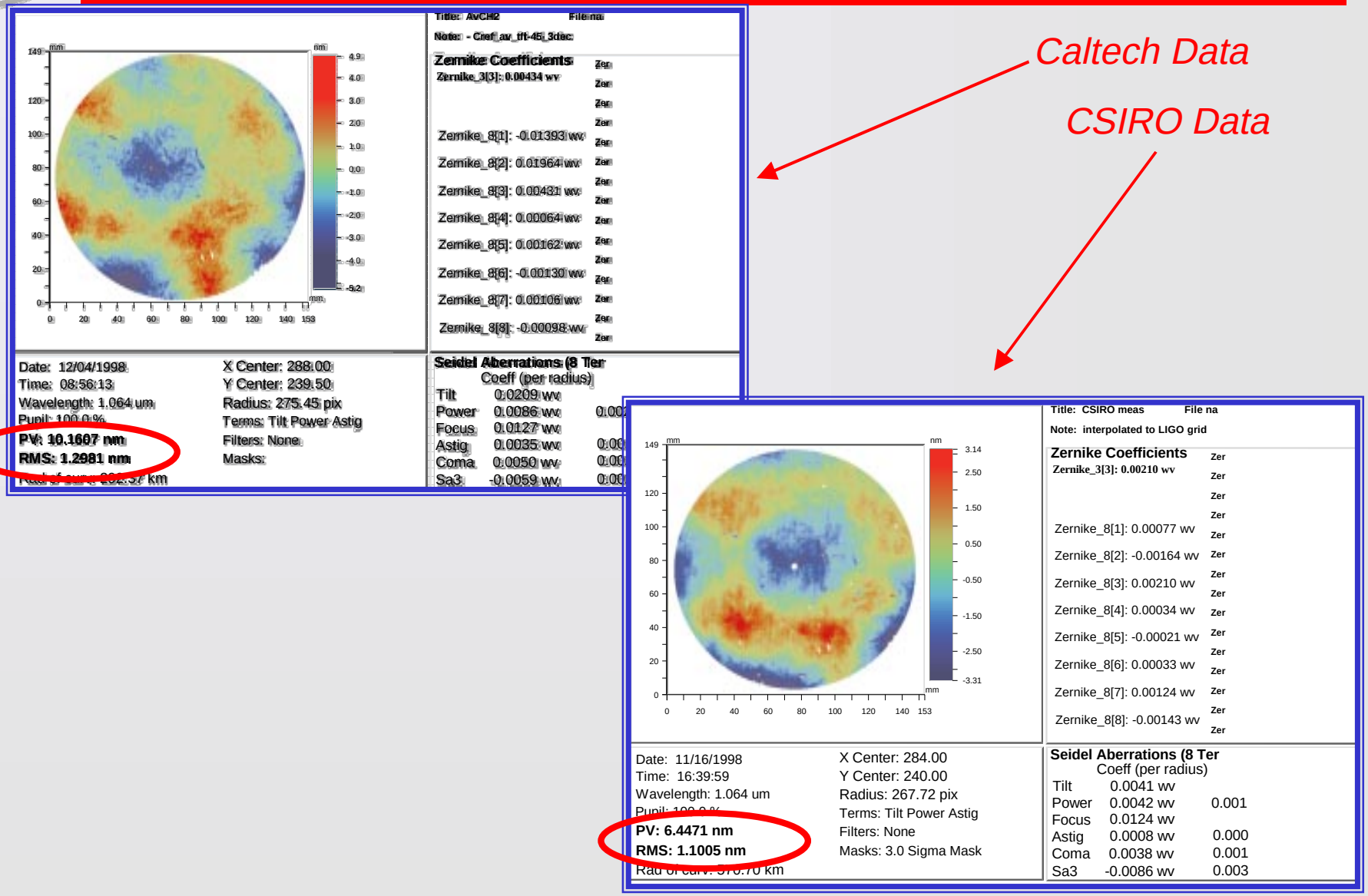


Detector: Large Core Optics

- All 40 optics polished, coated
  - *Microroughness within spec. (<10 ppm scatter)*
  - *ROC within spec. ($\delta R/R < 5\%$, except for BS)*
    - Hand-selection of matched pairs gives $\delta R/R < 3\%$,
  - *Coating defects within spec. (pt. defects < 2 ppm, 10 optics tested)*
    - Two optics rejected due to coating imperfections - need to be re-polished, re-coated
  - *Coating absorption within spec. (<1 ppm, 40 optics tested)*
- LHO 2km interferometer:
  - *All optics at site, complete*
- LLO:
  - *Characterization in progress at Caltech*
  - *Recycling mirror delivered for installation*



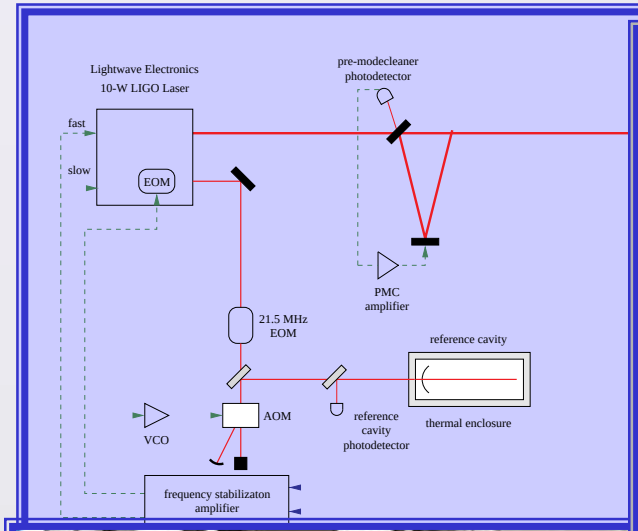
Large Optics Metrology at Caltech

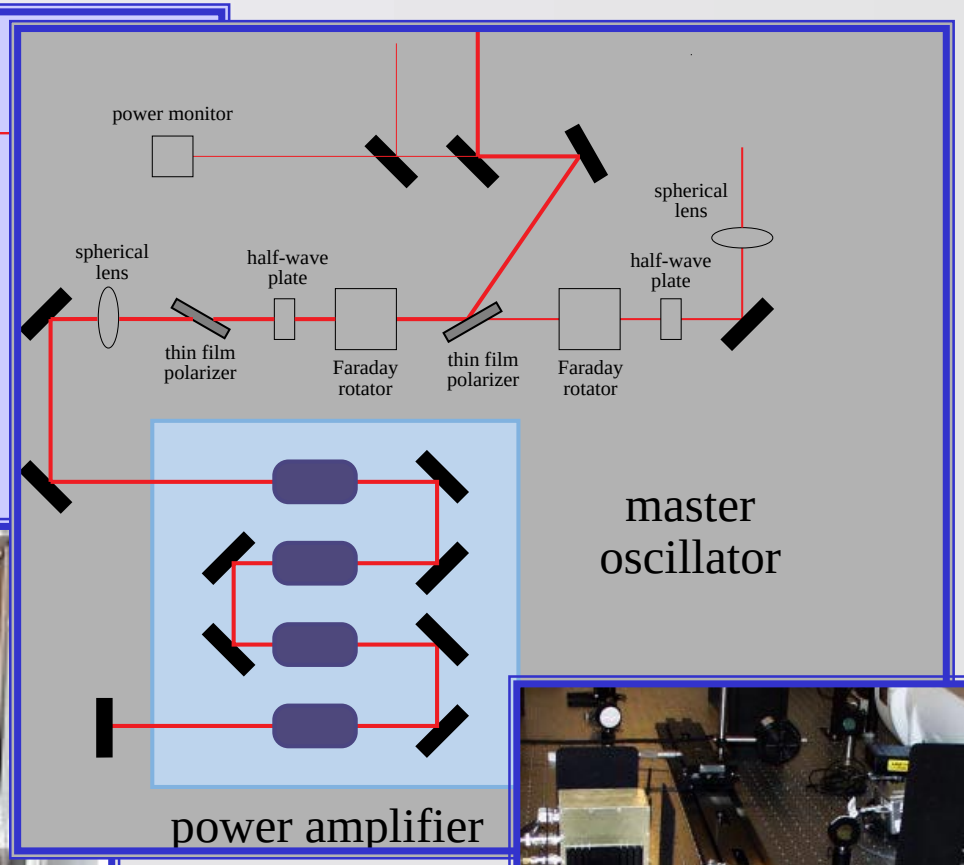


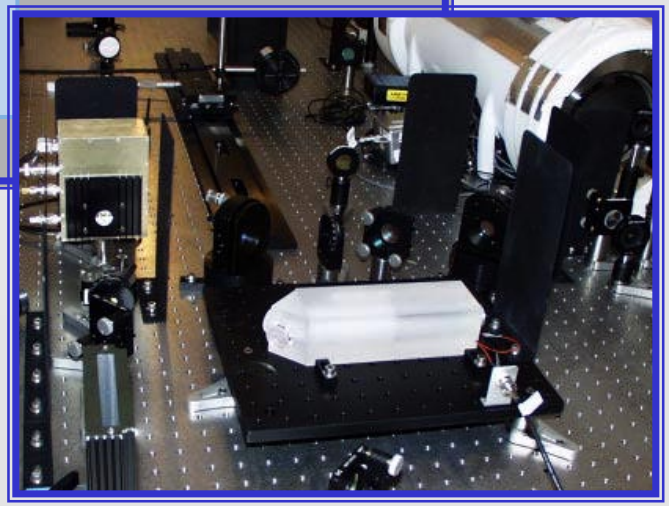
Detector: Prestabilized Laser Subsystem [PSL]

- Output power > 8W in TEM00 mode @ 1.064 µm
- Frequency noise: $\delta n(f) < 10^{-2}$ 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 of 10 ordered
- 2 total installed at LHO and LLO
  - *LHO frequency and intensity control servos implemented*
  - *LHO PSL subsystem routinely locks for days*
  - *LHO PSL integration with 15 m mode cleaner successfully tested*
  - *LLO installation nearing completion, incorporated lessons learned from LHO*
    - Intensity servo modified (use PA current shunt vs.. AO cell)
    - Frequency control servo changes

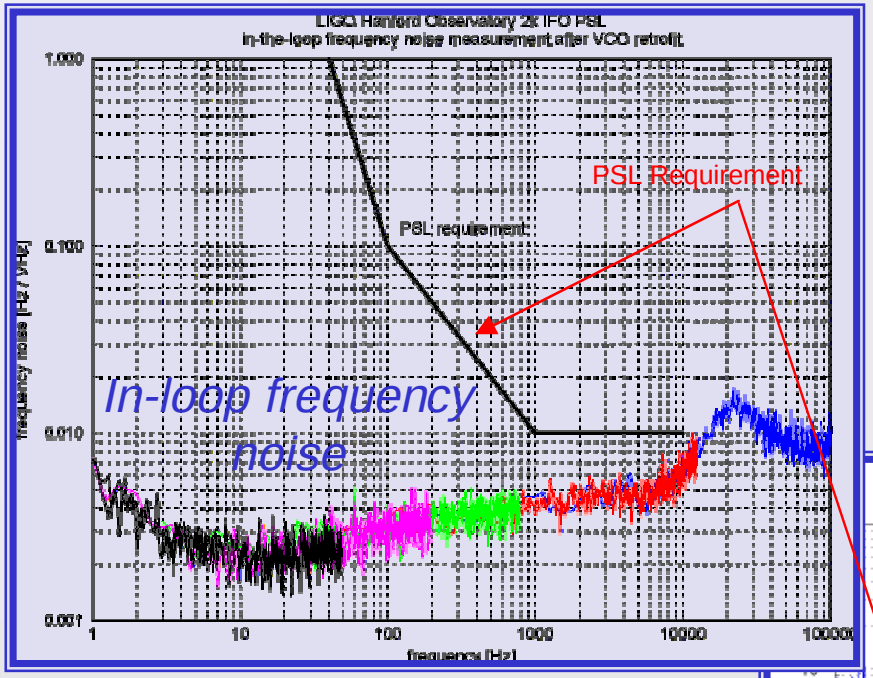
Detector: PSL System

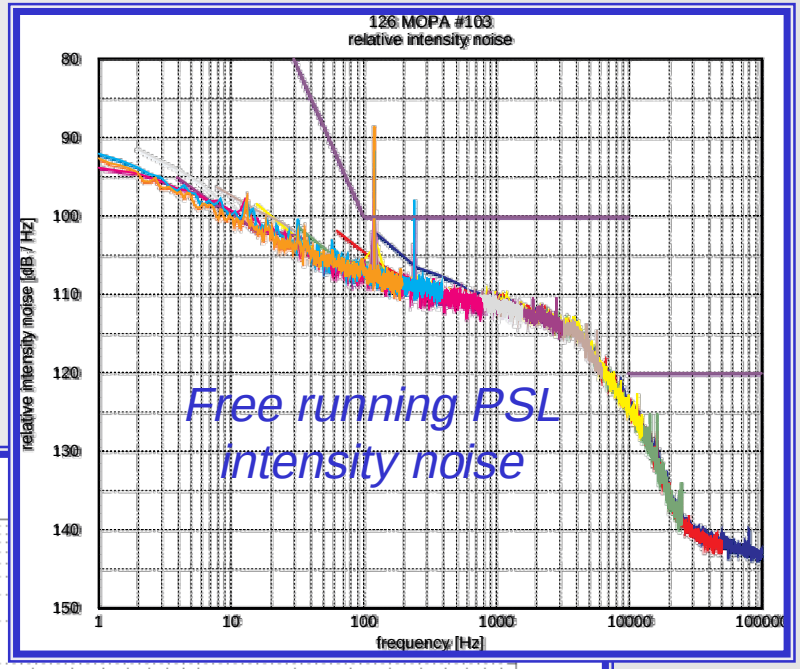


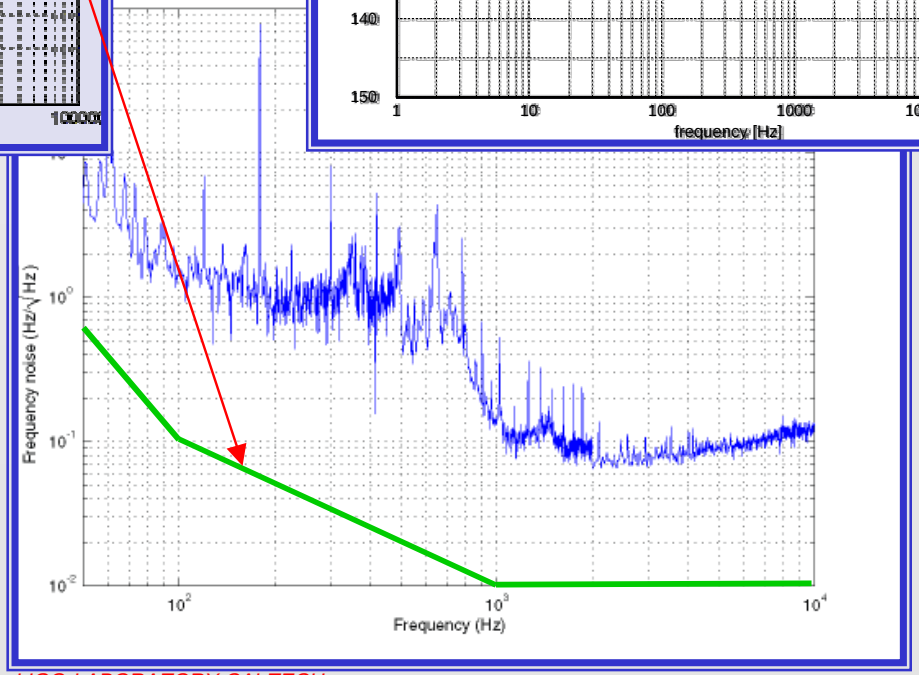




Prestabilized laser frequency noise measured with 15m mode cleaner [LHO]







- *Frequency noise measured by M.C.*
  - 1 Watt
  - ~10X discrepancy with in-loop error signal (above)
  - Work proceeding on identifying noise sources

Detector: Length/Alignment Sensing & Control

- LHO installations completed:
  - *All electronics, software for 15 m M.C.*
  - *EO shutter for MC photodiode protection*
  - *Pico-motors for MC steering*
  - *Vertex control/electronics racks for 2 km interferometer*
  - *Alignment control&sensing subsystems tested, signals transferred to diagnostics subsystem*
  - *Digital control performance timing tests on PIII Intel processor validated*
  - *Design complete, fabrication started for servo boards for 2 km single arm FP testing*

Detector: Data Acquisition & Control System Status

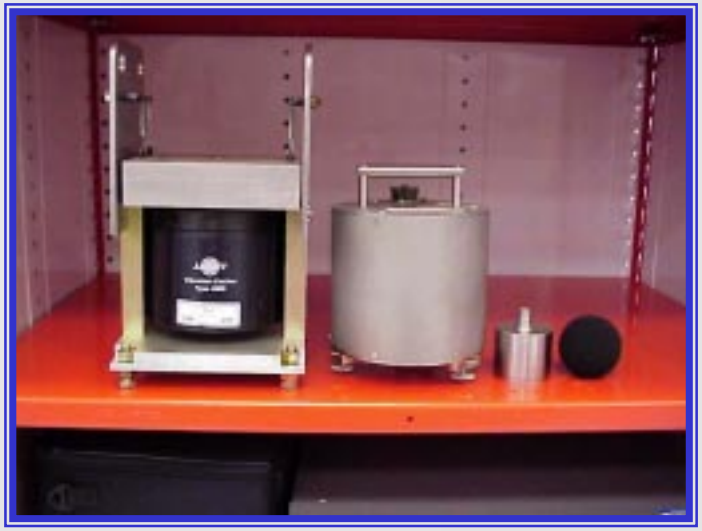
- LHO:
  - *DAQS for mid, end stations complete*
  - *Video systems (cavity modes) complete*
  - *Testing framed data multicasting for diagnostics access*
  - *Anti-aliasing filters for controls being fabricated, installed*
  - *Timing system being fabricated, installed*
  - *Converted C frame library to C++ (LDAS source)*

Detector: Data Acquisition & Control System Status

- LLO
  - *Installation of network servers electronics complete*
  - *DAQS installation at Y-end complete*
  - *Control & data systems for PSL and vacuum equipment complete*
  - *ATM network switch in control room installed*

Detector: Physical Environment Monitoring [PEM]

- All PEM hardware procured
- LHO
  - *All stay-clear zones near interferometers at LHO identified for sensitive equipment*
  - *X1 BT module instrumented (vibration/scattered light tests)*
  - *All accelerometers, microphones for 2 km interferometer installed*
  - *All seismometers, tiltmeters installed*
  - *B[f] measurements made at LHO (also LLO)*
- LLO
  - *High frequency transmission test performed on BSC SEI*
  - *Seismicity measurements ongoing (also at LHO)*



Detector: Global Diagnostics System [GDS]

- LHO:
  - *Low level data monitoring tool (DMT: 1ST level triggers) running at LHO*
  - *Demonstrated high BW data transmission on CDS network*
  - *Diagnostic software tests (for DMT)*
  - *Frame data multicasting interface on data server*
  - *Excitation (sine, swept sine, random time series) drivers for diagnostics completed*
  - *Continued development of ROOT interface for diagnostics analysis*
  - *Installed compute server for diagnostics analysis*

LIGO Data Analysis System [LDAS]

- On-site systems dedicated to processing 100% of the GW channel

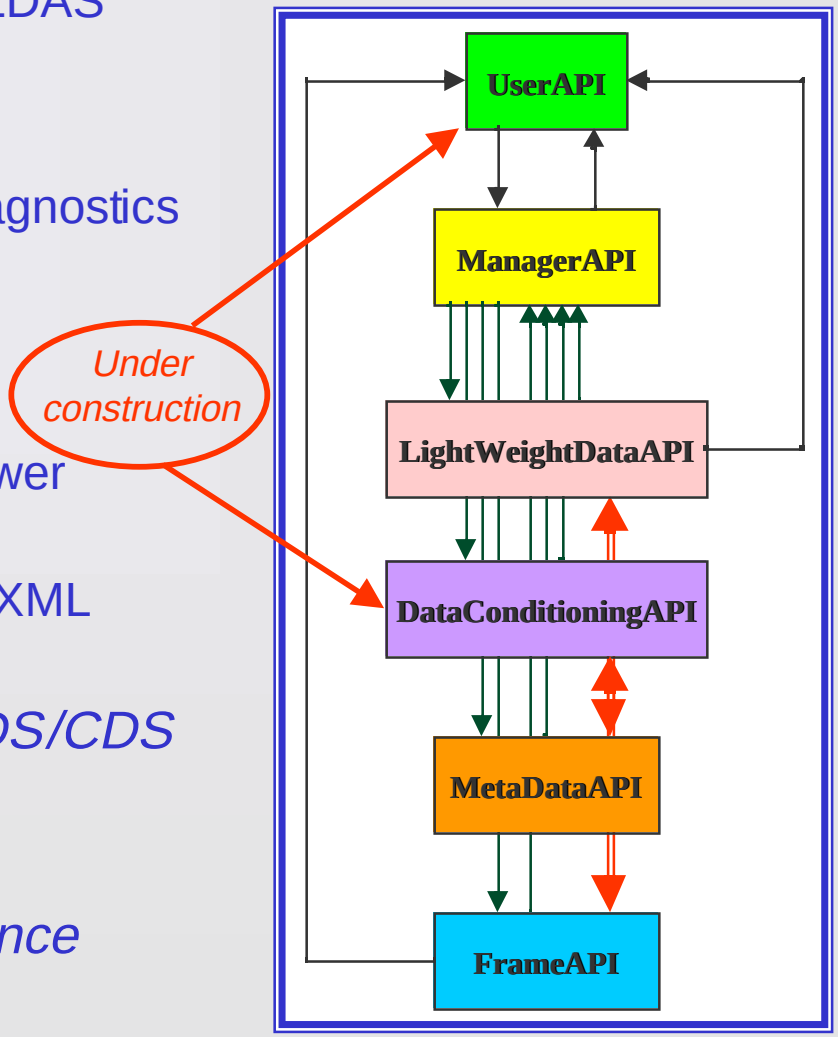
- Design is now complete

- 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

- remote system dedicated to archiving data, distribution,
computationally intensive re-analysis of the GW channel

LIGO Data Analysis System [LDAS]

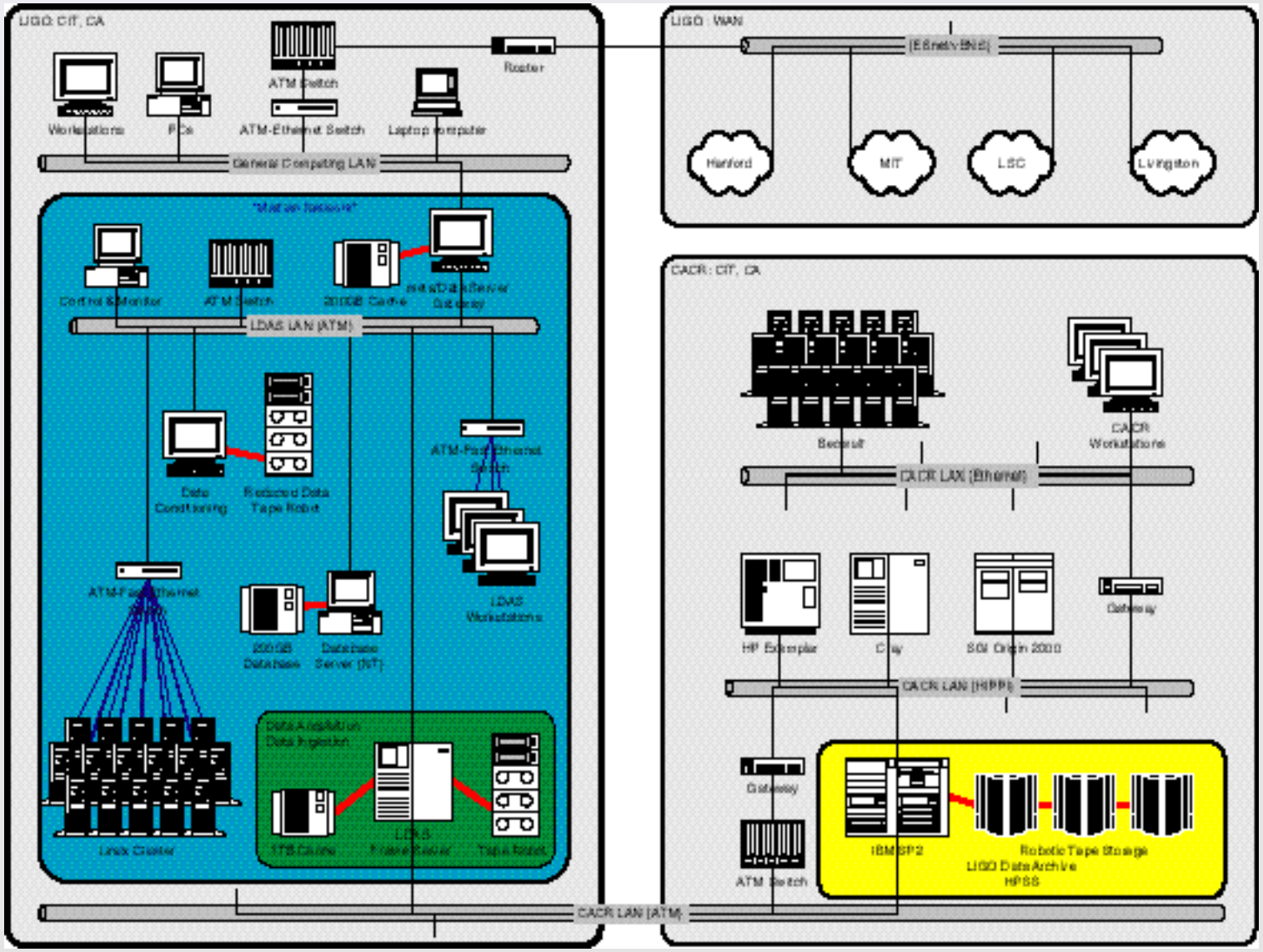
- Release 0.0.3 (α) of a subset of LDAS components installed at LHO
  - *APIs will permit users to:*
    - Ingest metadata (e.g., diagnostics trigger data) in DB2
    - Retrieve/sort metadata
    - Retrieve frame data
    - Create frame subsets (fewer channels)
    - Retrieve channel data in XML (LIGO_LW format)
  - *System integrated with GDS/CDS networks & servers*
  - *Presently doing: validation/debug/performance timing*



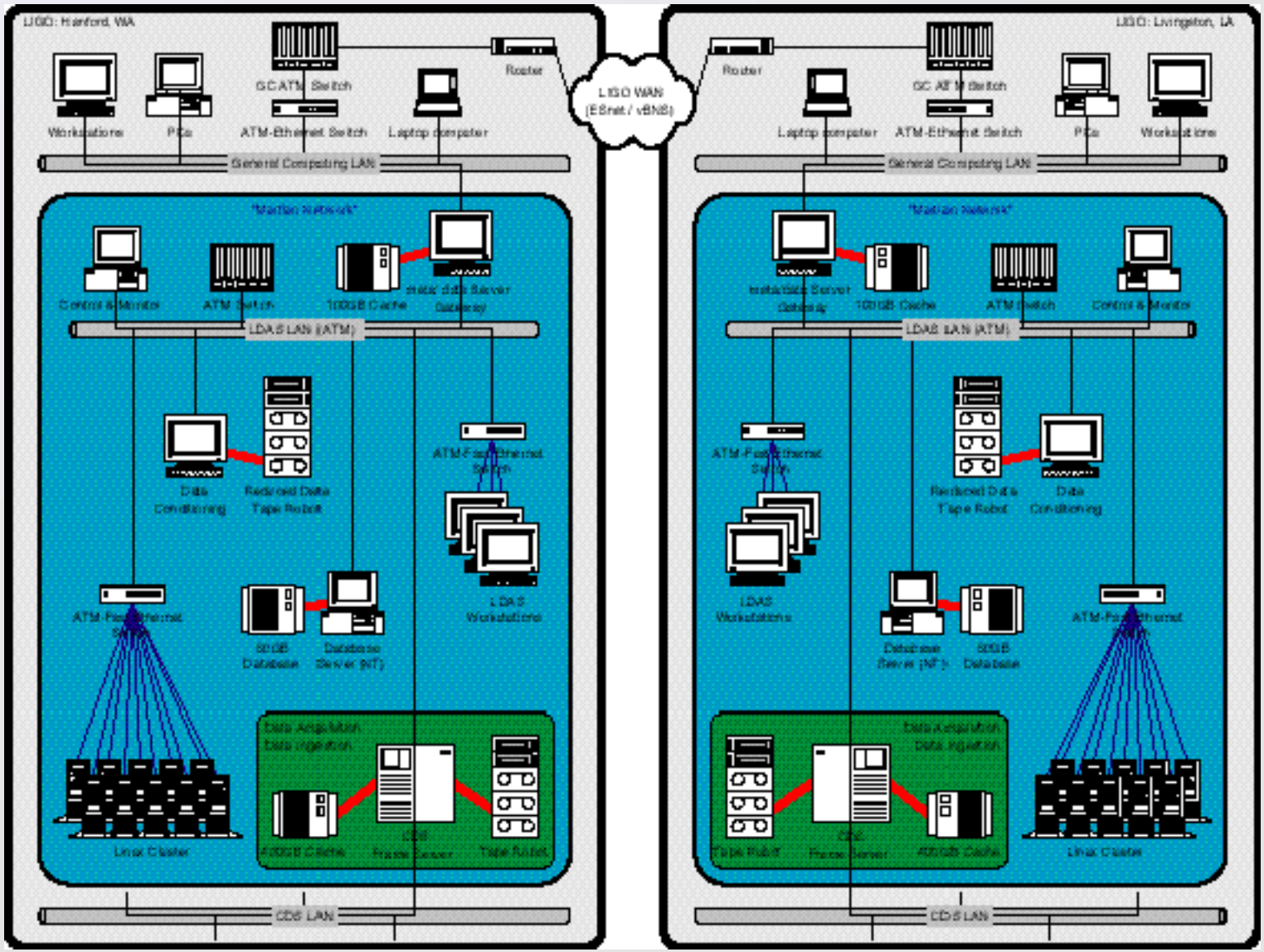
LIGO Data Analysis System [LDAS]

- Data challenge activities
  - *Carried out in concert with LSC members*
    - LIGO/LSC Algorithm Library [LLAL] - defines software C library coding style, conventions for software contributed by LSC membership for incorporation into LDAS
      - I/O behavior
      - Exception handling
      - Data types/data objects (time series, power spectrum, arrays, matrix objects, physical constants, …)
    - November 1994 40m data re-analysis (mock coincidence)
      - Extract events, ancillary channel vetoes (triggers)
      - Ingest into relational database
      - Perform correlation/coincidence studies using LDAS environment as much as possible
    - September 1999 40m+TAMA 300m coincidence run
      - Similar activities, develop protocols for true full coincidence analysis

LDAS Off-site system architecture

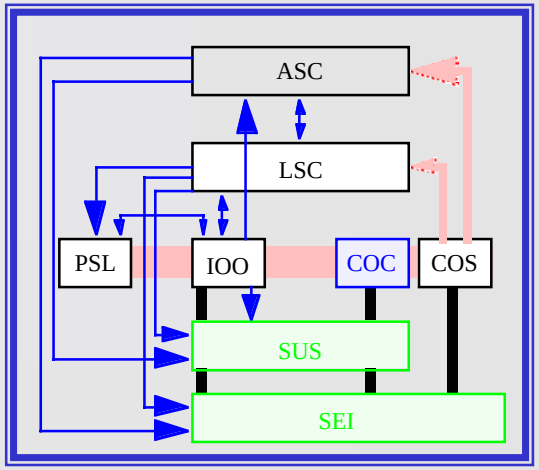


LDAS On-site system architecture



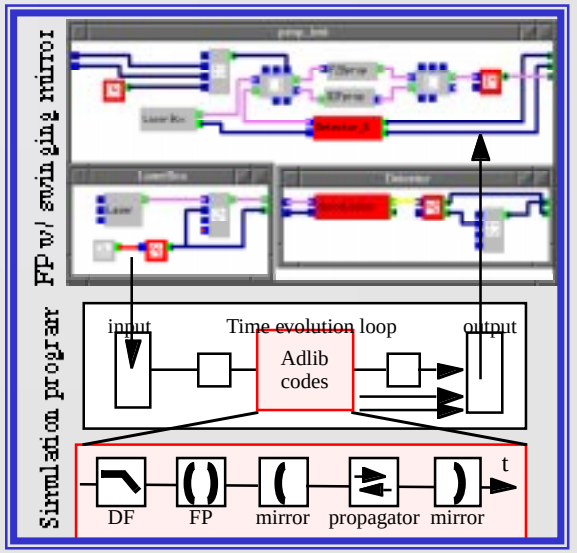
LIGO Simulation and Modeling

- **End-to-end model is complete and has been released for use to build up LIGO model elements:**
  - *Simulation Engine*
    - Time domain (arbitrarily large signal response), written in C++
    - Modular design for flexibility (software components map hardware)
      - Develop new models beyond LIGO I
    - Modal model permits spatio-temporal calculation of EM field - almost complete
    - Mechanics model
      - Primitive fixed configuration for LIGO I almost complete
      - Modular, extensible model for LIGO I and beyond almost complete (G. Cella, Univ. of Pisa)
    - Thermal noise model (phenomenological) almost complete (L.S. Finn, PSU)



LIGO Simulation and Modeling

- **End-to-end model is complete and has been released for use to build up LIGO model elements:**
  - *LIGO I Modeling: PSL+IO+COC+SEI/SUS+LSC/ASC*
    - PSL almost completed, includes frequency, amplitude noise
    - IO length control, frequency control complete, completing angular alignment part
  - *Build up model to support subsystem-by-subsystem commissioning*
    - Integrate & Validate model for 2 km FP arm tests
    - Extend model for vertex Michelson tests
    - Extend model for full 2km, 4km tests



Schedule

LIGO Hanford:

- tests of laser and mode cleaner — summer/fall 1999
- "first lock" down one arm — fall 1999
- complete installation/commissioning of 2K and 4K IFOs — 2000

LIGO Livingston:

- Complete optics suspension & installation — 2000
- complete installation and commissioning of 4K IFO — 2000

Simultaneous operation:

- Engineering run to improve strain sensitivity — 2001
- first coincidence operation — 2001
- Improve reliability and sensitivity — 2001
- First Astrophysics Run — 2002
  - *Expect uptime > 50% over 2 years operating at* $h_{RMS} \sim 10^{-21}$