



LIGO: Challenges Past, Present and Future

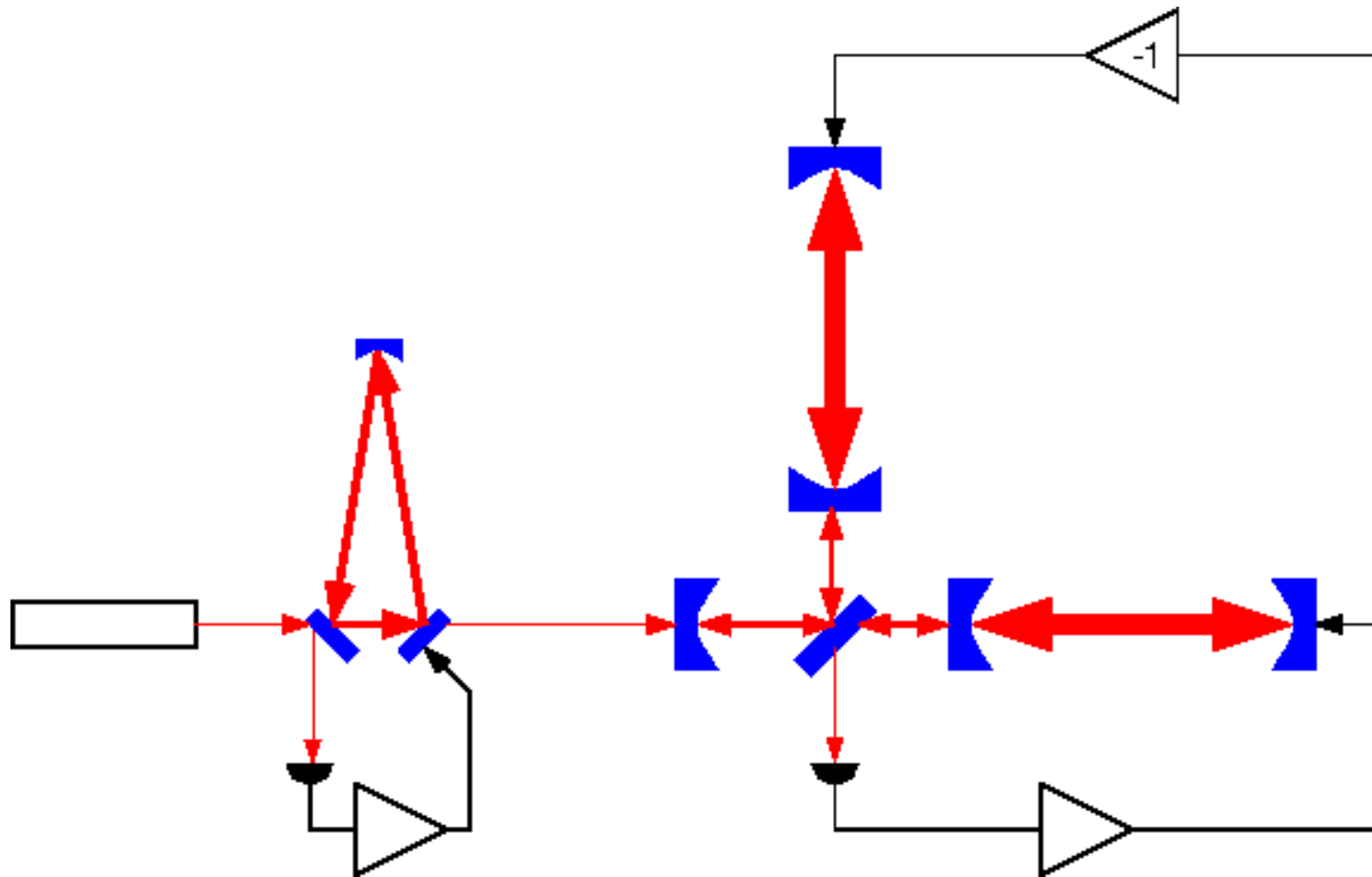
LIGO Science Symposium

Stan Whitcomb

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LIGO Interferometer





The Beam Tubes

The Challenge:

Provide a Low Noise Path for the Propagation of the Main Interferometer Beams

- Ultra-high vacuum level for all gases with increasingly severe requirements for higher masses
- Alignment requirement better than 1 cm
- Minimize cost
- Provide for future generations of gravitational wave detectors with minimal upgrades



Beam Tube Developments

- Special processing for low hydrogen outgassing
 - ›› High temperature bake of steel coils in dry air prior to tube fabrication
 - ›› Oxidation helps control scattered light as a side benefit
- Process for low temperature bakeout
 - ›› Use of beam tube itself as resistive heating element
 - ›› Temperature and duration optimized to minimize cost and risk
- GPS for alignment
- Process control, process control, process control!



Outgassing Results After Bakeout

- Far exceeds outgassing and leak needs for initial LIGO detectors
- Adequate for the next generation,and the generation after that...

NOTE: All results except for H₂ are upper limits

Species	Goal ^o	Hanford				Livingston	torr-l/sec/cm ²
		HY2	HY1	HX1	HX2	LX2	
H ₂	4.7	4.8	6.3	5.2	4.6	4.3	x 10 ⁻¹⁴
CH ₄	48000	< 900	< 220	< 8.8	< 95	< 40	x 10 ⁻²⁰
H ₂ O	1500	< 4	< 20	< 1.8	< 0.8	< 10	x 10 ⁻¹⁸
CO	650	< 14	< 9	< 5.7	< 2	< 5	x 10 ⁻¹⁸
CO ₂	2200	< 40	< 18	< 2.9	< 8.5	< 8	x 10 ⁻¹⁹
NO+C ₂ H ₆	7000	< 2	< 14	< 6.6	< 1.0	< 1.1	x 10 ⁻¹⁹
H _n C _p O _q	50-2 ^a	< 15	< 8.5	< 5.3	< 0.4	< 4.3	x 10 ⁻¹⁹
air leak	1000	< 20	< 10	< 3.5	< 16	< 7	x 10 ⁻¹¹ torr-l/sec

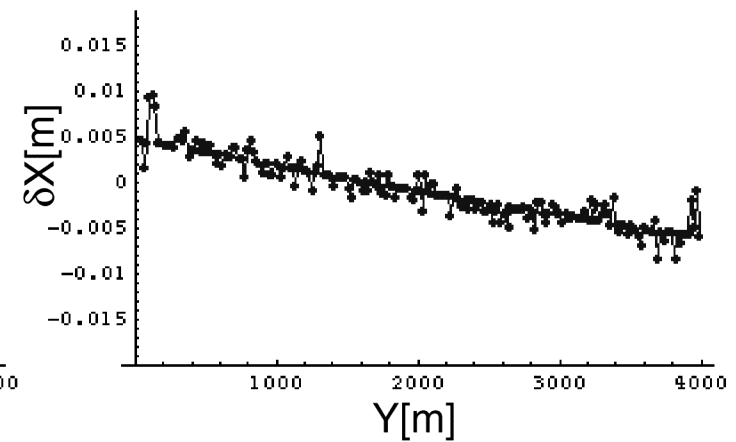
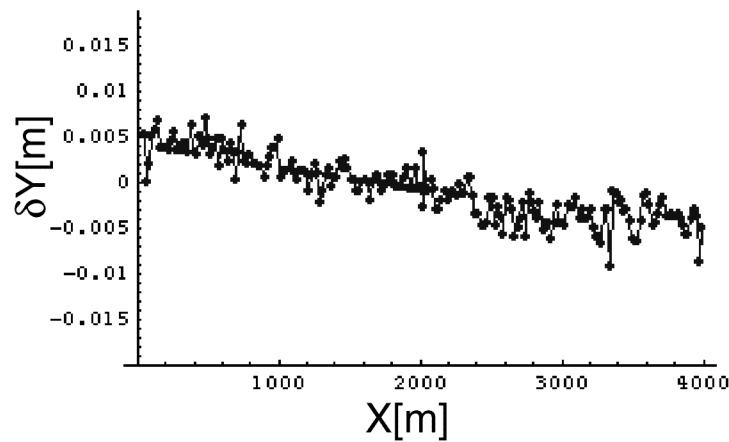
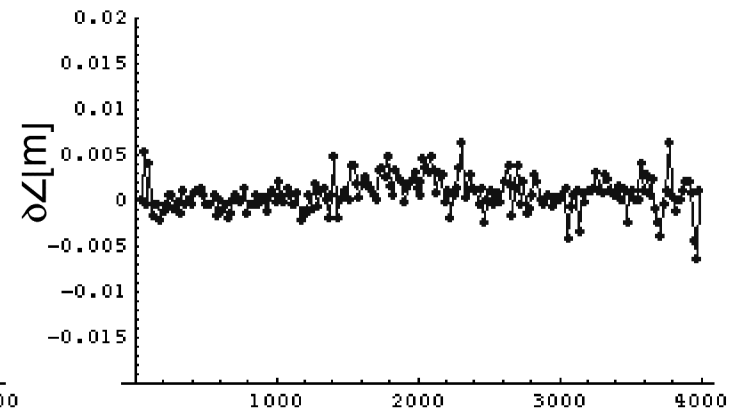
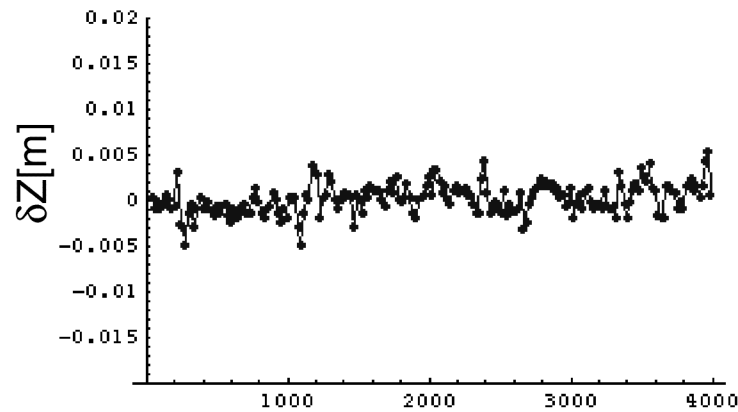
^a Goal for hydrocarbons depends on weight of parent molecule; range given corresponds with 100-300 AMU



Beam Tube Alignment

LLO X Arm

LLO Y Arm





Beam Tube Process Control

- Over 1600 He leak tests performed
 - ›› 800 beam tube sections (20 m long)
 - ›› 800 section to section welds in the field
 - ›› Over 50 km of weld length
- No weld leak ever made it past visual inspection !



Test Masses/Optics

The Challenge:

Demanding Simultaneous Optical and Mechanical Requirements

- Optical
 - ›› Coating scatter < 50 ppm, absorption < 2 ppm
 - ›› Polishing and coating uniformity < 1 nm RMS
 - ›› Substrate homogeneity $< 5 \times 10^{-7}$
 - ›› Radii of curvature measured and matched to 1-3%
- Mechanical
 - ›› Q's of internal vibrational modes $> 2 \times 10^6$



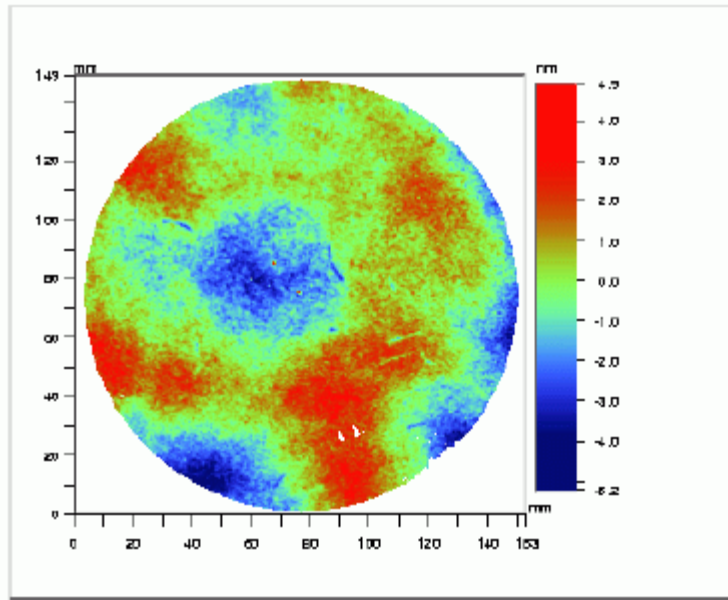
Test Masses/Optics Developments

- “Pathfinder” process to work with industry in a collaborative development of the required technologies
 - ›› 2 manufacturers of fused silica blanks
 - ›› 4 polishers
 - ›› 5 metrology companies/labs
 - ›› 1 optical coating company
- Successfully demonstrated all requirements!

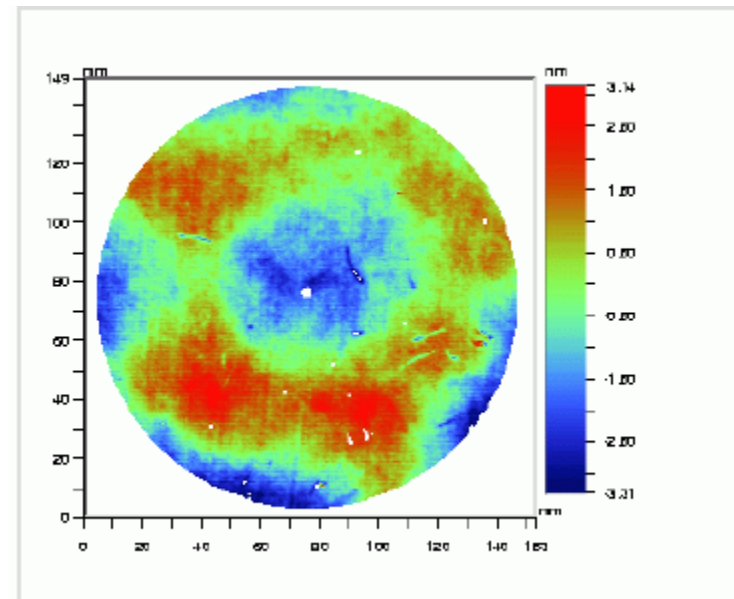


Comparison of CSIRO and LIGO Metrology

LIGO 1.3 nm RMS



CSIRO 1.1 nm RMS





Mode Cleaner

The Challenge:

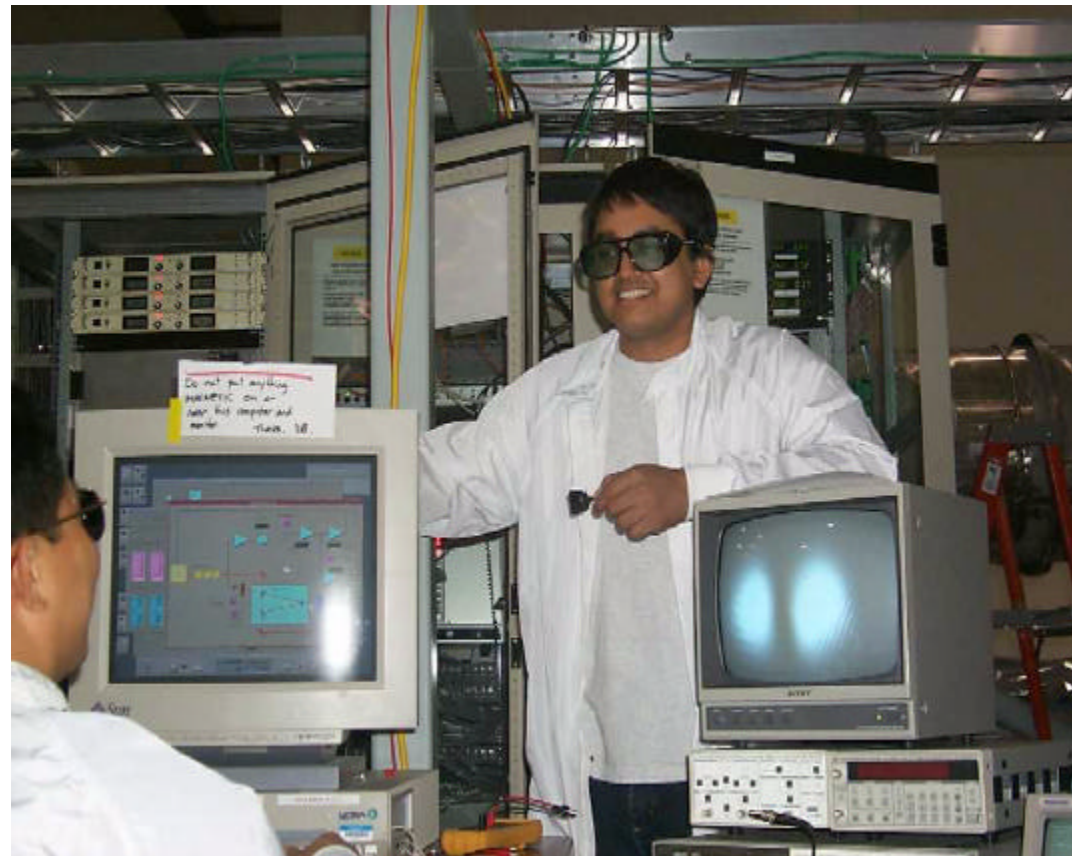
Stabilize the Laser Beam Entering the Interferometer

- Stabilize beam geometry by suppressing higher order transverse modes (hence, the name Mode Cleaner)
- Serve as intermediate frequency reference in the hierarchy of laser frequency controls
- Integration “microcosm” of a full interferometer:
 - ›› Seismic Isolation - Suspended optics
 - ›› Stabilized laser
 - ›› Control systems for laser, optics suspensions
 - ›› Data acquisition and diagnostics



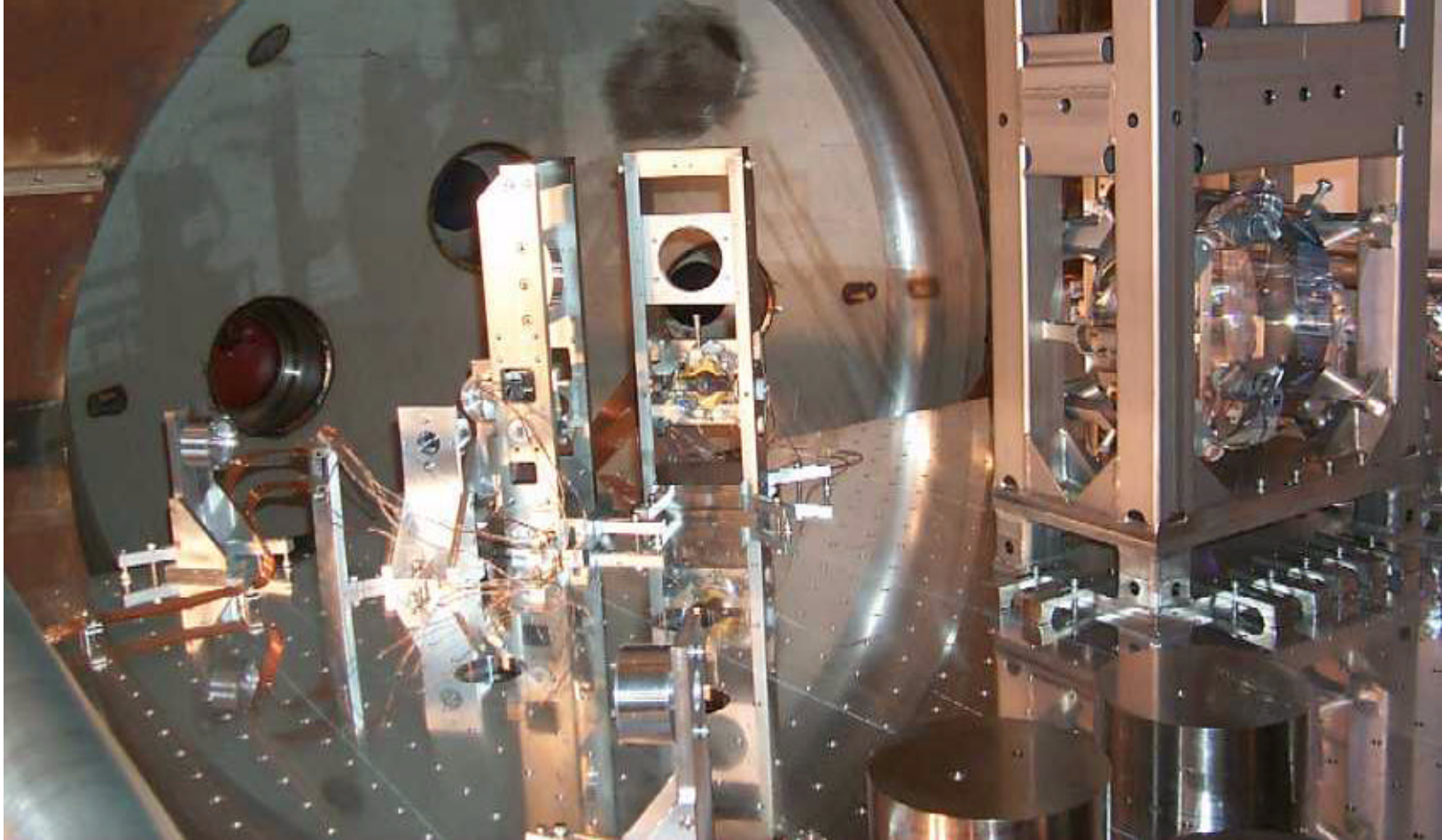
Mode Cleaner Lock Achieved/ Characterization Underway

- (After a couple weeks of tuning)
Lock acquisition typically within 15 seconds,
lock duration ~ day
- Wavefront-sensing for alignment operational





Mode Cleaner Optics Installed in Vacuum System



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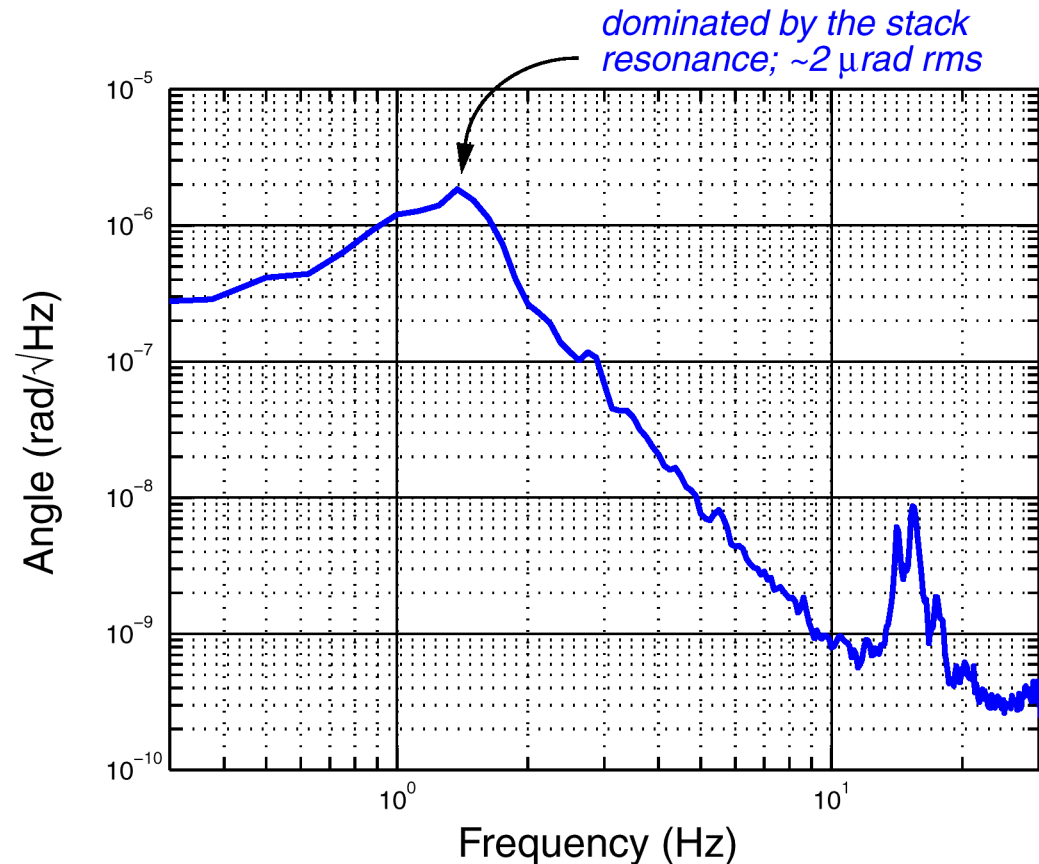
Preliminary Measurements of Mode Cleaner Properties

- Mode Cleaner length within 400 μm of desired length
- Mode matching into Mode Cleaner $\sim 97\%$
- Measured optical linewidth (7.4 kHz FWHM) near design value (6.3 kHz)
- Internal Q's of mode cleaner optics all meet spec ($> 2 \times 10^5$)
 - ›› 3.7×10^5 , 7.8×10^5 , 1.3×10^6



Angular Fluctuations of Beam After the Mode Cleaner

- Mode matching telescope reduces angles 10X
- Beam pointing servo reduces by another factor 10
- Tuning of suspension control electronics gave another factor 3
- Result: should meet requirement (10^{-8} rad)





Alignment and Length Control Systems

The Challenge:

Hold interferometer at its optimal operating point and measure the gravitational wave signal

- Control 14 coupled degrees of freedom
- Stringent control requirements
 - ›› Length degrees of freedom controlled to 10^{-11} - 10^{-13} m
 - ›› Angular degrees of freedom controller to 10^{-8} rad
- Stringent noise requirements
 - ›› Must not degrade detector sensitivity



Control System Development

- Analytical models (including noise propagation) to determine optical and control system requirements
 - ›› Tabletop experiments to verify model validity and completeness
 - ›› Resulted in three Ph.D theses
- Numerical models of servocontrol system as a part of the design process
 - ›› Several different models: time and frequency domains, length, angular and combined, etc.
 - ›› Available to use during commissioning
- Mode Cleaner uses similar design process



Major Phases in Control System Commissioning

- Single 2 km arm cavity (12/99-2/00)
 - ›› First measure of optical properties of arm cavities
 - ›› Correlation of seismic noise over site, adequacy of servos for suppressing microseismic peak
- Power-recycled (short) Michelson (2-4/00)
 - ›› First use of full mixed digital/analog servos
- Full recycled Fabry-Perot Michelson (4-11/00)
 - ›› Lock acquisition of full interferometer
 - ›› Stability and noise suppression of length and alignment servos with strongly coupled degrees of freedom
 - ›› Tuning to achieve full sensitivity!



The Staff to Make It All Happen

The Challenge:

Assemble an enthusiastic staff, capable of operating state-of-the-art detectors 'round the clock

- Two new facilities far away from the on-campus bases
- No large body of GW experimenters to draw on
- Compressed learning period, concurrent with installation



The Staff



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The Staff



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