Detector Installation and Commissioning

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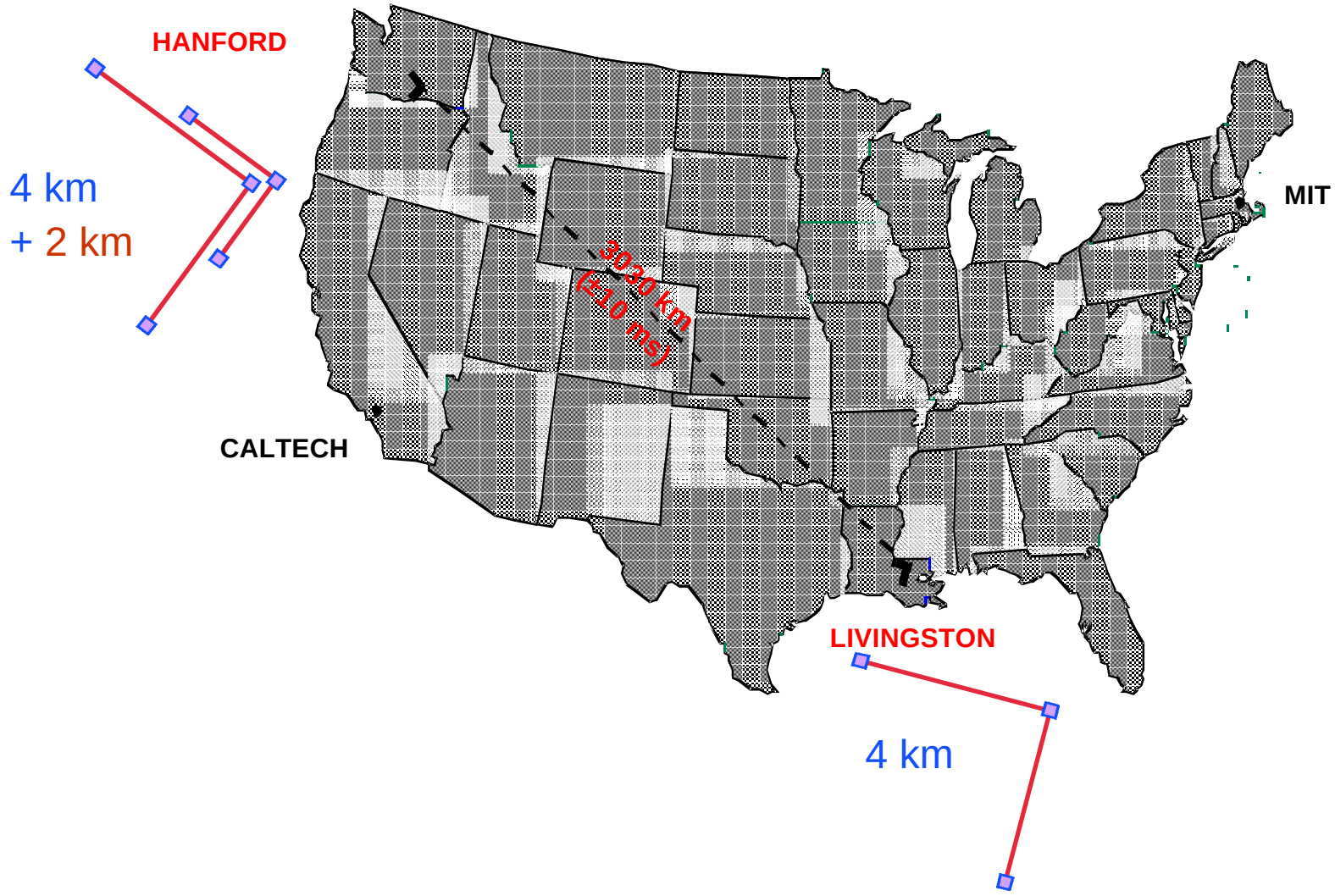
NSF Operations Review

26 February 2001

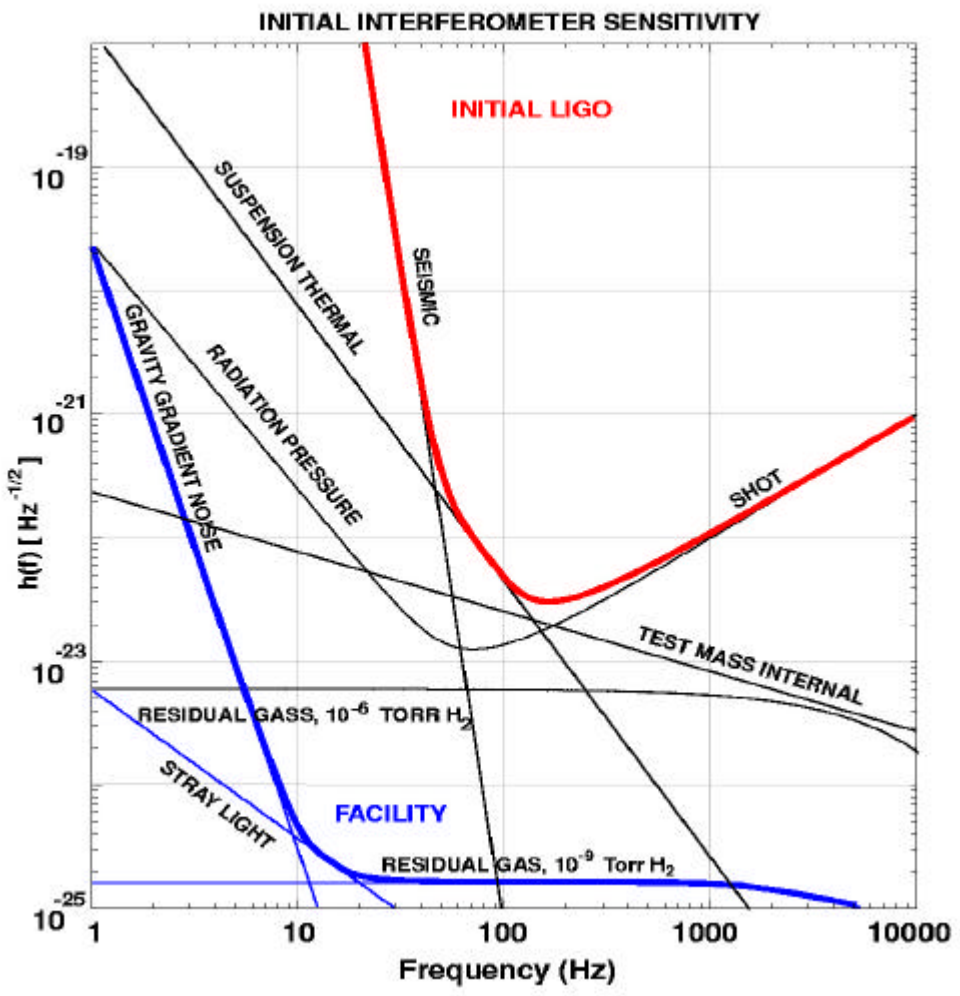
LIGO Hanford Observatory

LIGO-G010035-00-D

LIGO Observatories



Initial LIGO Sensitivity Goal



- Strain sensitivity
  $<3\times10^{-23}$ $1/Hz^{1/2}$
  at 200 Hz
- Sensing Noise
  - » Photon Shot Noise
  - » Residual Gas
- Displacement Noise
  - » Seismic motion
  - » Thermal Noise
  - » Radiation Pressure

Installation/Commissioning Philosophy

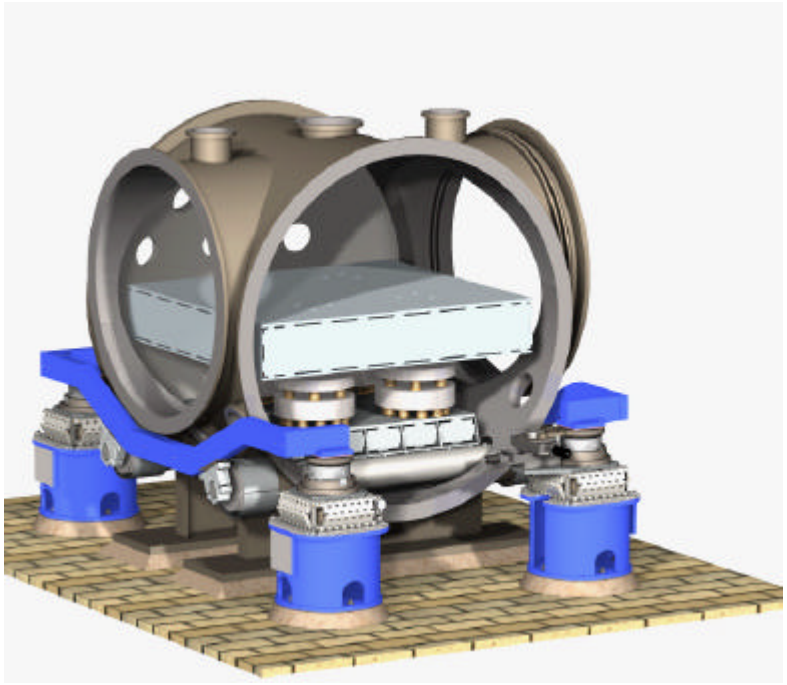
- Each interferometer has a specific role in commissioning
  - » 2 km Interferometer: “Pathfinder”, move quickly, identify problems, move on
  - » LLO 4 km Interferometer: Systematic characterization, problem resolution
  - » LHO 4 km Interferometer: Scheduled so that all fixes can be implemented prior to installation
- Stagger the installation and commissioning activities to make optimal use of available staff

Installation Status

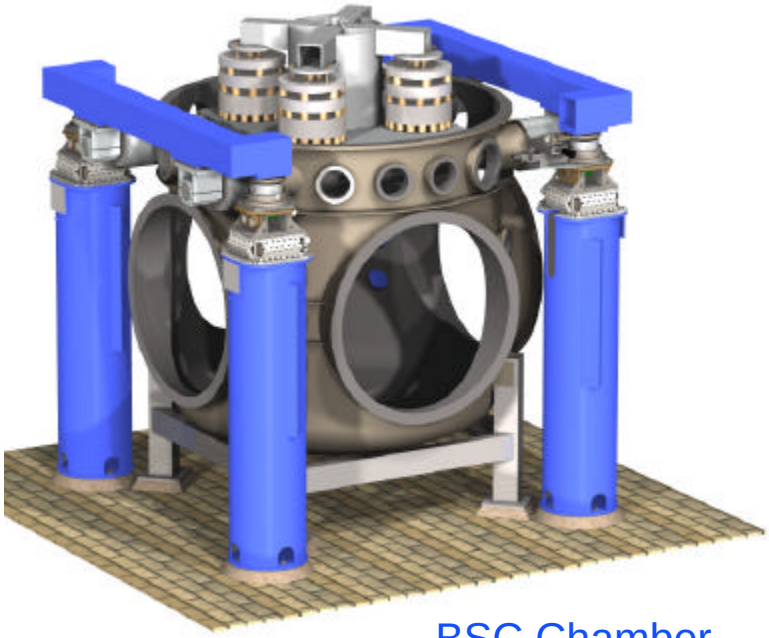
- All installation complete for LHO 2km and LLO 4km interferometers
  - » Commissioning underway
- LHO 4km interferometer
  - » Seismic isolation complete
  - » Prestabilized laser installation underway
  - » In-vacuum optics installation currently underway
- Data Acquisition/Control Network infrastructure complete at both sites
  - » Basic functionality all in place; still working on reliability, enhancements

Vibration Isolation Systems

- Reduce in-band seismic motion by 4 - 6 orders of magnitude
- Large range actuation for initial alignment and drift compensation
- Quiet actuation to correct for Earth tides and microseism at 0.15 Hz during observation

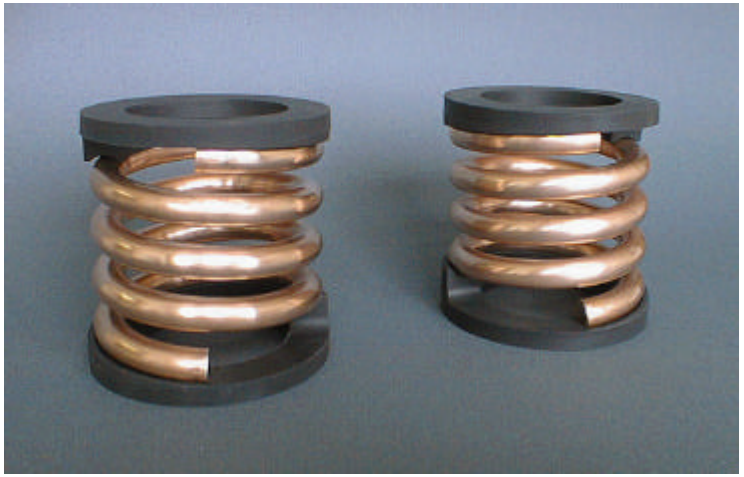


HAM Chamber

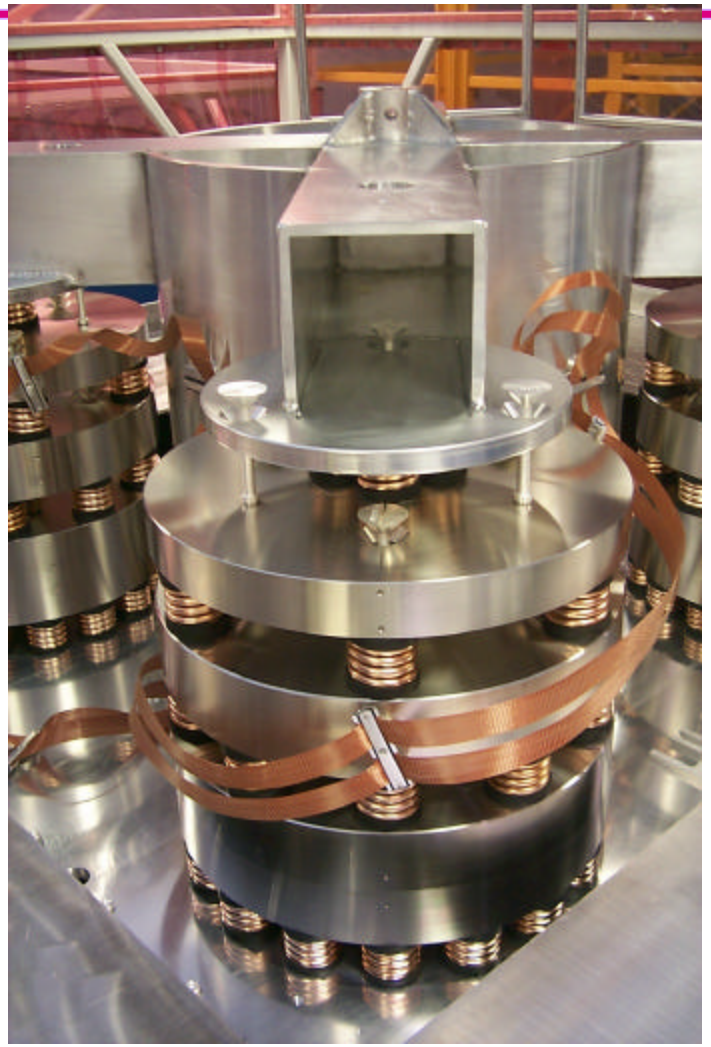


BSC Chamber

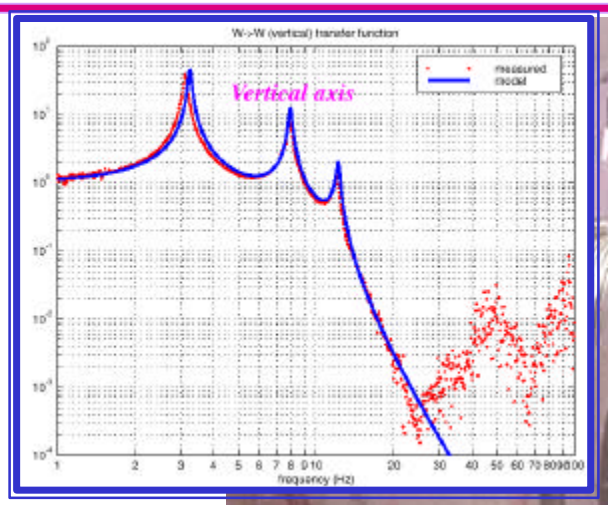
Seismic Isolation – Springs and Masses



damped spring
cross section

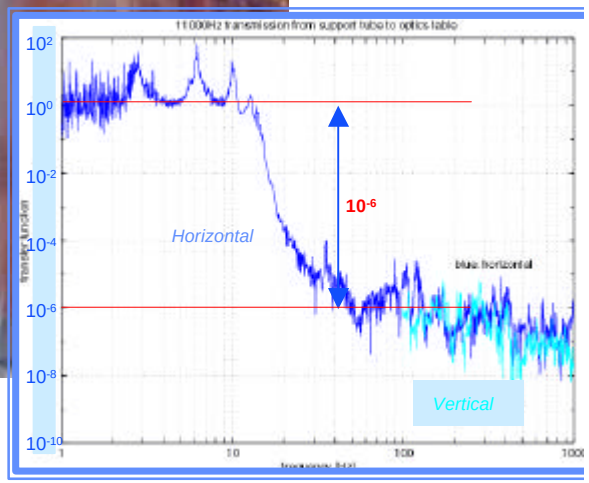


Seismic System Performance



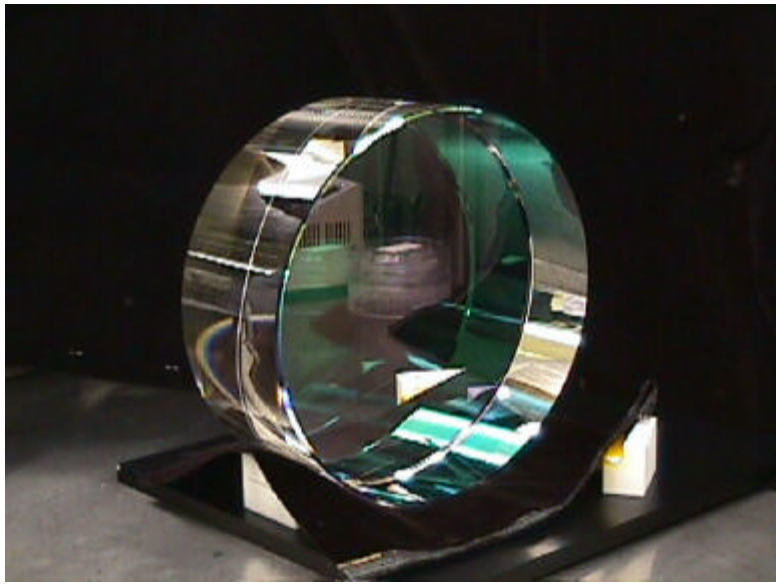
HAM stack
in air

BSC stack
in vacuum



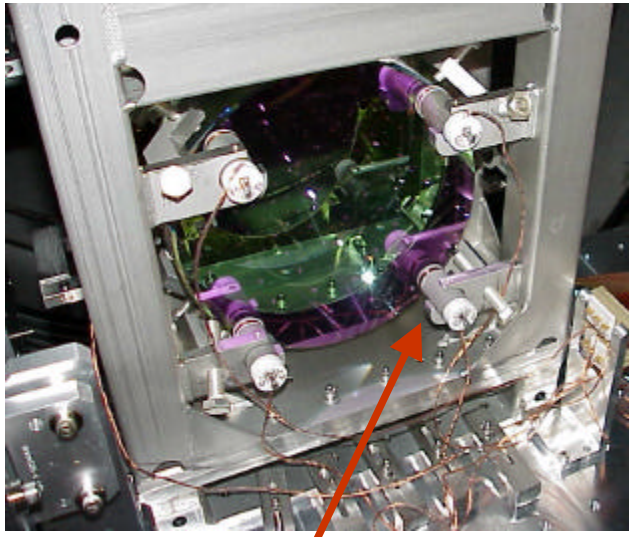
Core Optics

- Substrates: SiO_2
  - » 25 cm Diameter, 10 cm thick
  - » Homogeneity < 5 x 10^{-7}
  - » Internal mode Q's > 2 x 10^{6}
- Polishing
  - » Surface uniformity < 1 nm rms
  - » Radii of curvature matched < 3%
- Coating
  - » Scatter < 50 ppm
  - » Absorption < 2 ppm
  - » Uniformity <10^{-3}



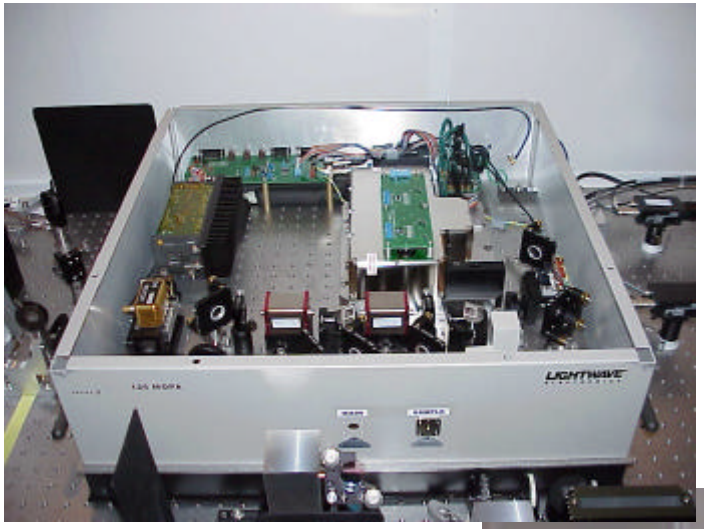
- Successful production involved 6 companies, NIST, and the LIGO Lab
- All optics for three interferometers delivered to sites

Core Optics Suspension and Control

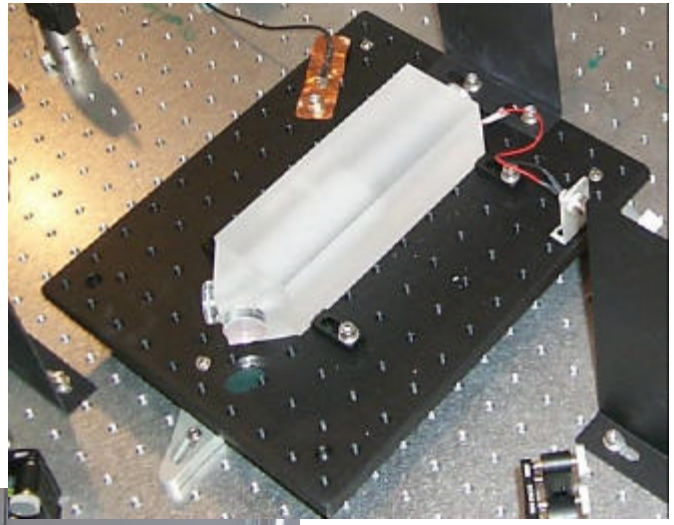


- Optics suspended as simple pendulums
- Local sensors/actuators for damping and control
- Problem with local sensor sensitivity to laser light

Pre-stabilized Laser



Custom-built
10 W Nd:YAG Laser,
joint development with
Lightwave Electronics
(now commercial product)

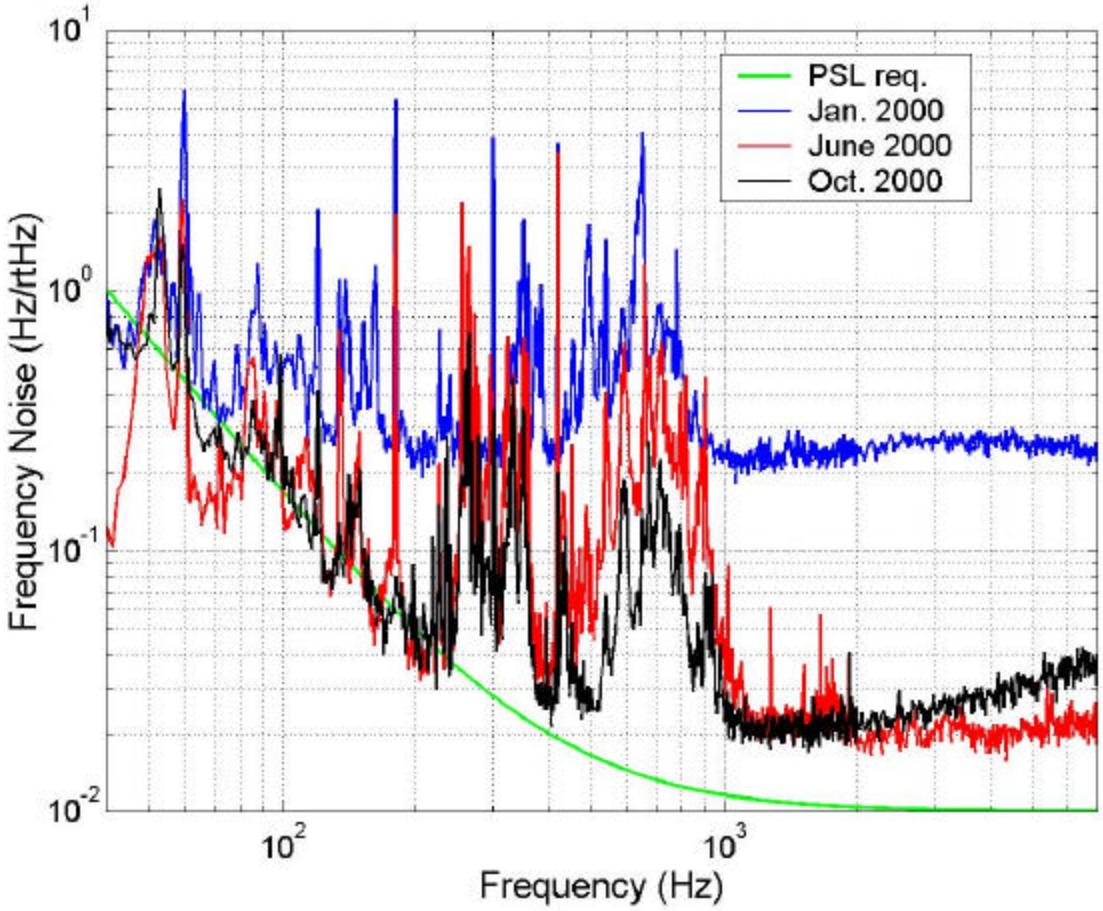


Cavity for
defining beam geometry,
joint development with
Stanford

Frequency stabilization
cavity

WA 2k Pre-stabilized Laser Performance

- > 20,000 hours continuous operation
- Frequency lock typically holds for months
- Improvement in noise performance
  - » electronics
  - » acoustics
  - » vibrations



Control and Data System

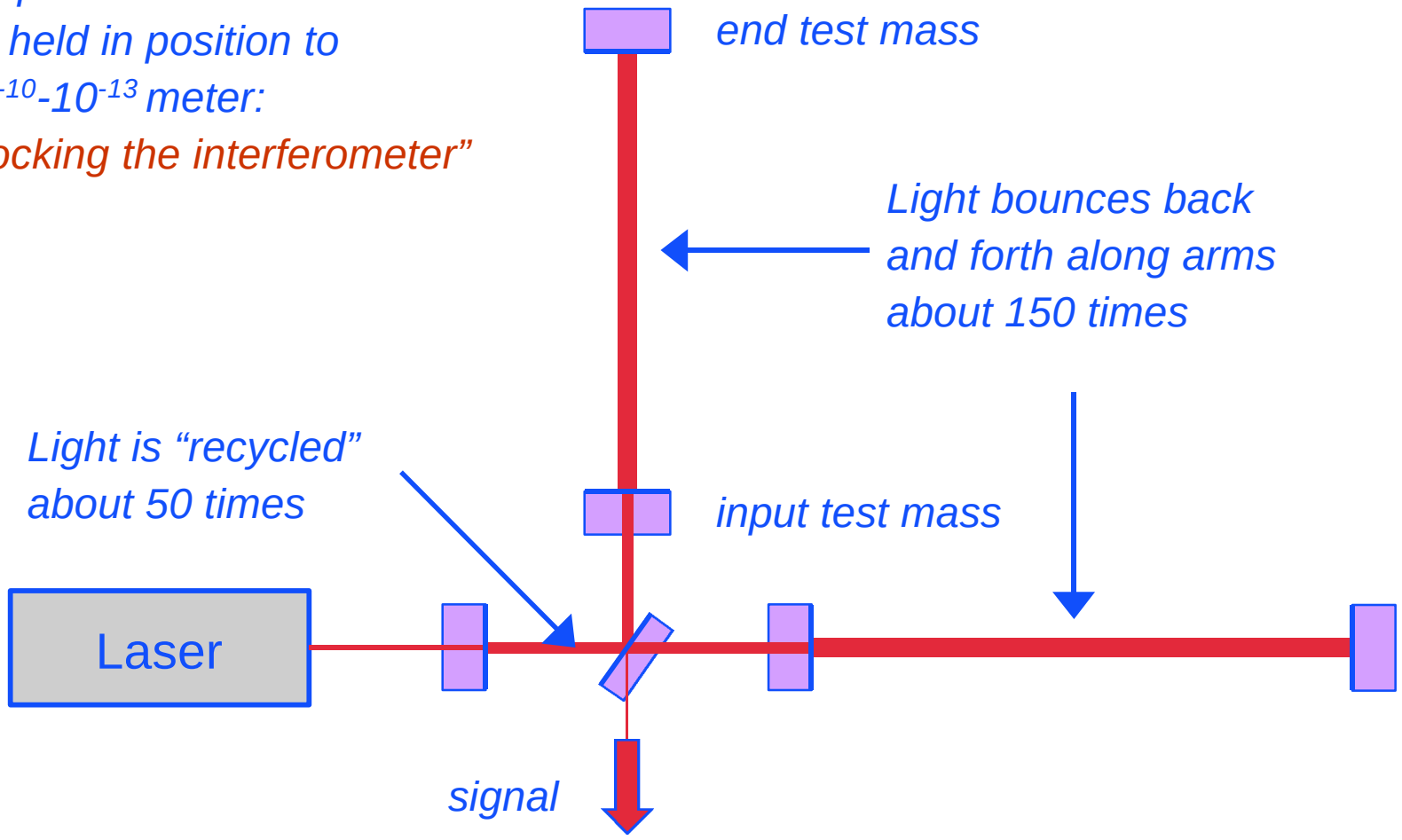
- EPICS-based distributed realtime control system
  - » ~50 realtime processors, ~20 workstations per site
  - » ~5000 process variables (switches, sliders, readings, etc) per interferometer
  - » Fiber optic links between buildings
- Data acquisition rate of 3 MB/s per interferometer
  - » Reflective memory for fast channels, EPICS for slow ones
  - » Synchronized using GPS
  - » Data served to any computer on site in realtime or playback mode using same tools
- Multiplexed video available in control room and next to the interferometer

Commissioning Status

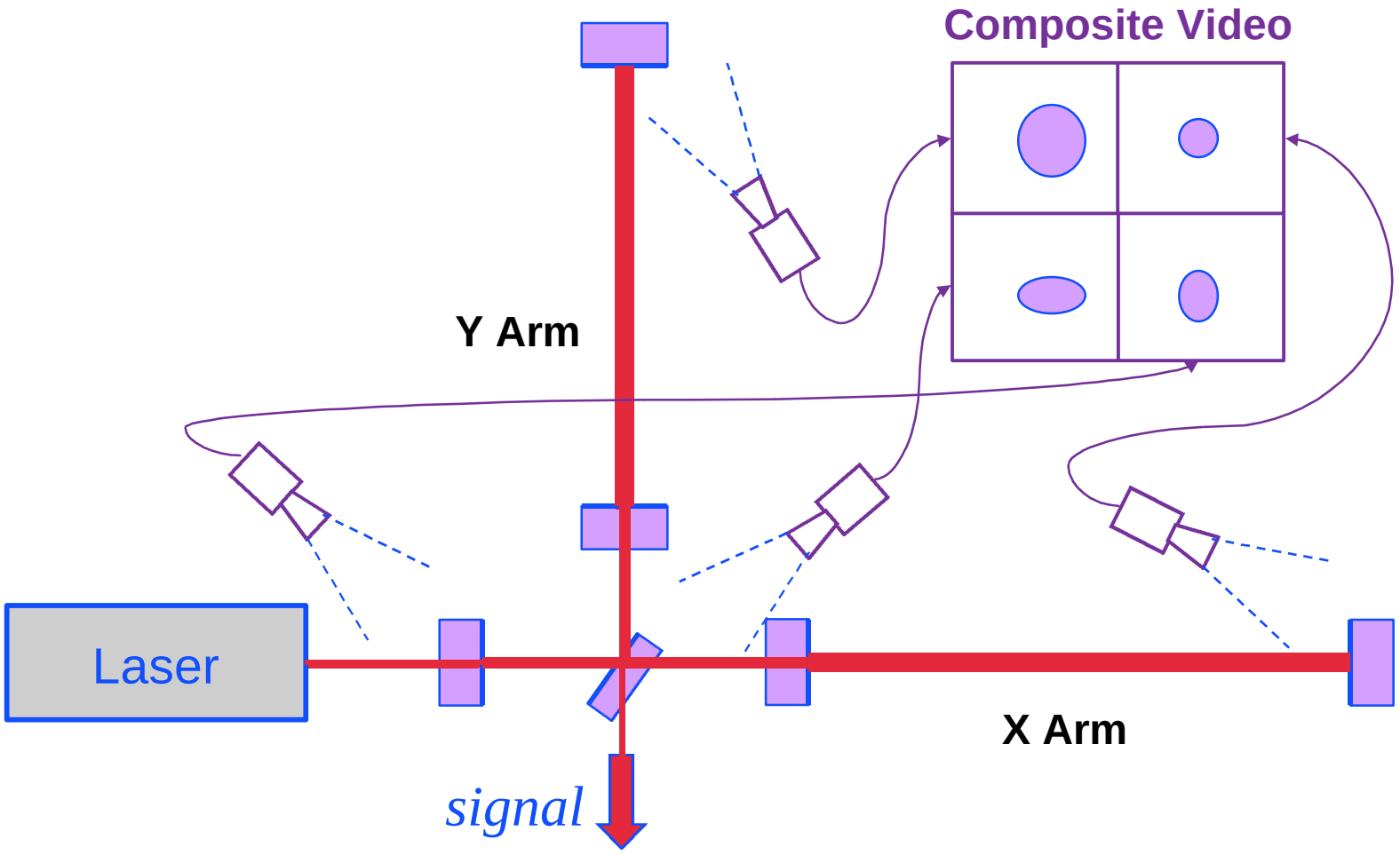
- LHO 2 km interferometer
  - » Identified problem with scattered light in suspension sensors during modecleaner testing – moved to lower power and continued on
  - » Early test of individual arm cavities performed before installation was complete
  - » Full interferometer locked at low input power (100 mW)
    - All longitudinal degrees of freedom controlled
    - Partial implementation of wavefront-sensing alignment control
  - » Still tuning servo loops to get design performance
- LLO 4 km interferometer
  - » Careful characterization of laser-modecleaner subsystems
  - » Single arm testing underway (discovered that there was no need for separate single arm configuration for hardware)
  - » Repetition of 2 km integrations taking much less time than (I) expected (20 times shorter to date, but probably can't continue)

Locking an Interferometer

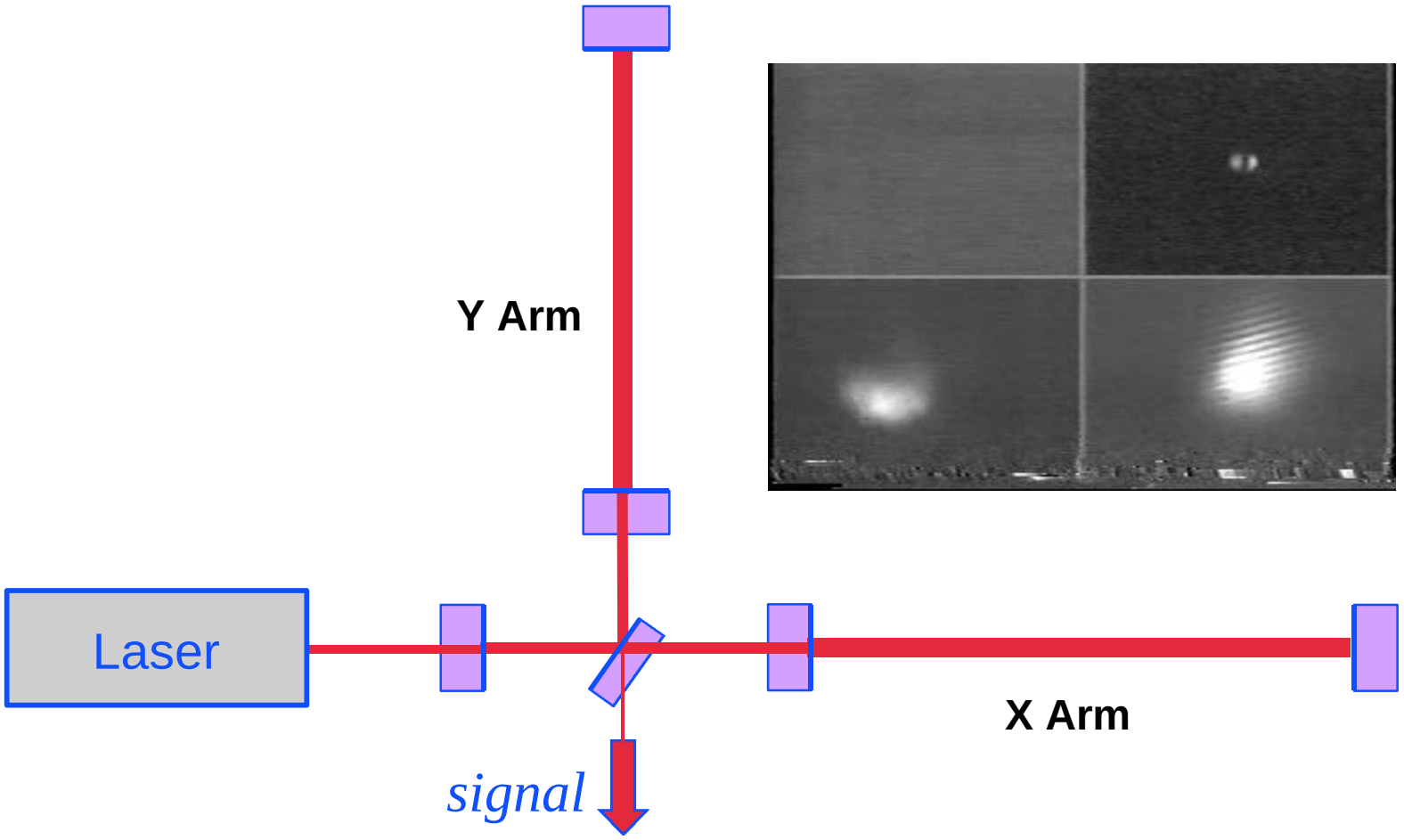
Requires test masses to be held in position to 10^{-10}-10^{-13} meter:
"Locking the interferometer"



Steps to Locking the Interferometer



Watching the Interferometer Lock

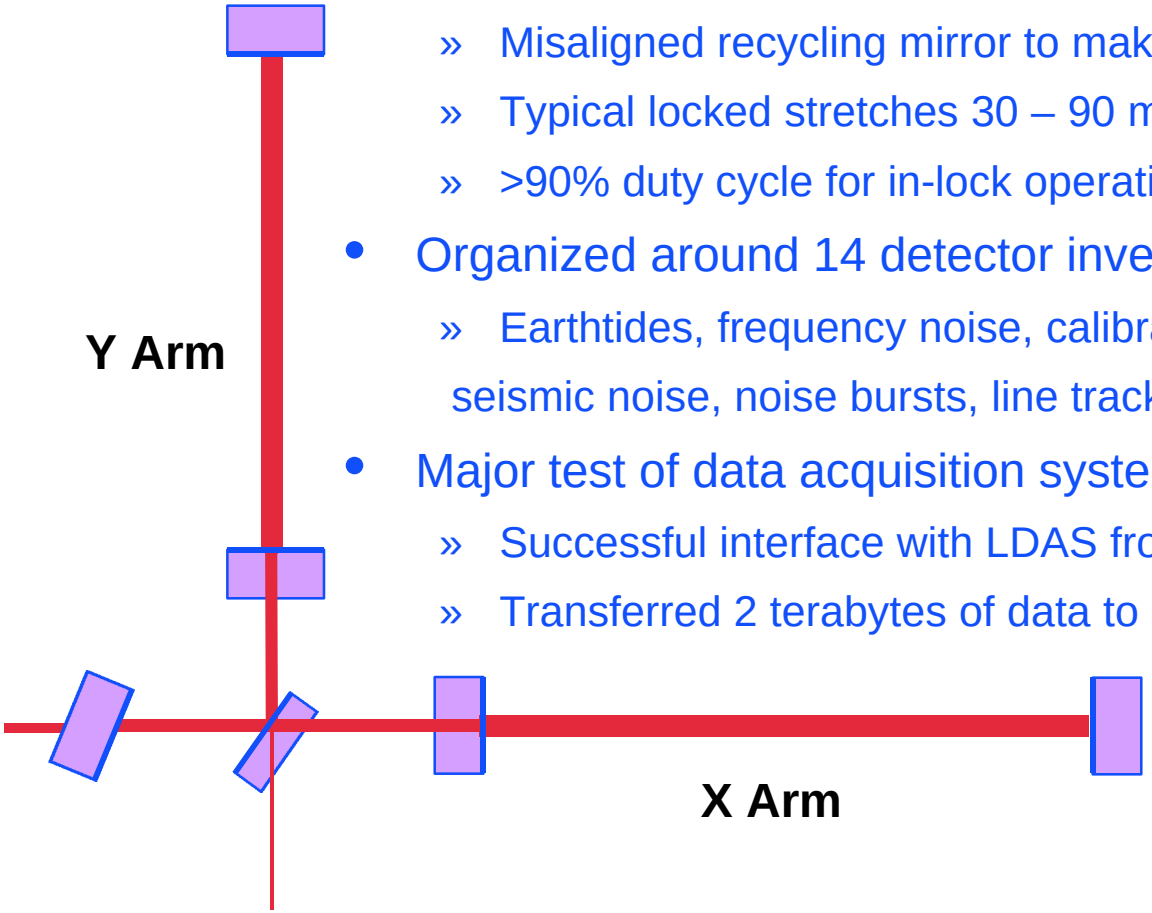


Engineering Runs

- Means to involve the broader LSC in detector commissioning
- Engineering Runs are a key part of our commissioning plan
  - » Test interferometer stability, reliability
  - » Well-defined dataset for off-site analysis
  - » Develop procedures for later operations
- First Engineering Run (E1) in April 2000
  - » Single arm operation of 2 km interferometer with wavefront sensing alignment on all angular degrees of freedom
  - » 24 hour duration
  - » Lots of interest, seven LSC groups made arrangements for data access

Second Engineering Run (E2)

- November 2000
  - » One week of 24/7 operation of 2 km interferometer
  - » Approximately 35 scientists participated on site
- Recombined Michelson with Fabry-Perot arms
  - » Misaligned recycling mirror to make for more robust locking
  - » Typical locked stretches 30 – 90 minutes (longest ~ 3 hours)
  - » >90% duty cycle for in-lock operation
- Organized around 14 detector investigations
  - » Earthtides, frequency noise, calibration, noise stationarity, seismic noise, noise bursts, line tracking, …
- Major test of data acquisition system
  - » Successful interface with LDAS front-end
  - » Transferred 2 terabytes of data to Caltech archive

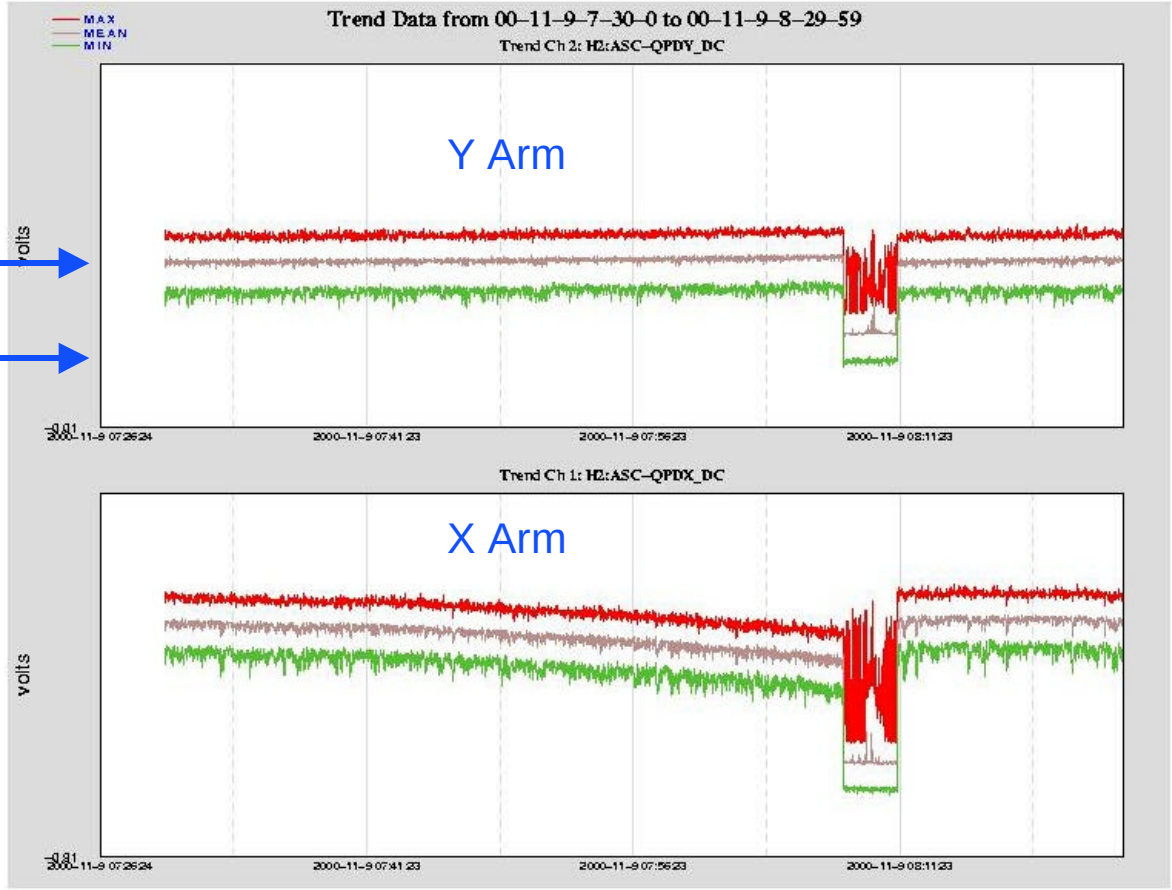


E2: Recombined Michelson Robustness

Randomly chosen hour from recent engineering run

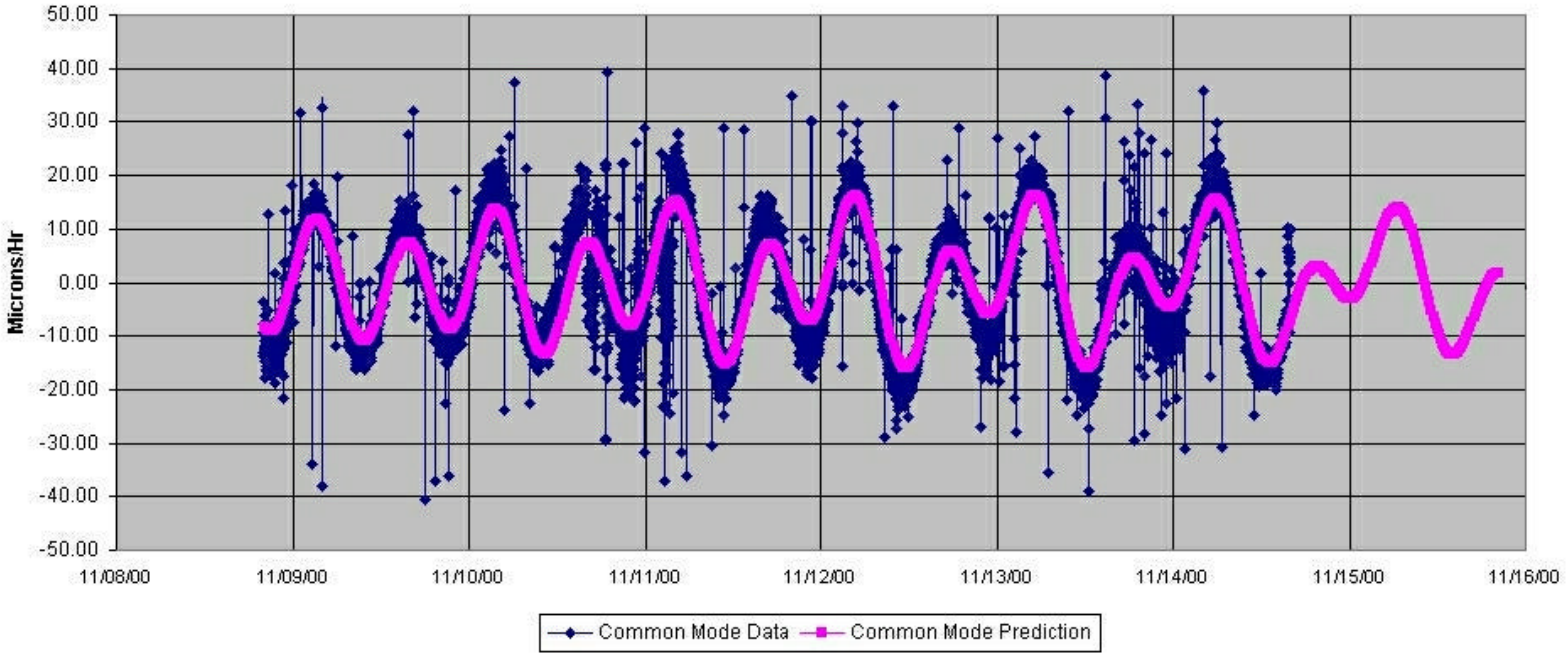
Locked

Unlocked

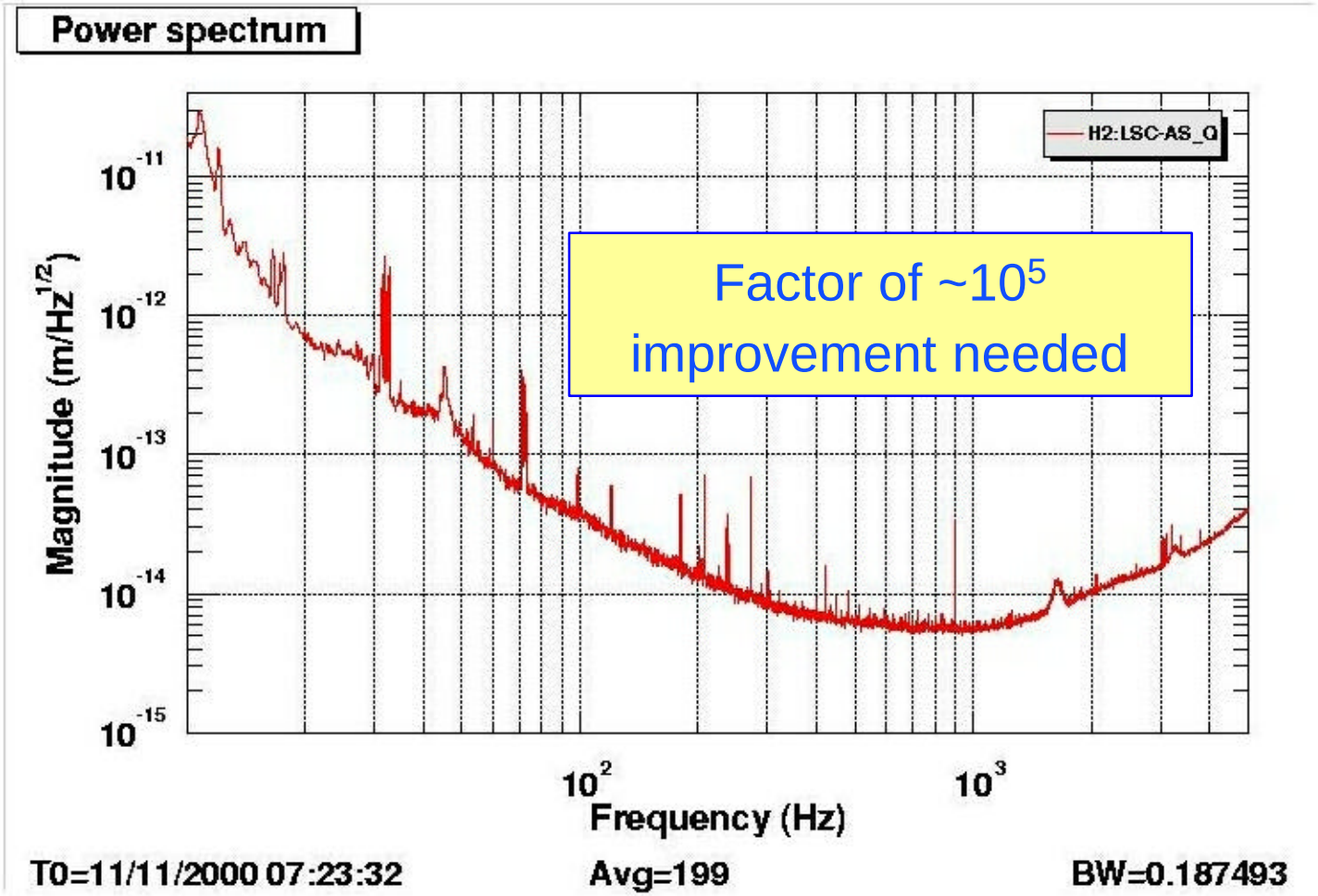


E2: Earthtide Investigation

- Observed in earlier E1 Run
- Main cause of loss of lock in E2 run: ~200 microns p-to-p
- Tidal actuator being commissioned for continuous lock
- Common mode (both arms stretch together) and differential mode (arms stretch by different amounts)



E2: Recombined Interferometer Spectrum



First differential arm spectrum, Nov. 2000

E3 Engineering Run

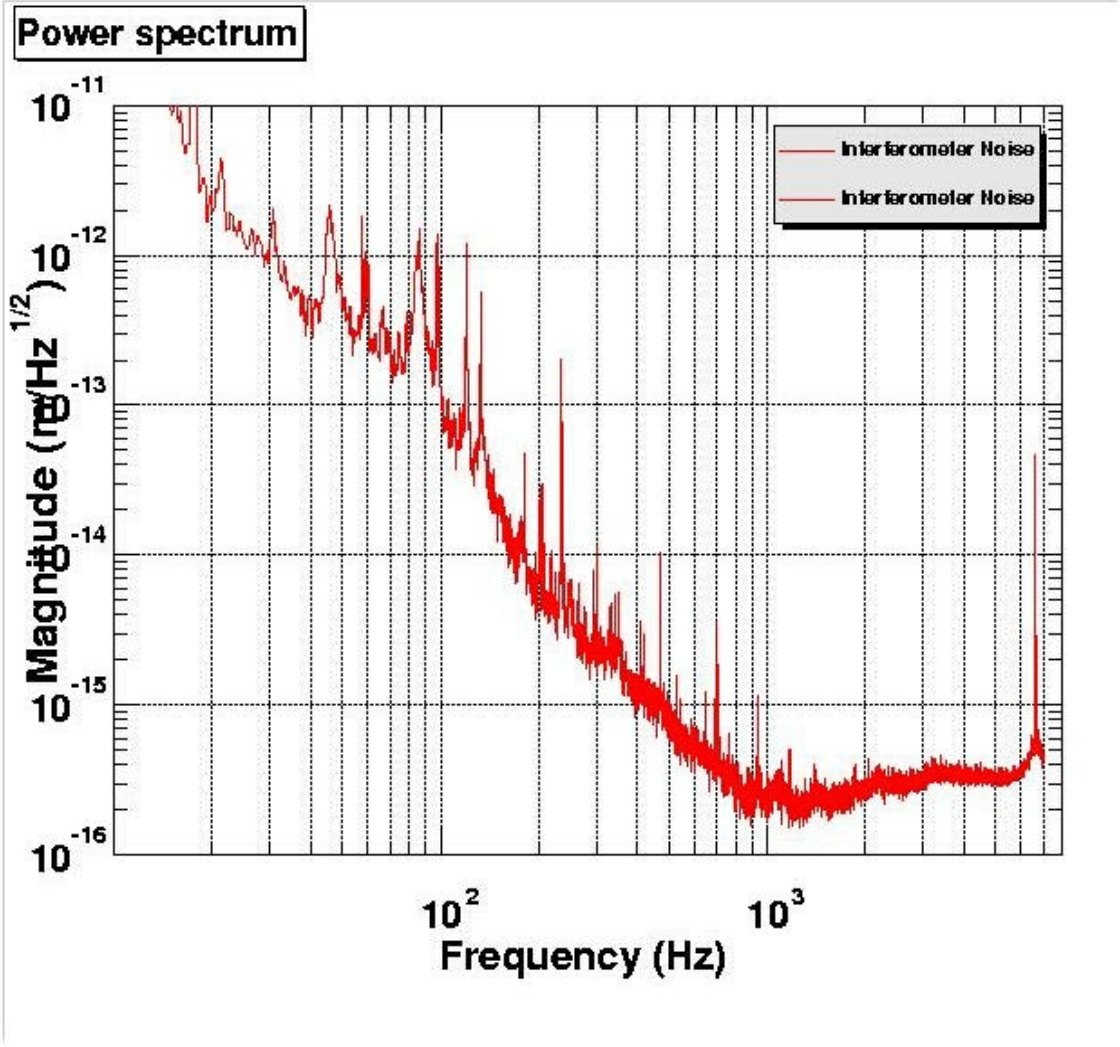
- Scheduled for March 9-12
- First coincidence run between LHO 2 km interferometer (full recycled configuration) and LLO
  4 km interferometer (recombined F-P Michelson)
- Again organized around investigations
- Specific goals
  - » Correlations between environmental signals
  - » Integration of data streams from two sites
  - » First operation of full recycled F-P Michelson interferometer

Work on Interferometer Noise

Pretty much what we expected from first noise spectrum:

- Electronics noise dominant at high frequencies in E2 spectrum (due to low input power)
- Laser frequency noise dominates in mid frequency band (stabilization servos still being tuned up)
- Low frequencies seismic noise?
- Many resonant features to investigate and eliminate
- No showstoppers!

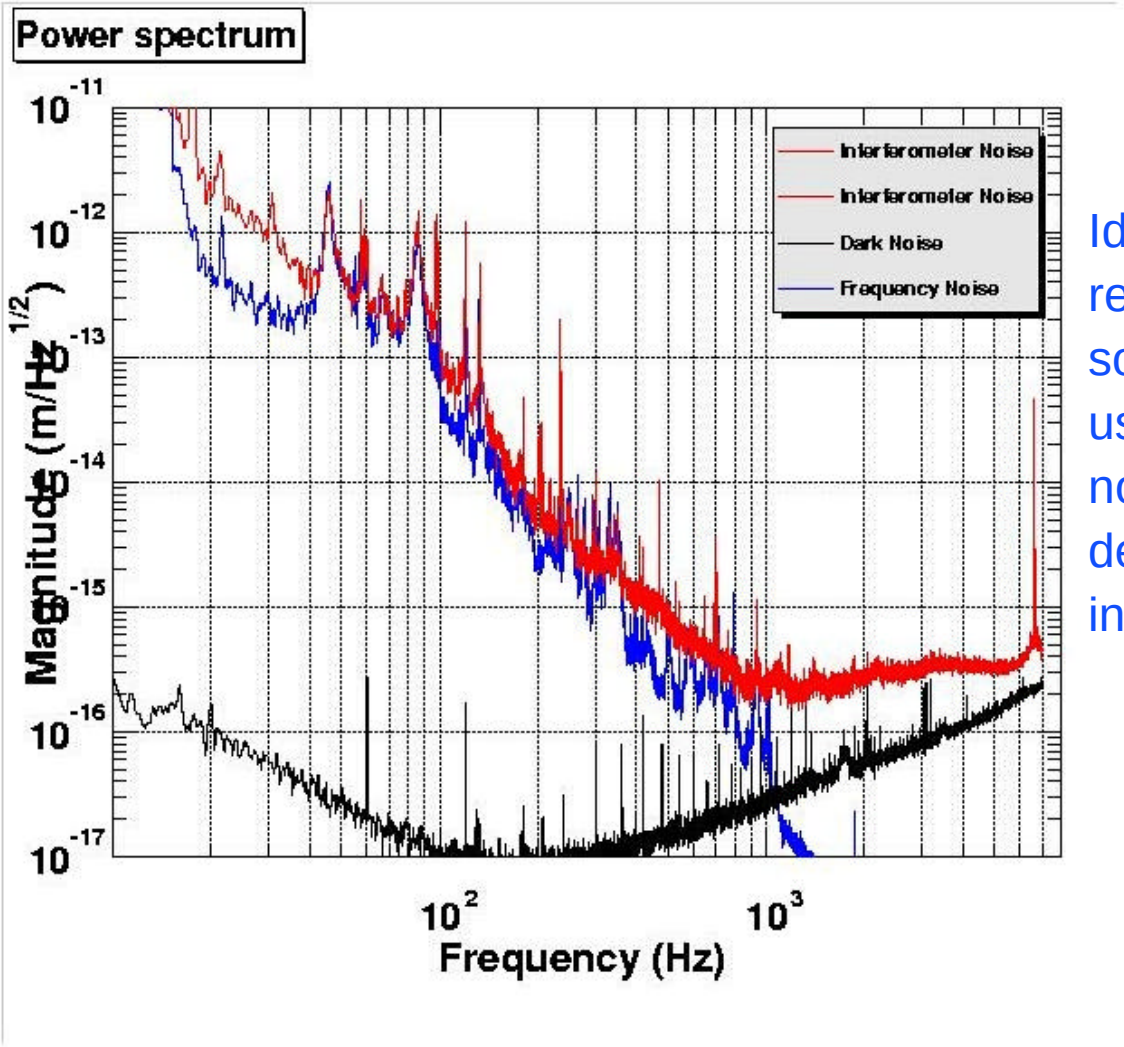
Current Noise Spectrum



Factor of 20 improvement:

- Recycling
- Reduction of electronics noise
- Partial implementation of alignment control

Known Contributors to Noise

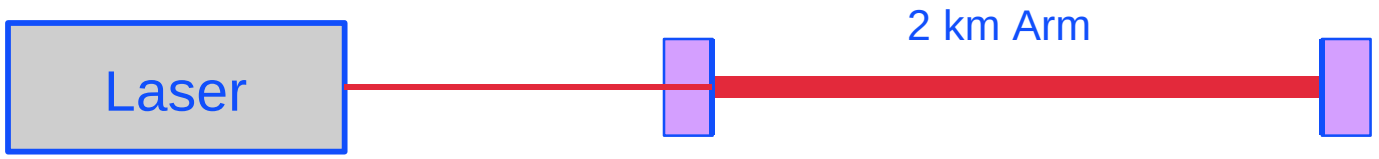


Identification and reduction of noise sources underway using well-established noise-hunting techniques developed on prototype interferometers

Progress Toward Robust Operation

- Different measure of interferometer performance (in contrast with sensitivity)
  - » Interferometer lock duration goal is 40 hours
- 2 km Prestabilized Laser
  - » Two years continuous operation with ~20% loss in power (recovered in recent tune-up)
  - » Locks to reference cavity and premodecleaner for months
- Mode Cleaner
  - » Locks for weeks at a time, reacquires lock in few seconds
- Data Acquisition and Control
  - » Data Acquisition and Input Output Controllers routinely operate for days to months without problems
  - » Tools in place for tracking machine state: AutoBURT, Conlog

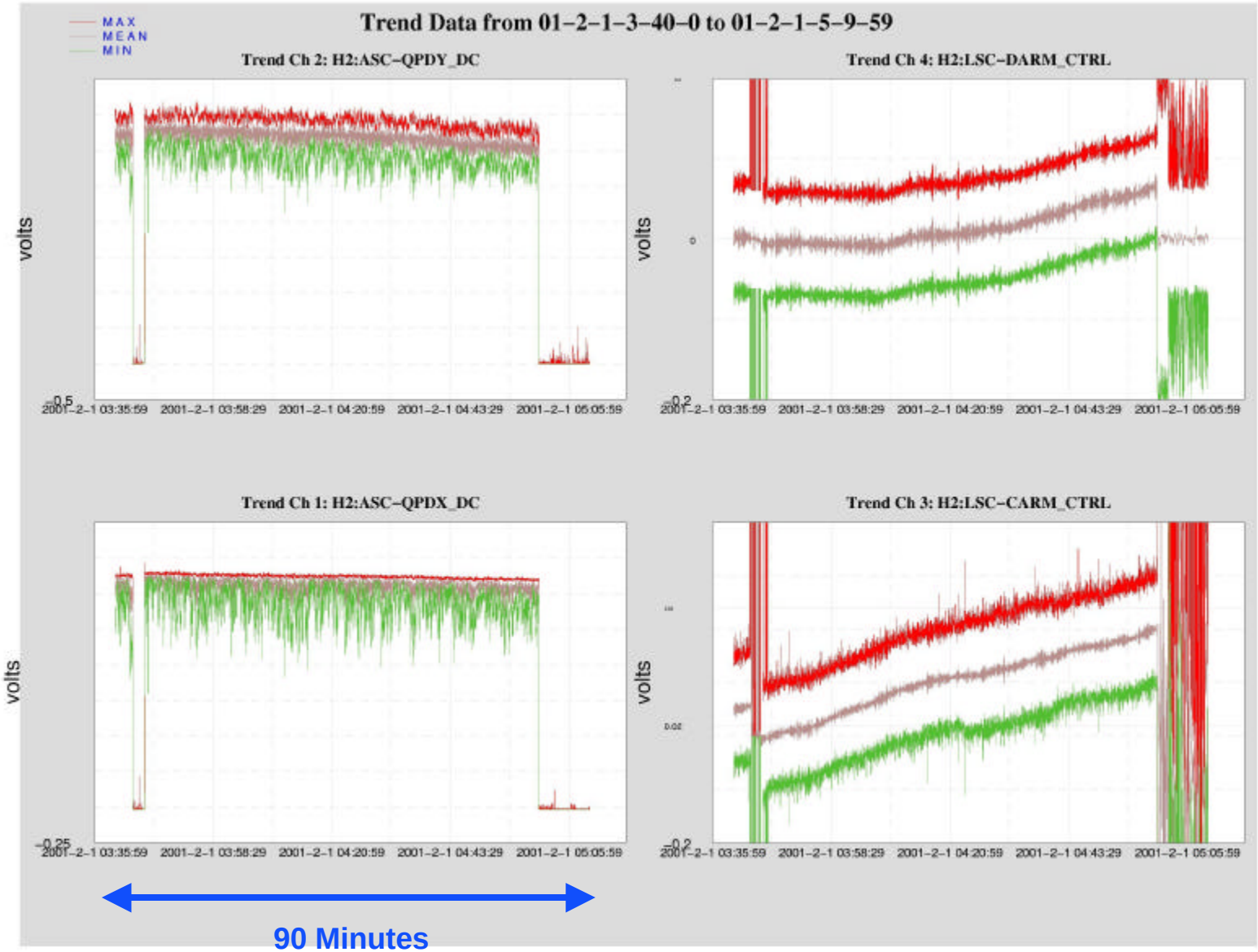
Extending the Lock on a Single Arm



- Start with Y Arm
  - » 12/1/99 Flashes of light
  - » 12/9/99 0.2 seconds lock
  - » 1/14/00 2 seconds lock
  - » 1/19/00 60 seconds lock
  - » 1/21/00 5 minutes lock
- Change to X Arm
  - » 2/12/00 18 minutes lock
  - » 3/4/00 90 minutes lock
  - » 3/26/00 10 hours lock

Result of: -automatic alignment system
-tuning electronics
-reduction of noise sources

Full Interferometer Locking



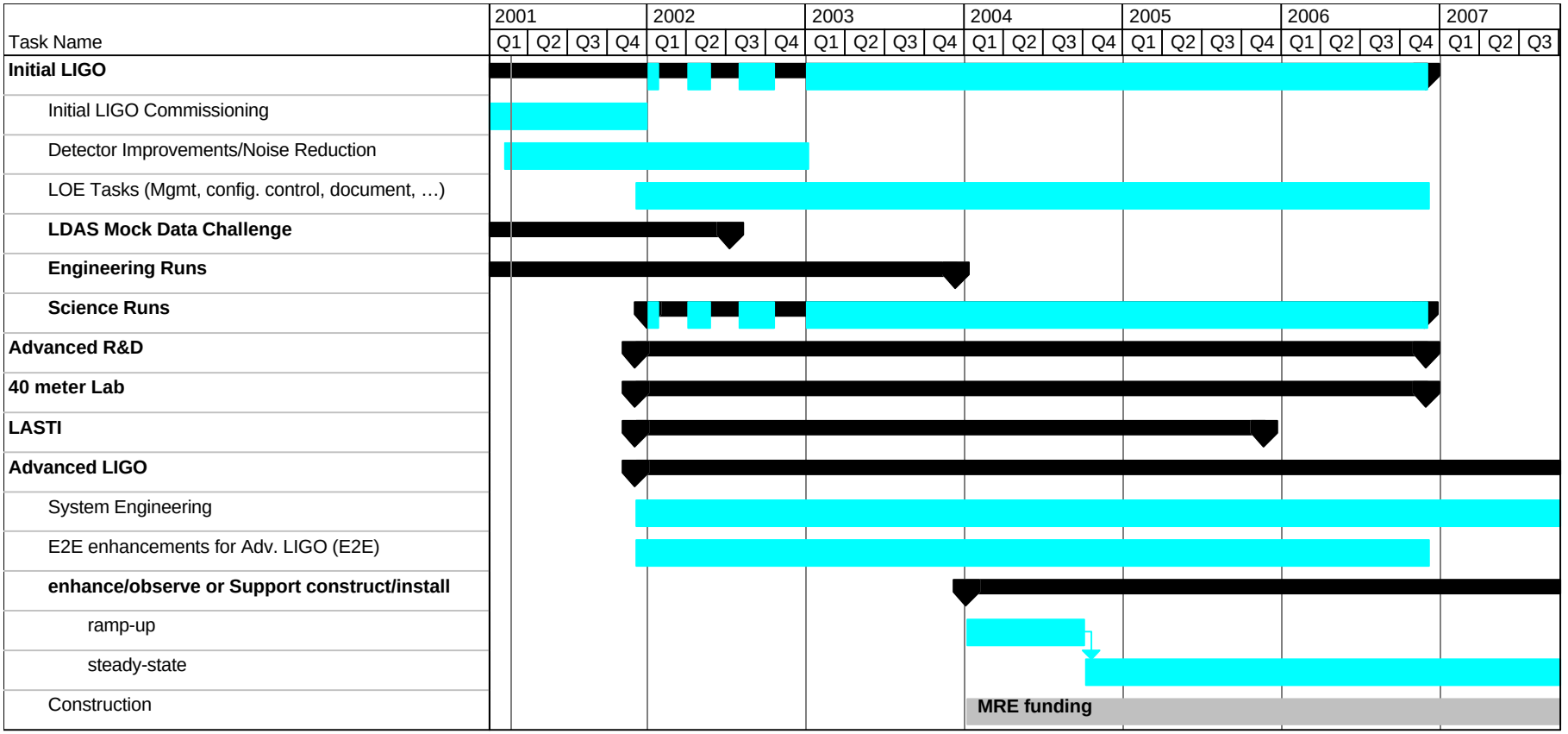
Plan to Reach Science Run

- Jan to mid-March
  - » LHO 2k, continued work on improving robustness of lock, some work on sensitivity
  - » LLO 4k, Lock single arm, recombined Michelson with Fabry-Perot (F-P) arms, Power Recycled Michelson (PRM)
  - » LHO 4k, installation
- March 9-12
  - » E3 (engineering run): coincidence run between full 2km interferometer and recombined Michelson with F-P arms (possibly single arm) at LLO
- mid-March to mid-May
  - » LHO 4k, complete installation, lock modecleaner
  - » LHO 2k, suspension sensor replacement, PRM studies
  - » LLO 4k, lock full interferometer, sensitivity/robustnessearly
- May
  - » E4 run: LLO 4 km only, operating in recombined mode (possibly recycling)

Plan to Reach Science Run, Part 2

- May - June
  - » LHO 2k, bring full interferometer back on-line, sensitivity studies
  - » LLO 4k, improve full interferometer lock, sensitivity studies
  - » LHO 4k, PRM locking (no arms yet)
- late June - early July
  - » E5 LHO 2k and LLO 4k in full recycled configuration, LHO 4k in PRM mode
- July - Sept
  - » LLO 4 k suspension sensor replacement, bring back on-line
  - » LHO 2km sensitivity studies, 4k lock full interferometer
- late Sept
  - » E6 triple coincidence run with all 3 interferometers in final optical configuration (“upper limit run”)
- Oct – early 2002
  - » Improve sensitivity and reliability
  - » Alternate diagnostic testing with engineering runs

Overall Proposed Schedule



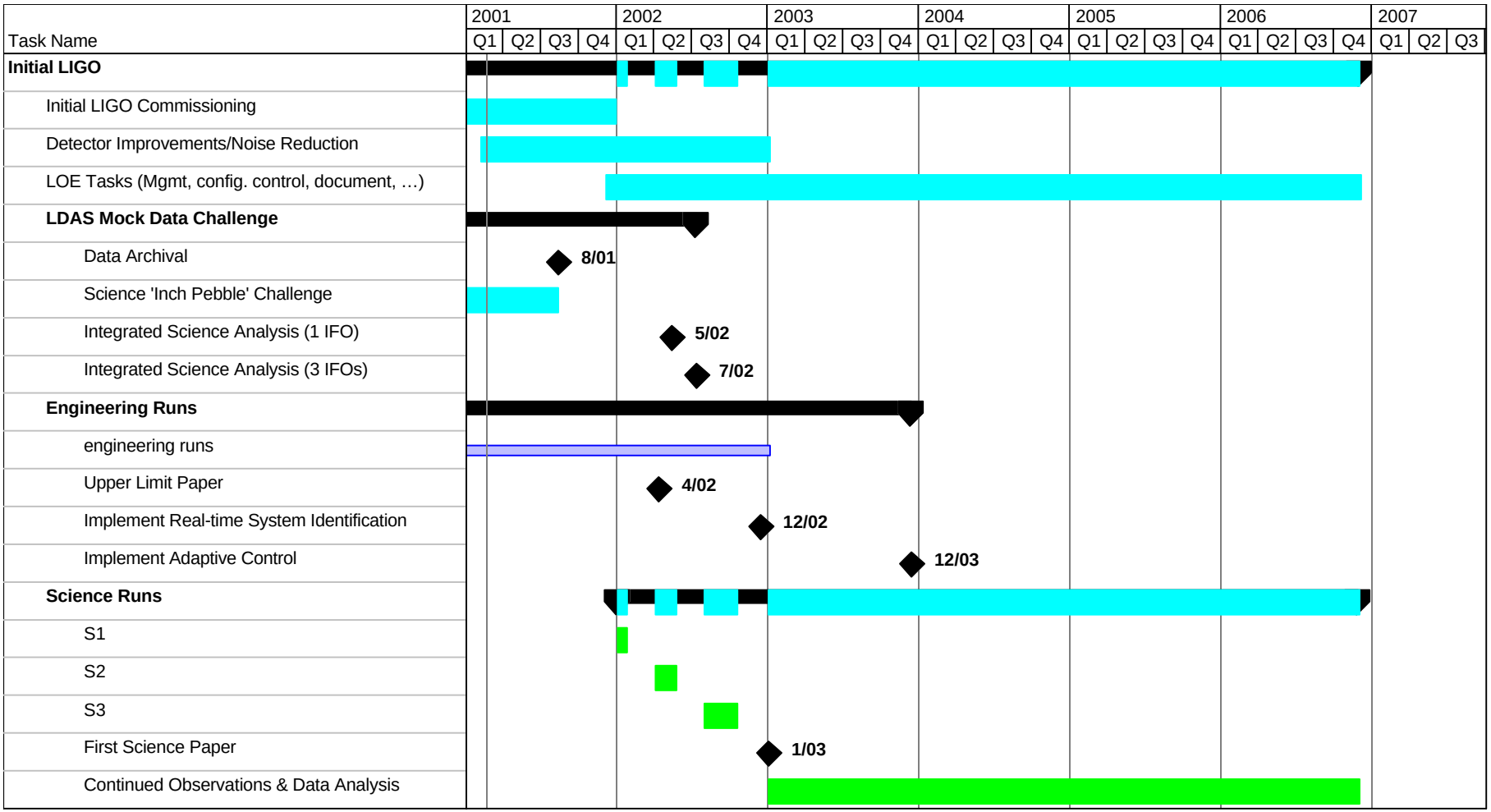
Detector Upgrades

- Planned Detector Upgrades
  - » Redesigned Damping Sensor/Actuator Heads (increased immunity from the laser light)
  - » Digital Suspension Controllers (frequency dependent diagonalization)
  - » Servo-control and diagnostic software modifications (continuous)
  - » On-line system identification (enable controls improvement)
  - » Adaptive interferometer control (for improved control robustness)

Detector Upgrades (continued)

- Possible Future Detector Upgrades
  - » Modulated damping sensor electronics (increased immunity to laser light)
  - » Improved laser frequency stabilization servo electronics (noise reduction)
  - » Improved interferometer sensing & control servo electronics (noise reduction)
  - » Redesigned pre-mode cleaner (enable higher bandwidth control)
  - » additional physics environment monitoring (PEM) sensors (after correlation analyses indicate useful deployment)
  - » TBD -- as commissioning and characterization studies determine needs

Initial Detector Milestones



Increase for Full Operations

Increases for initial LIGO Detector 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**

Covered in Observatory Operations Talk

*** Need recognized by NSF Review Panel**

Increases for Initial LIGO Detector Operation

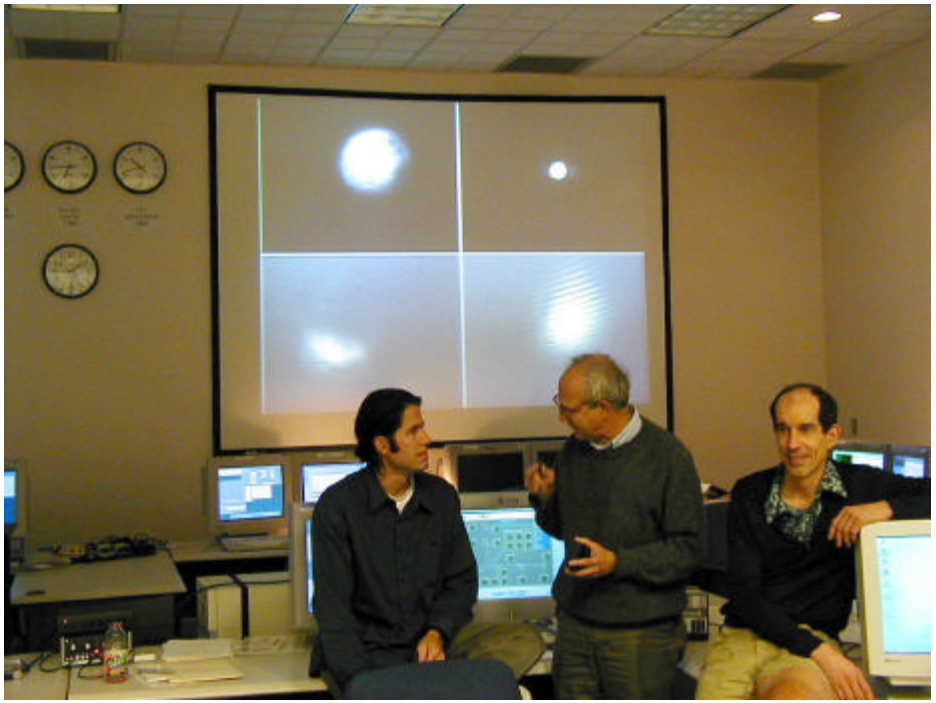
- Computer & Data System (CDS) Hardware Maintenance
  - » Annual replacement and maintenance of the control room data acquisition and control hardware plus overhead
  - » installed detector computer and network infrastructure at both sites is ~$3M; estimate 10% maintenance and replacement costs per year
  - » installed custom electronics and embedded computers is also ~$3M; estimate 5% maintenance and replacement costs per year
- LIGO Data Analysis System (LDAS) Equipment Maintenance
  - » ~ $4M of computing equipment for LDAS
  - » assume 25 percent replacement rate per year plus over-head
  - » missing budget was recommended by an NSF review panel

Initial Detector Operations Staffing

Group	Roles	Proposed Staff	Incremental Staff
Hanford Observatory & Livingston Observatory	Maintain up-time & peak performance (continuous operator coverage)	14 Scientists 18 operations specialists 14 engineers 2 administrators	+ 4 operations specialists
	Ensure quality of detector operation & data stream		
	Maintain detector support infrastucture (computer network, labs, instruments, spares, ...)		+1 Computer Admin
	Maintain installed detector & LDAS equipment		+2 Scientist, +2 Engineer
	Physical configuration control of detector & LDAS equipment		
	Assist in software configuration control		
	Participate in detector characterization studies		
	Support subsystem upgrade installation & commissioning		
	visiting LSC observatory liaison		+2 Scientist
Data & Computing Group (LDAS & Simulation subgroups)	Maintain, enhance & configuration control LDAS software	9 Scientists 4 Graduate Students 9 Software Engineers	
	Data QA, distribution & archival		
	Provide LSC community with processed & QA'd data		
	Pipeline analysis of data stream		
	Astrophysics searches		
	Simulation & modeling		
Detector Support (CIT)	Lead commissioning	8 Scientists	
	Lead detector characterization studies		
	Instrumentation support to LDAS & Simulation		
	Train Observatory Staff		
Detector Support (MIT)	Lead commissioning	4 Scientists 2 Graduate Students	
	Lead detector characterization studies		
	Instrumentation support to LDAS & Simulation		
	Train Observatory Staff		
Technical & Engineering Support (CIT)	Lead installation	4 Engineers & Technicians	
	Support comissioning		
	Support detector characterization		
	Centralized design documentation & configuration control (HW & SW)		
	Lead re-dsign for upgrades & fixes		
		35 Scientists 18 Operations Specialists 27 Engineers 6 Graduate Students 2 Adminstrators	4 Scientists 4 Operations Specialists 2 Engineers 1 Administrator

Summary

- Detector installation is nearly complete
- Commissioning is proceeding well
- 2001
  - » Improve sensitivity/reliability
  - » First coincidence operation
  - » Initial data run (“upper limit runs”)
- 2002
  - » Begin Science Run
  - » Interspersed data taking and machine improvements
- 2003-2006
  - » Minimum of one year of integrated data at 10^{-21} sensitivity



First Lock in the Hanford Observatory control room