LIGO:
Challenges Past, Present and Future

LIGO Science Symposium

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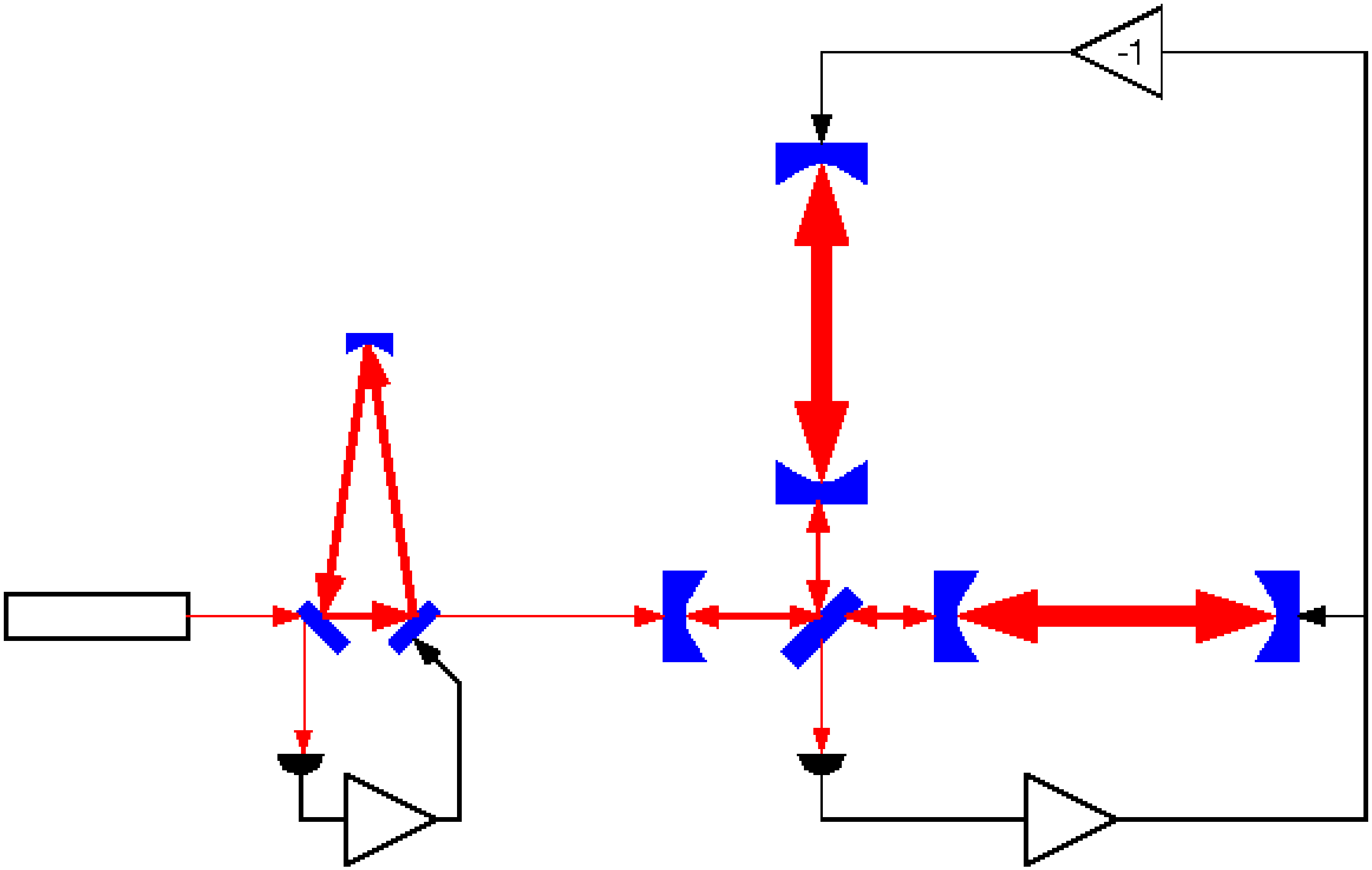
LIGO Interferometer



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

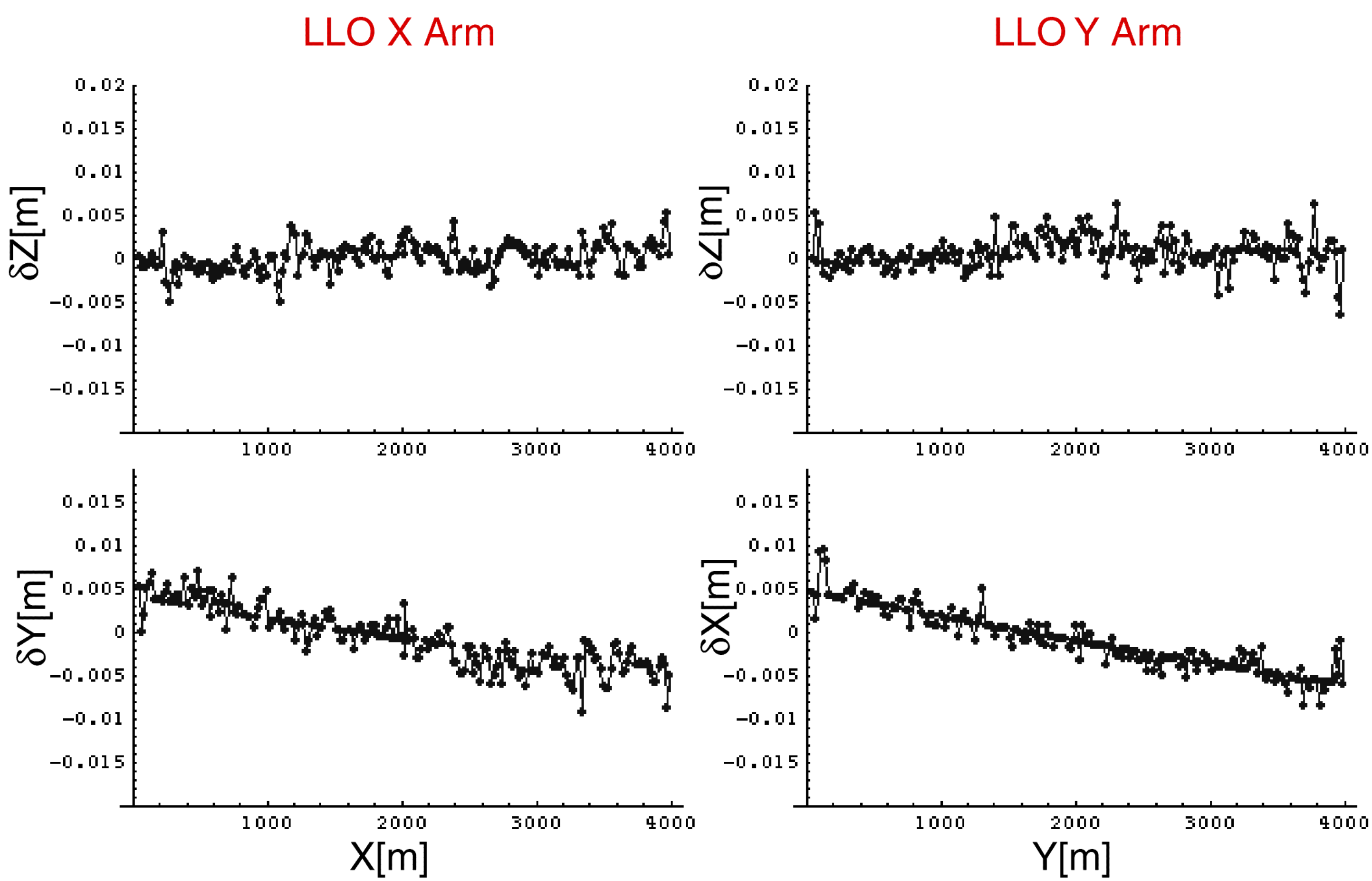
- Far exceeds outgassing and leak needs for initial LIGO detectors
- Adequate for the next generation, ...and the generation after that...

NOTE: All results except for H_2 are upper limits

Species	Goal[b]	Hanford HY2	Hanford HY1	Hanford HX1	Hanford HX2	Livingston LX2	torr-l/sec/cm^2
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_2O	*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}
$NO+C_2H_6$	*7000*	< 2	< 14	< 6.6	< 1.0	< 1.1	x 10^{-19}
$H_nC_pO_q$	*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



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

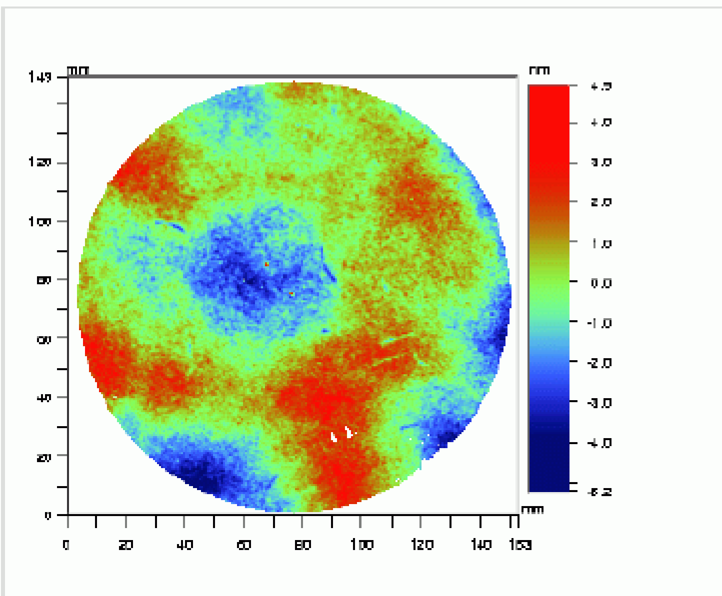
- Optical
  - Coating scatter < 50 ppm, absorption < 2 ppm
  - Polishing and coating uniformity < 1 nm RMS
  - Substrate homogeneity $< 5 \times 10^{-7}$
  - Radii of curvature measured and matched to 1-3%
- Mechanical
  - Q's of internal vibrational modes $> 2 \times 10^{6}$

Test Masses/Optics Developments

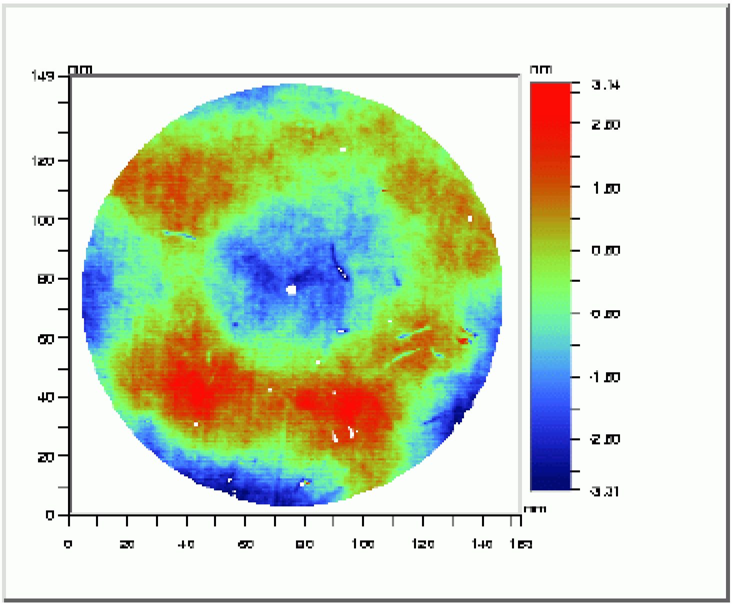
- "Pathfinder" process to work with industry in a collaborative development of the required technologies
  - 2 manufacturers of fused silica blanks
  - 4 polishers
  - 5 metrology companies/labs
  - 1 optical coating company
- Successfully demonstrated all requirements!

Comparison of CSIRO and LIGO Metrology

LIGO 1.3 nm RMS



CSIRO 1.1 nm RMS



Mode Cleaner

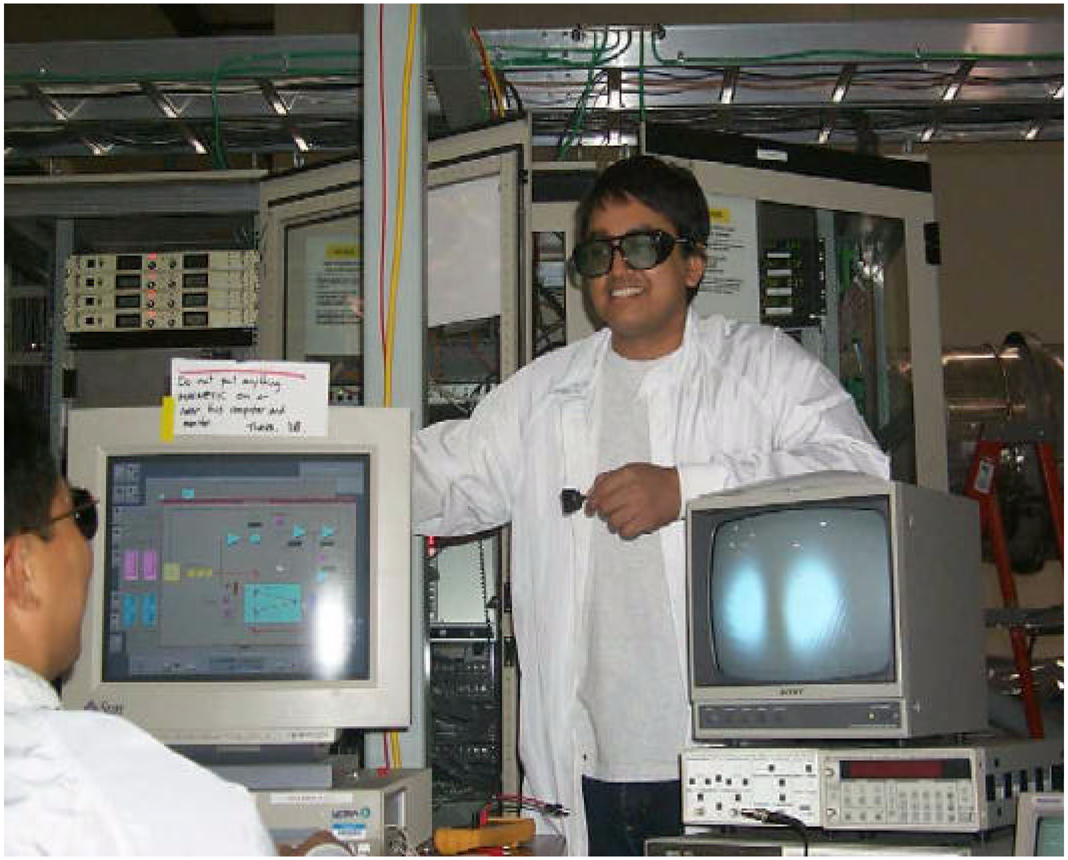
The Challenge:

Stabilize the Laser Beam Entering the Interferometer

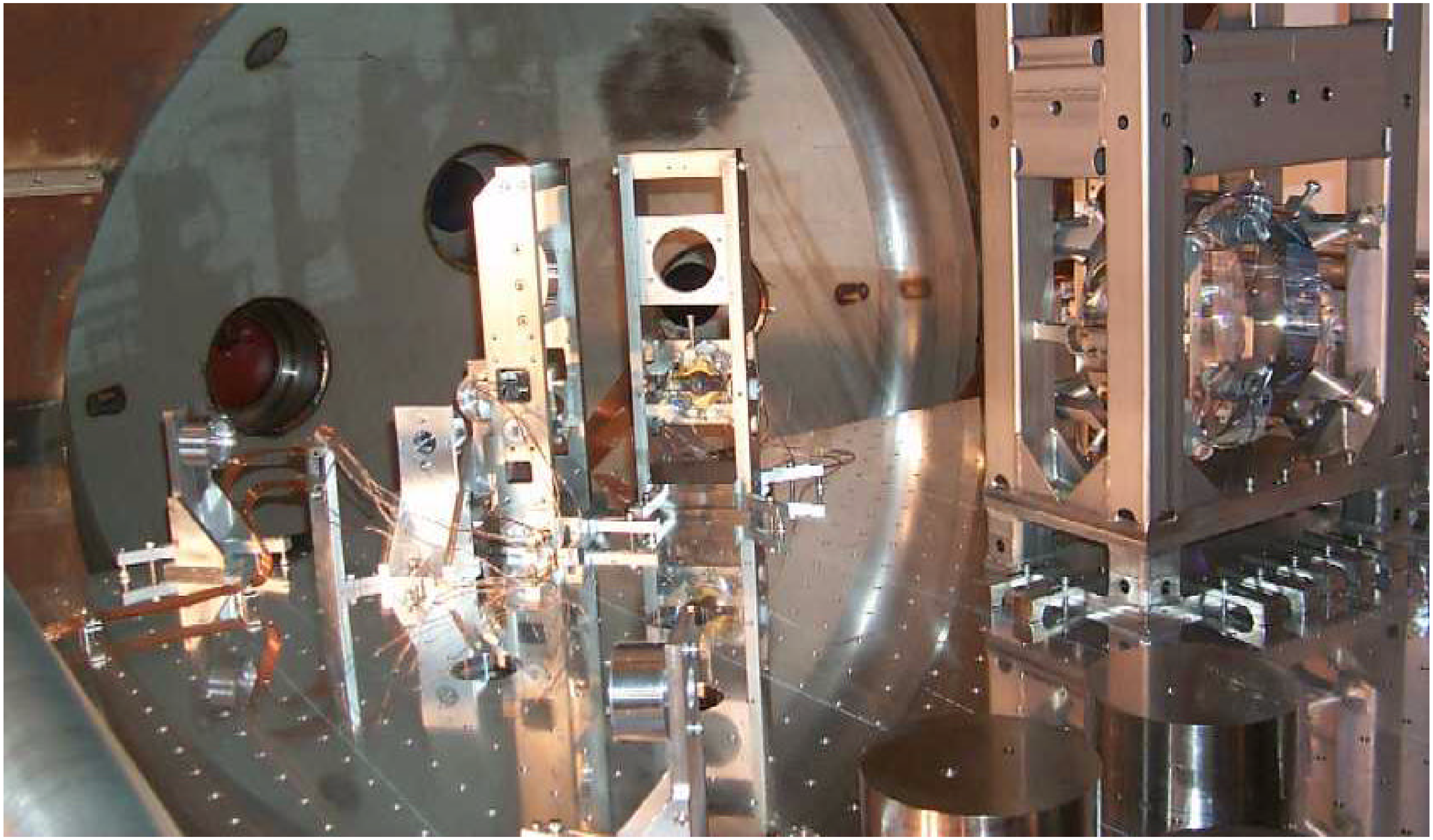
- Stabilize beam geometry by suppressing higher order transverse modes (hence, the name Mode Cleaner)
- Serve as intermediate frequency reference in the hierarchy of laser frequency controls
- Integration "microcosm" of a full interferometer:
  - Seismic Isolation - Suspended optics
  - Stabilized laser
  - 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

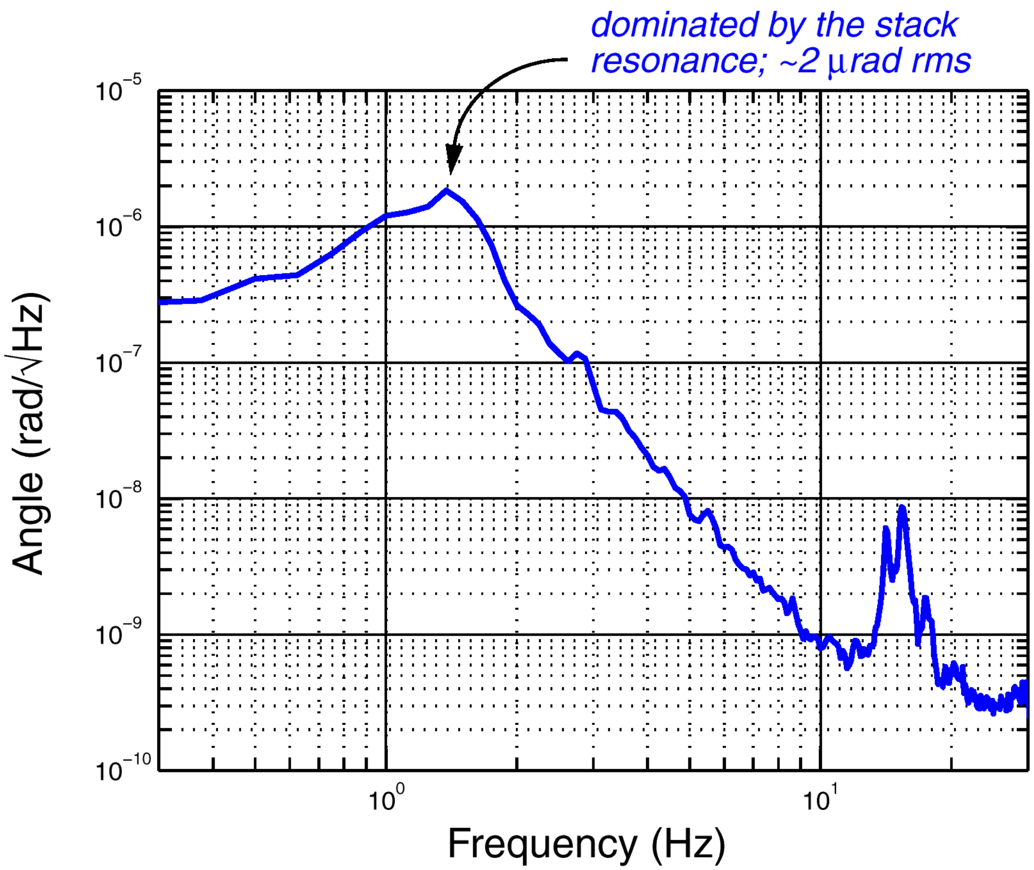


Preliminary Measurements of Mode Cleaner Properties

- Mode Cleaner length within 400 μm of desired length
- Mode matching into Mode Cleaner ~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 x 10^5)
  - 3.7 x10^5, 7.8 x 10^5, 1.3 x 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 contoller 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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