R&D for Advanced LIGO 2002-2006

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Overview

- Evolution intrinsic to LIGO mission
- Next step in detector design:
  - Should be of astrophysical significance if it observes GW signals or if it does not
  - Should be at the limits of reasonable extrapolations of detector physics and technologies
  - Should lead to a realizable, practical instrument
- Much effort is inextricably entwined with LSC research
  - LIGO Lab and other LSC members in close-knit teams
  - Lab coordinates, provides infrastructure/engineering

Overview

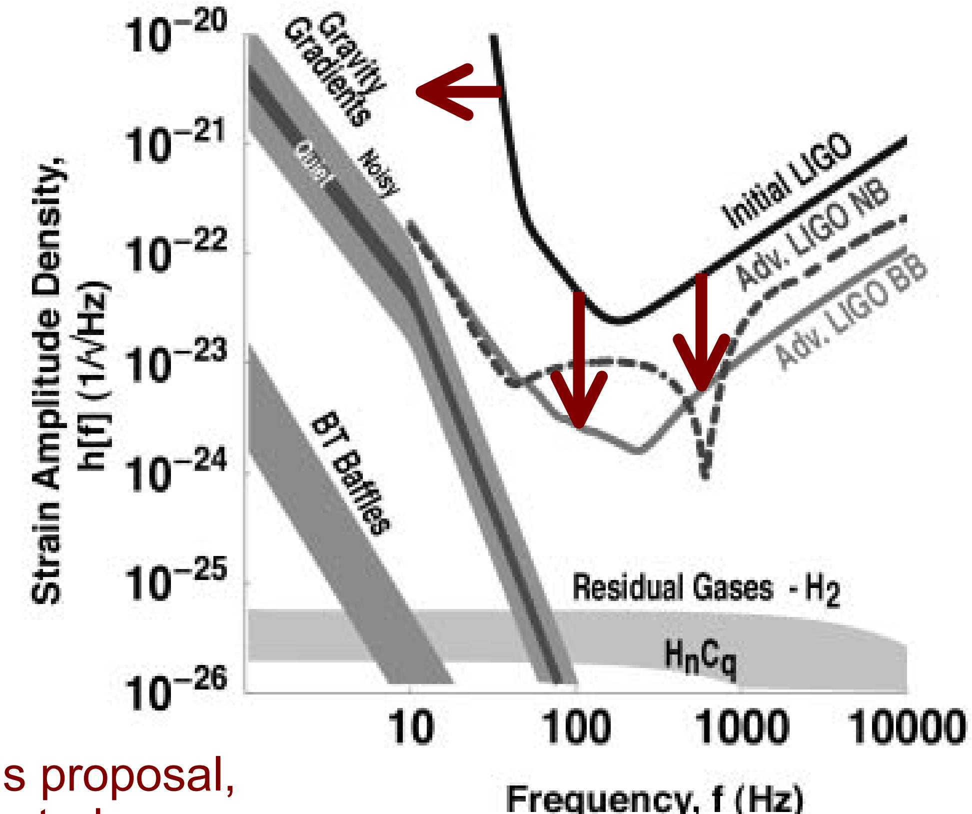
- Talk organization:
  - » Present and future limits to sensitivity; system trades
  - » Introduction to the detector, subsystems, systems issues
  - » Mechanical aspects of design: Isolation, Suspension, Thermal noise, and system tests
  - » Optics: Laser, Test Masses, Input Optics, Auxiliary Optics
  - » Sensing and control: Design and prototype tests
- Detailed technical, schedule, and budget information available

Choosing an upgrade path

- Wish to maximize astrophysics to be gained
  - » Must fully exploit initial LIGO
  - » Any change in instrument leads to lost observing time at an Observatory
  - » Studies based on LIGO I installation and commissioning indicate 1-1.5 years between decommissioning one instrument and starting observation with the next
  - » → Want to make one significant change, not many small changes
- Technical opportunities and challenges
  - » Can profit from evolution of detector technologies since initial LIGO design ‘frozen’
  - » ‘Fundamental’ limits: quantum noise, thermal noise provide point of diminishing returns (for now!)

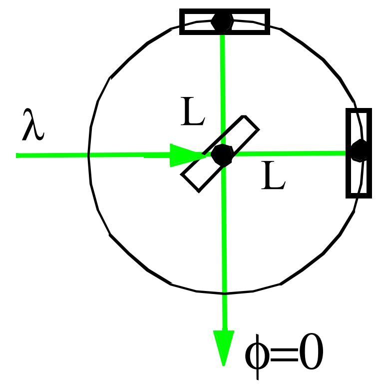
Present and future limits to sensitivity

- Advanced LIGO
  - » Seismic noise 40→10 Hz
  - » Thermal noise 1/15
  - » Shot noise 1/10, tunable
- Facility limits
  - » Gravity gradients
  - » Residual gas
  - » (scattered light)
- Beyond Adv LIGO
  - » Thermal noise: cooling of test masses
  - » Quantum noise: quantum non-demolition
  - » Not the central focus of this proposal, but exploration must be started now

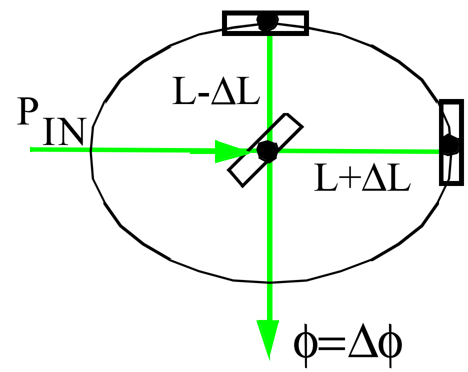


Introduction to the detector

- Michelson as strain sensor
- Sensitive to differential strains
- Insensitive to common-mode motion
- Signal proportional to
  - » length (in short-wavelength limit, true for 4km and kHz)
  - » laser power (shot noise grows as square root, so overall gain as square root of laser power)
- Mechanical isolation needed from external forces
- Stochastic forces due to Thermal noise present (equilibrium with heat bath)
- Fluctuations in light path due to gas also a limit (index fluctuations)

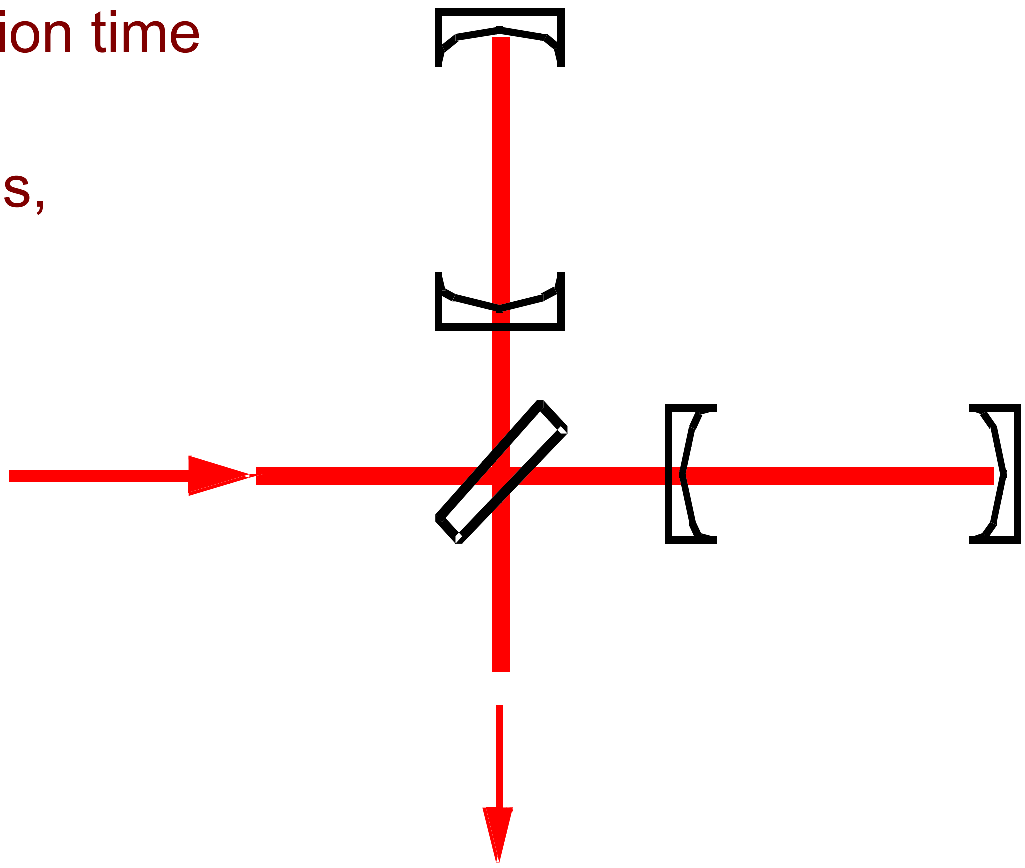


$$\Delta L = h\, L$$



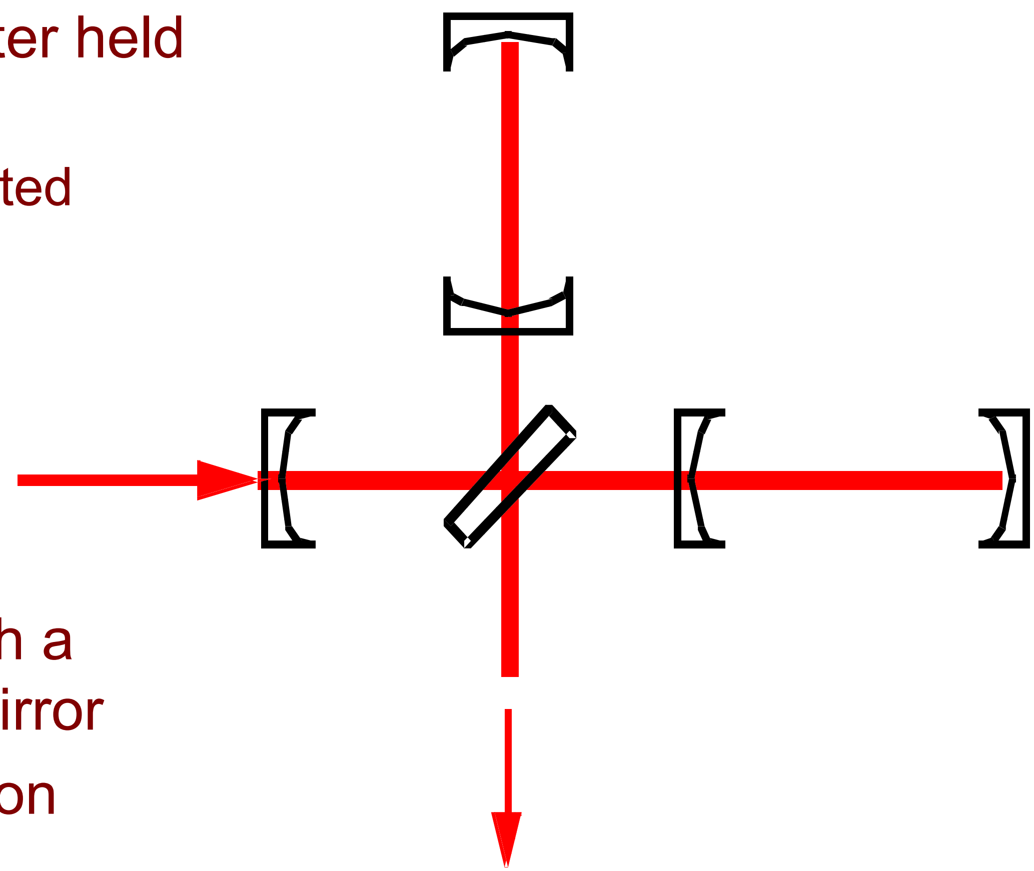
Increasing the interaction time

- Alternative to longer arms
- Increase in the interaction time of strain with light
- Multi-bounce delay lines, or Fabry-Perot cavities



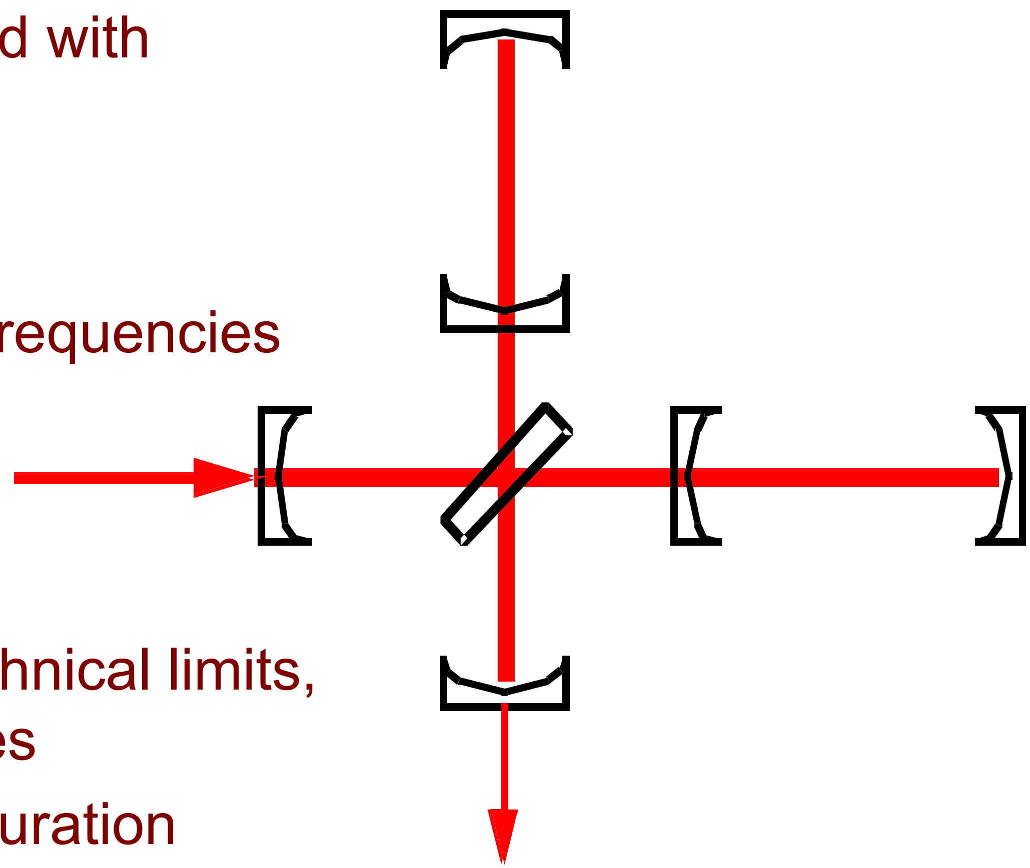
Increasing the circulating power

- Introduction of Power Recycling
- Michelson interferometer held at ‘dark fringe’
  - » Most input light reflected back to laser
- ‘Impedance match’ with a partially transmitting mirror
- Initial LIGO configuration



Tailoring the frequency response

- Signal Recycling
- Additional cavity formed with mirror at output
- Can be resonant, or anti-resonant, for gravitational wave frequencies

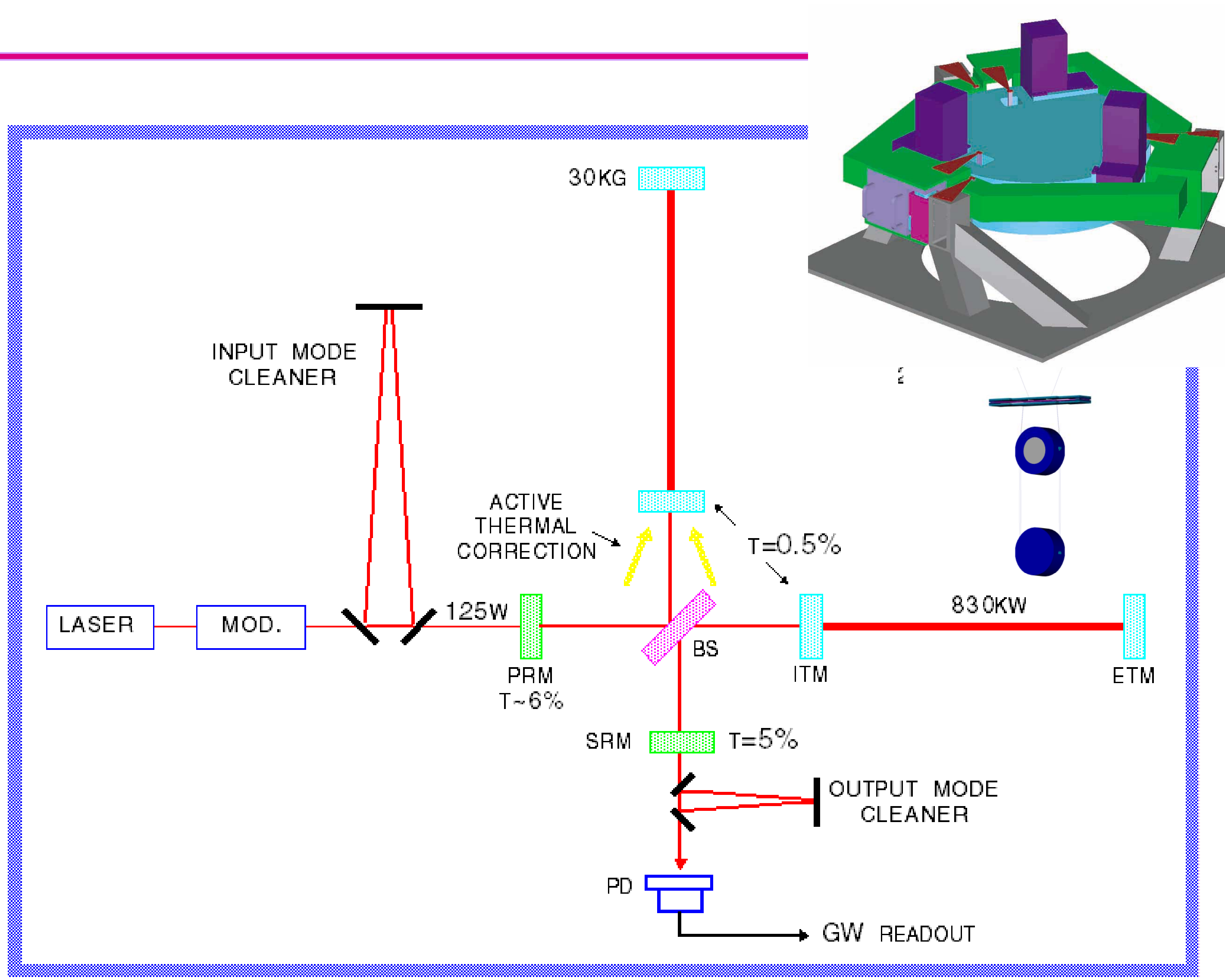


- Allows optimum for technical limits, astrophysical signatures
- Advanced LIGO configuration

Interferometer subsystems

Subsystem	Function	Implementation	Principal challenges
Interferometer Sensing and Control (ISC)	Gravitational Readout; length and angle control of optics	RF modulation/demod techniques, digital real-time control	Lock acquisition, S/N and bandwidth trades
Seismic Isolation (SEI)	Attenuation of environmental forces on test masses	Low-noise sensors, high-gain servo systems	Reduction of test mass velocity due to 0.01-1 Hz input motion
Suspension (SUS)	Establishing 'Free Mass', actuators, seismic isolation	Silica fibers to hold test mass, multiple pendulums	Preserving material thermal noise performance
Pre-stabilized Laser (PSL)	Light for quantum sensing system	Nd:YAG laser, 100-200 W; servo controls	Intensity stabilization: 3e-9 at 10 Hz
Input Optics (IOS)	Spatial stabilization, frequency stabilization	Triangular Fabry-Perot cavity, suspended mirrors	EO modulators, isolators to handle power
Core Optics Components (COC)	Mechanical test mass; Fabry-Perot mirror	40 kg monolithic sapphire (or silica) cylinder, polished and coated	Delivering optical and mechanical promise; Developing sapphire
Auxiliary Optics (AOS)	Couple light out of the interferometer; baffles	Low-aberration telescopes	Thermal lensing compensation

Interferometer subsystems

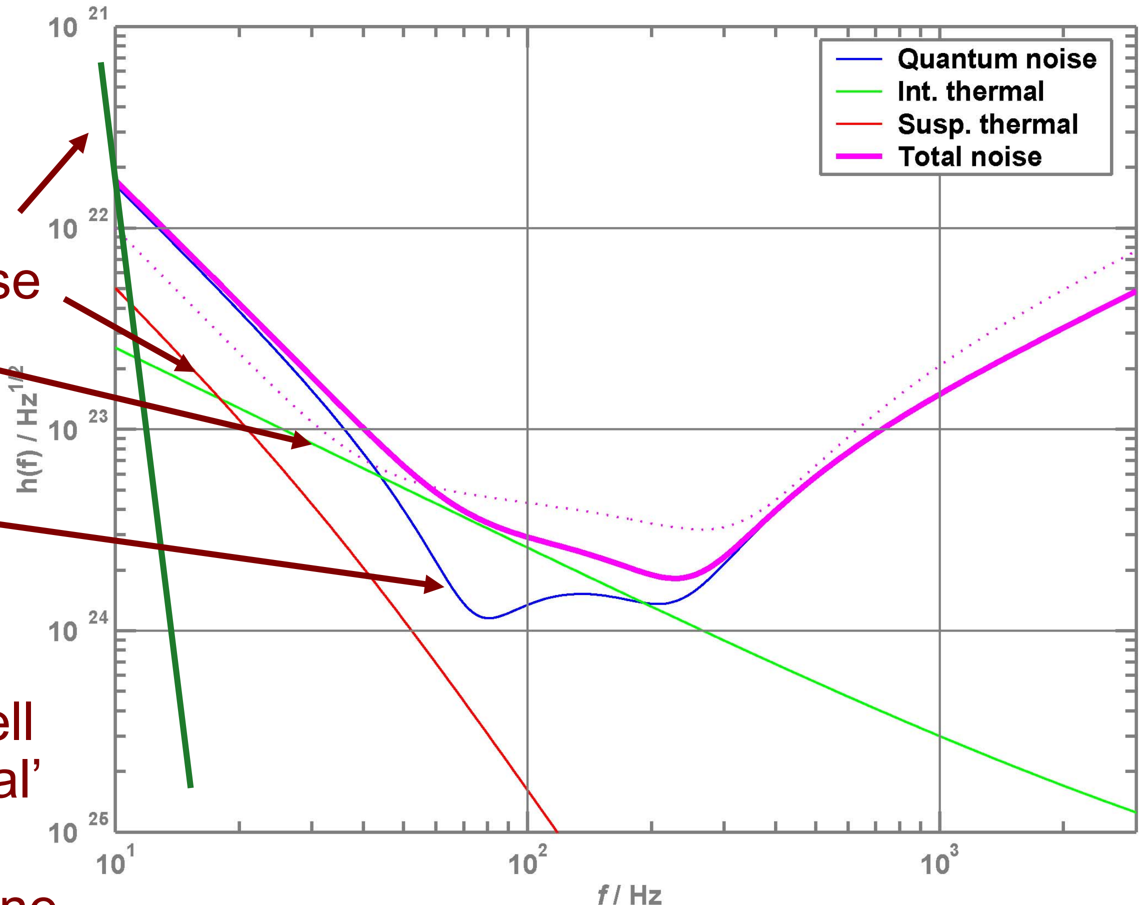


System trades

- Laser power
  - » Trade between improved readout resolution, and momentum transfer from photons to test masses
  - » Distribution of power in interferometer: optimize for material and coating absorption, ability to compensate
- Test mass material
  - » Sapphire: better performance, but development program, crystalline nature
  - » Fused silica: familiar, but large, expensive, poorer performance
- Lower frequency cutoff
  - » ‘Firm’, likely, and possible astrophysics
  - » Technology thresholds in isolation and suspension design

Anatomy of the projected detector performance

- Sapphire test mass baseline system
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Internal thermal noise
- Unified quantum noise dominates at most frequencies
- 'technical' noise (e.g., laser frequency) levels held in general well below these 'fundamental' noises
- Silica test mass dotted line



Nominal top level parameters

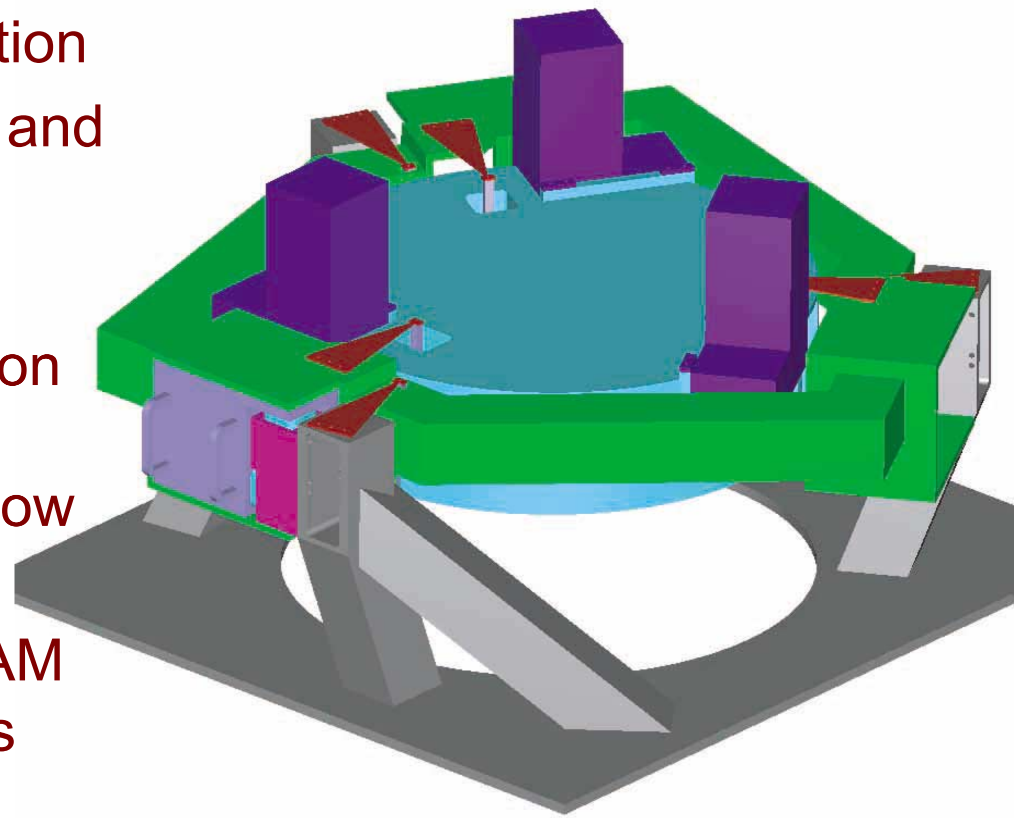
	Sapphire	Fused Silica
Fabry-Perot arm length	4000 m	
Laser wavelength	1064 nm	
Optical power at interferometer input	125 W	80 W
Power recycling factor	17	17
FP Input mirror transmission	0.5%	0.50%
Arm cavity power	830 kW	530 kW
Power on beamsplitter	2.1 kW	1.35 kW
Signal recycling mirror transmission	6.0%	6.0%
Signal recycling mirror tuning phase	0.12 rad	0.09 rad
Test Mass mass	40 kg	30 kg
Test Mass diameter	32 cm	35 cm
Beam radius on test masses	6 cm	6 cm
Neutron star binary inspiral range (Bench)	300 Mpc	250 Mpc
Stochastic GW sensitivity (Bench units)	8 x 10-9	3 x 10-9

Active Seismic Isolation R&D (SEI): Requirements

- Goal: render seismic noise a negligible limitation to GW searches
  - » Other ‘irreducible’ noise sources limit sensitivity to uninteresting level for frequencies less than ~20 Hz
  - » Suspension and isolation contribute to attenuation
  - » Choose to require a 10 Hz ‘brick wall’
- Goal: reduce or eliminate actuation on test masses
  - » Actuation source of direct noise, also increases thermal noise
  - » Seismic isolation system can reduce RMS/velocity through inertial sensing, and feedback
  - » Acquisition challenge greatly reduced
  - » Choose to require RMS of <10^-11 m

SEI: Conceptual Design

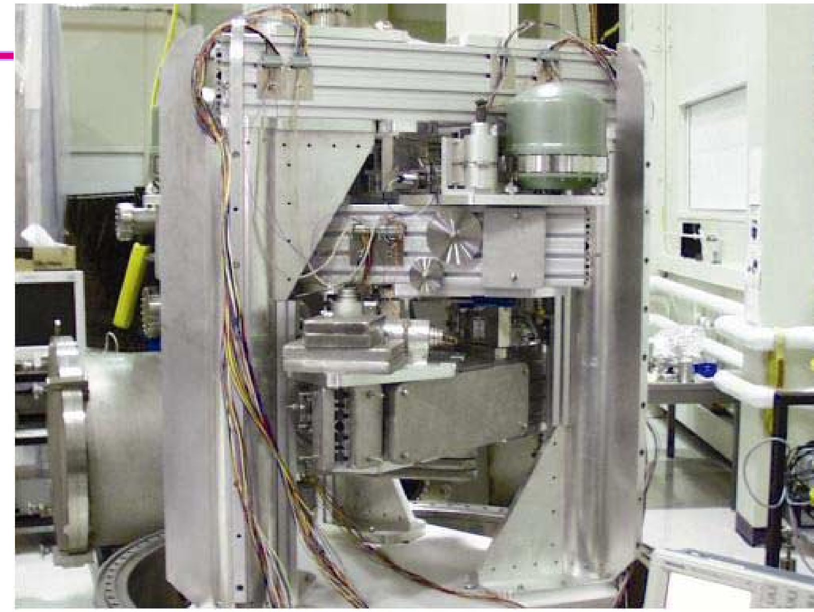
- Two in-vacuum stages in series, external slow correction
- Each stage carries sensors and actuators for 6 DOF
- Stage resonances ~5 Hz
- High-gain servos bring motion to sensor limit in GW band, reach RMS requirement at low frequencies
- Similar designs for BSC, HAM vacuum chambers; provides optical table for flexibility



SEI: Organization

- Initial work done by teams at Caltech, MIT, Stanford, LSU, JILA – significant input from LSC teams, suspension working group
- Strategic organization by Lab of continued development at LLO, with continued LSC scientific leadership (Giaime/LSU)
- Engineering effort and prototype fabrication managed by LLO (Stapfer)
- Next prototype to be installed and tested in Stanford ETF (Lantz)
- Installation and test at MIT LASTI to be performed by development team of engineers/scientists, plus MIT LASTI staff

SEI: Progress and Plans



- Parallel design effort on passive, active systems
  - ✓ 4Q99: Draft requirements and interface established
  - ✓ 2Q00: SAS reference design, prototype tests
  - ✓ 2Q00: Active reference design, prototype tests
  - ✓ 2Q00: Choice of design to pursue
- Prototyping and test of active systems
  - ✓ 3Q00: All 12 DOF active system locked
  - ✓ 4Q00: initial design and demonstrator bid package ready
  - » 4Q01: demonstrator test complete (at Stanford)
  - » 3Q02: HAM prototype standalone testing completed (MIT LASTI)
  - » 1Q03: BSC prototype standalone testing completed (MIT LASTI)

SEI: Manpower and equipment

FY02

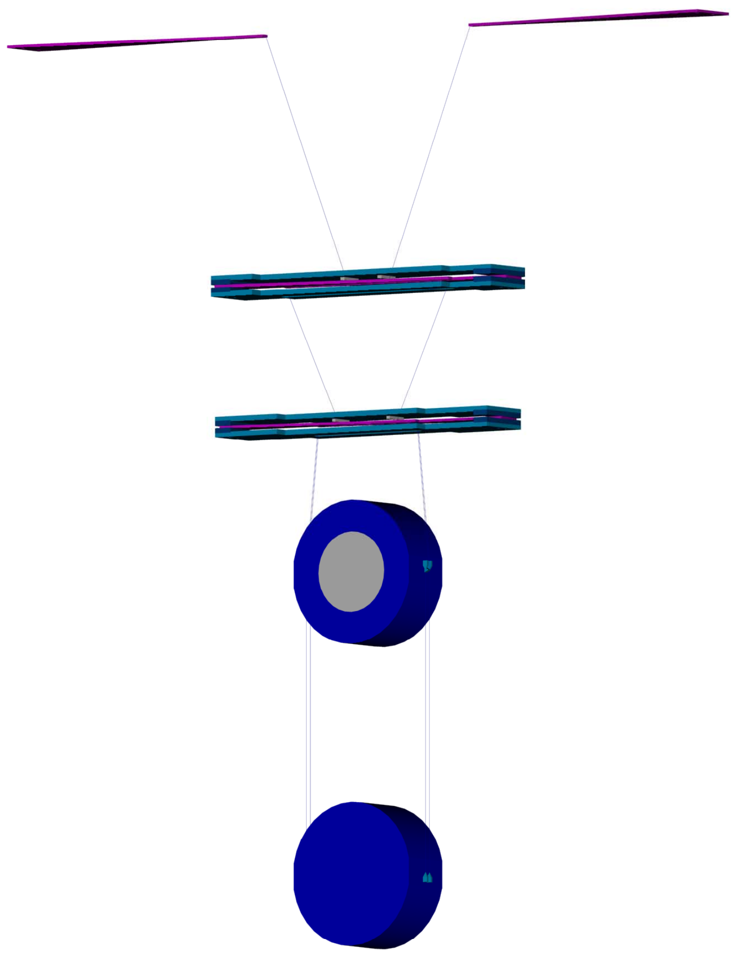
Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE)	
Active Seismic Isolation (SEI)						
Gerry Stapfer	LLO			0.5	0.5	
Joe Giaime	LSU					
Sci & PD	MIT				0	0.5
	CIT	0.5			0.5	
UG & Grads	MIT				0	0
	CIT				0	
Eng & Techs	MIT				0	5
	CIT			0.5	0.5	
	LLO			4	4	
Totals (FTE):		0.5	0	5	5.5	
Equip. & Supplies ($K)		$0	$845	$0	$845	

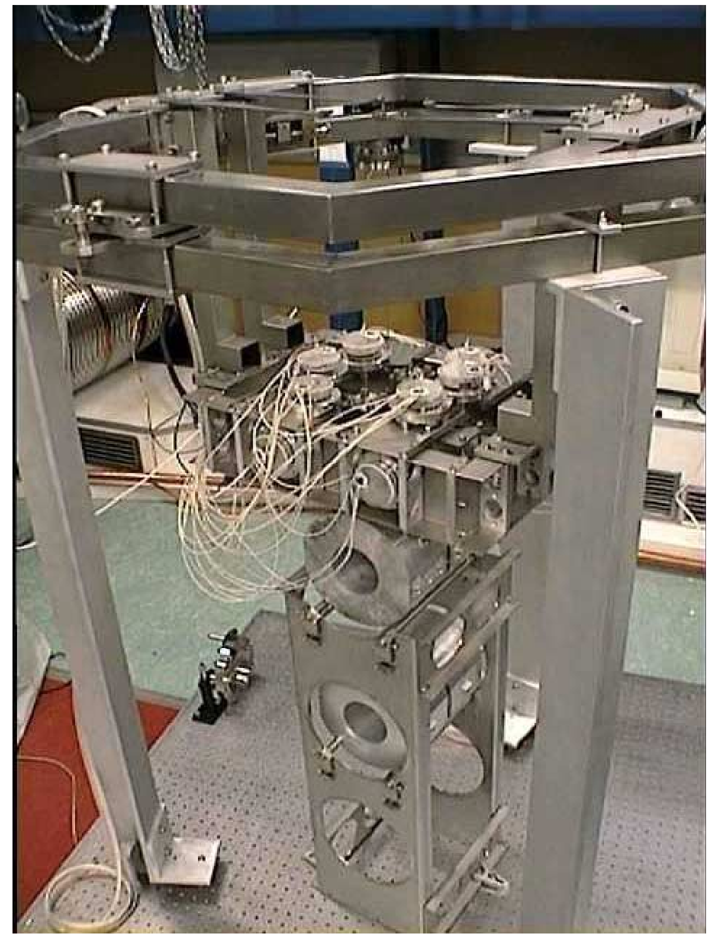
N.B.: Does not include LSC research staff.

Suspension Research (SUS)

- Adopting a multiple-pendulum approach
  - » Allows best thermal noise performance of suspension and test mass; replacement of steel suspension wires with fused silica
  - » Offers seismic isolation, hierarchy of position and angle actuation
- Close collaboration with GEO (German/UK) GW group
  - » Similar design used in GEO-600, being installed now
  - » GEO takes responsibility for initial design
  - » LIGO takes over design as we deal with fabrication/installation issues
- Schedule highlights:
  - » 2Q01: Install first fused silica GEO-600 suspension
  - » 2Q02: Controls prototypes complete, in testing
  - » 2Q03: Noise prototypes complete, in testing

GEO suspension

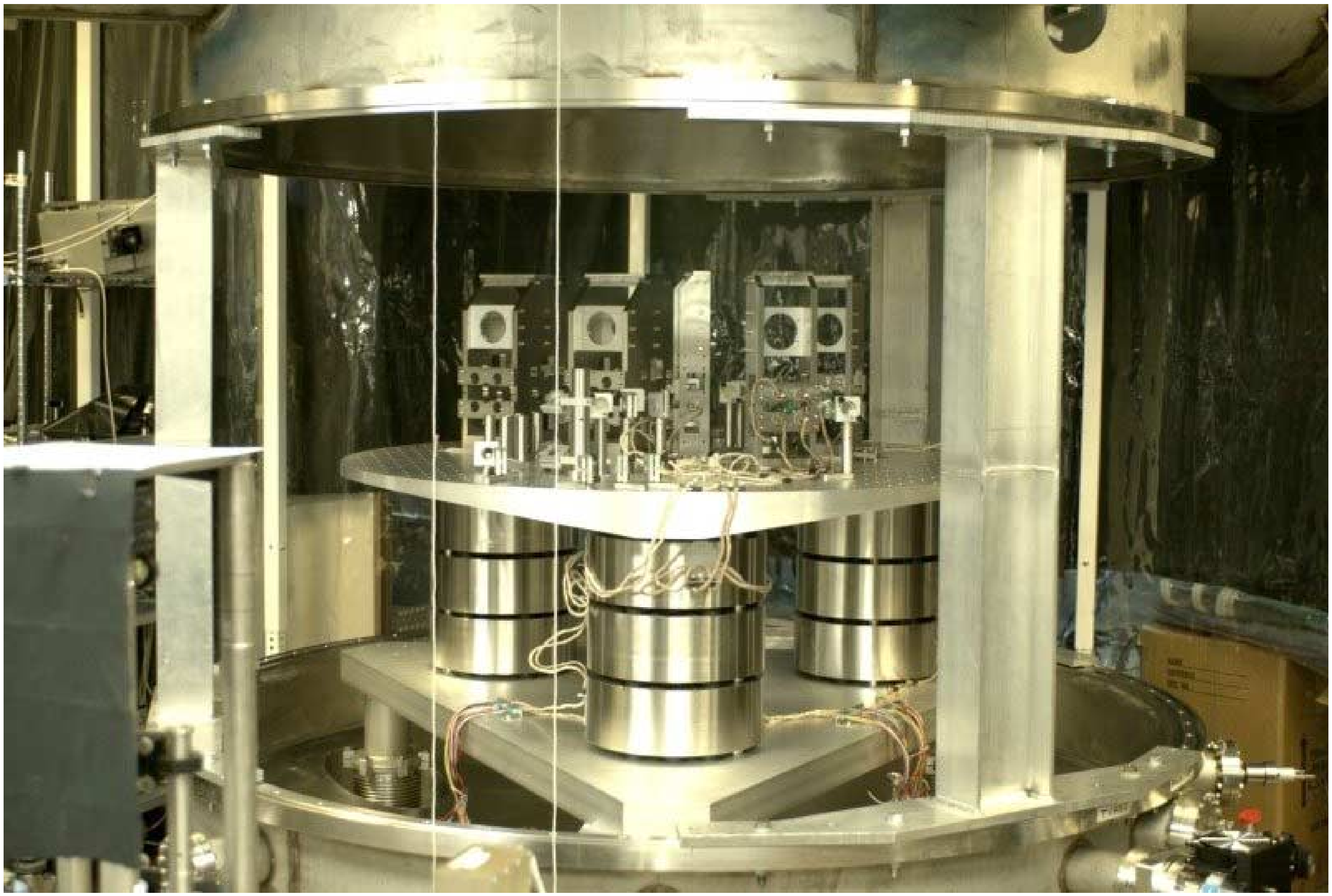




Thermal Noise Interferometer (TNI)

- Direct measurement of thermal noise, at LIGO Caltech
  - » Test of models, materials parameters
  - » Search for excesses (non-stationary?) above anticipated noise floor
- In-vacuum suspended mirror prototype, specialized to task
  - » Optics on common isolated table, ~1cm arm lengths
- Schedule highlights:
  - ✓ 4Q00: TNI cavity locks
  - » 2Q01: TNI studies for initial LIGO completed
  - » 2Q02: Sapphire substrates installed
  - » 1Q03: TNI final Sapphire/fused silica results

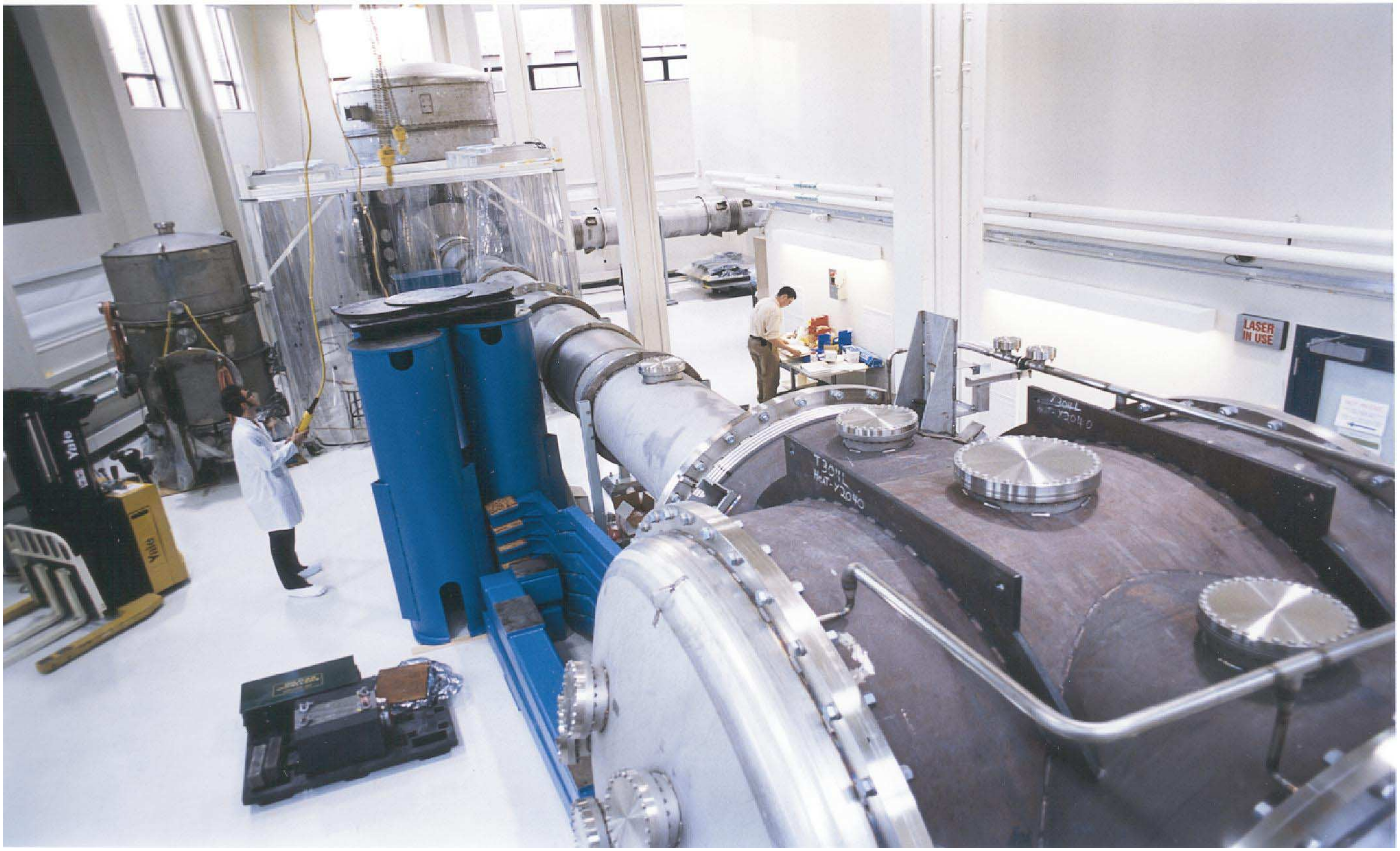
Thermal Noise Interferometer



Stochastic noise system tests: LASTI

- Full-scale tests of Seismic Isolation and Test Mass Suspension.
  - » Takes place in the LIGO Advanced System Test Interferometer (LASTI) at MIT: LIGO-like vacuum system.
  - » Allows system testing, interfaces, installation practice.
  - » Characterization of non-stationary noise, thermal noise.
- Subsystem support to LASTI system tests.
  - » teams learn how their system works, installs, etc.
  - » MIT support of infrastructure, and collaborative shakedown and test.
- Schedule highlights:
  - ✓ 4Q00: Vacuum system qualified, seismic supports in place.
  - » 4Q01: ‘infrastructure’ Laser, test cavity, DAQ, etc. tested.
  - » 3Q02: HAM isolation testing completed.
  - » 2Q03: Suspension noise prototypes installed.
  - » 2Q04: integrated Isolation/suspension testing completed.
  - » 1Q05: PSL-Mode Cleaner integrated performance test completed.

LASTI Laboratory



Isolation Research

(STO, SUS, TNI, SEI)

FY02

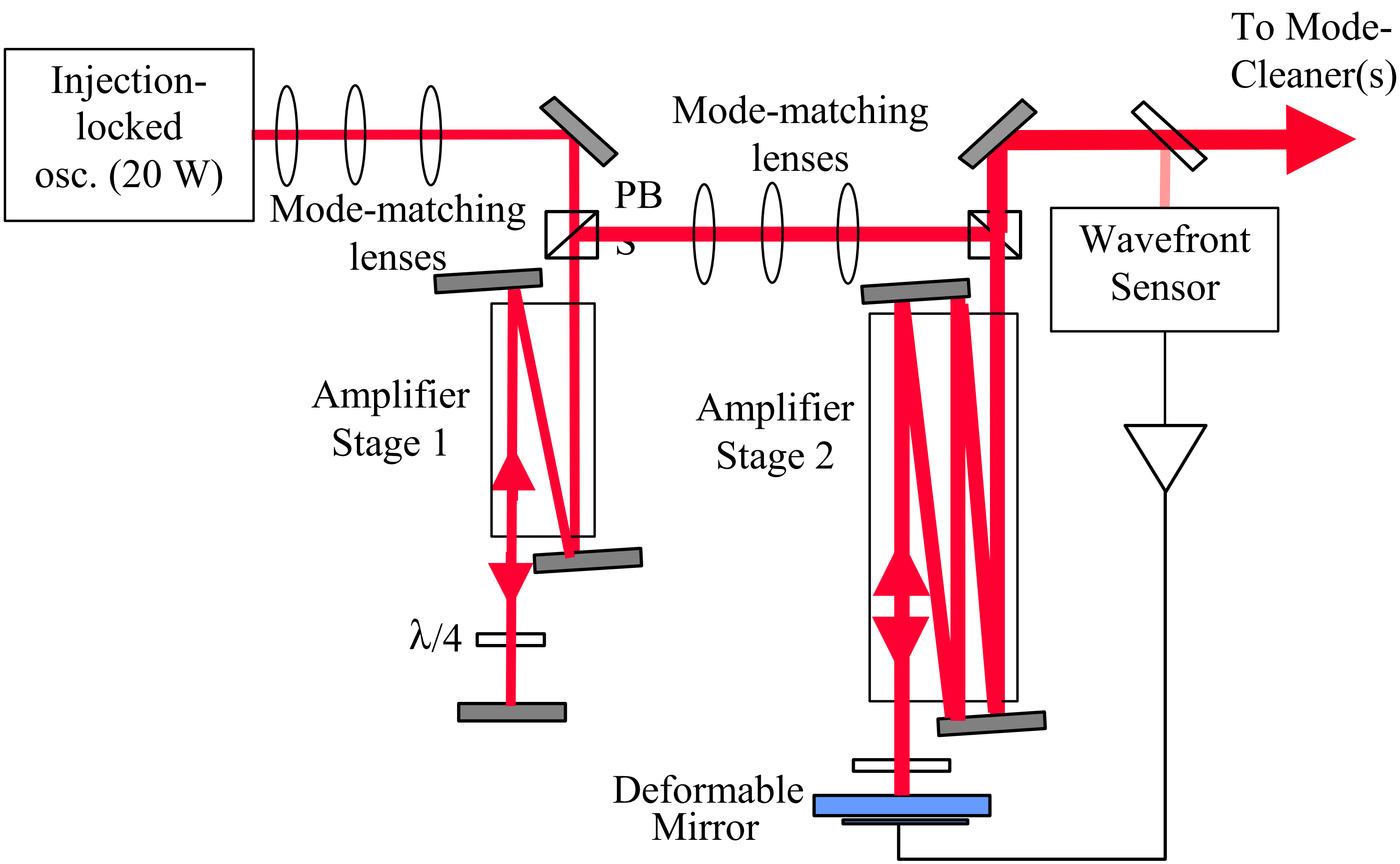
Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE, $K)	
ISOLATION						
Sci & PD	MIT	1	0	2.4	3.4	8.1
	CIT	3	0	1.7	4.7	
UG & Grads	MIT	3	0	0.0	3.0	5.0
	CIT	2	0	0.0	2.0	
Eng & Techs	MIT	0	0	2.8	2.8	14.2
	CIT	0	0	6.9	6.9	
	LLO	0	0	4.5	4.5	
Totals (FTE):		9	0	18.3	**27.3**	
Equip. & Supplies		$54	$1,595	0.0	**$1,649**	

N.B.: Does not include LSC research staff.

Advanced Laser R&D (LAS)

- Require optimal power, given fundamental and practical constraints:
  - » Shot noise: having more stored photons improves sensitivity, but:
  - » Radiation pressure: dominates at low frequencies
  - » Thermal focussing in substrates: limits usable power
- Optimum depends on test mass material, 80 – 180 W
- Power amplifier or injection-locked topology in trade study
- Laser Zentrum Hannover/GEO to take lead; LIGO Lab supplies requirements, interface, and test
- Schedule highlights:
  - » 4Q01: laser diode tests done / selection
  - » 1Q02: 100 W demonstration
  - » 2Q02: Laser concept downselect
  - » 2Q04: Install advanced LIGO PSL in the LASTI facility

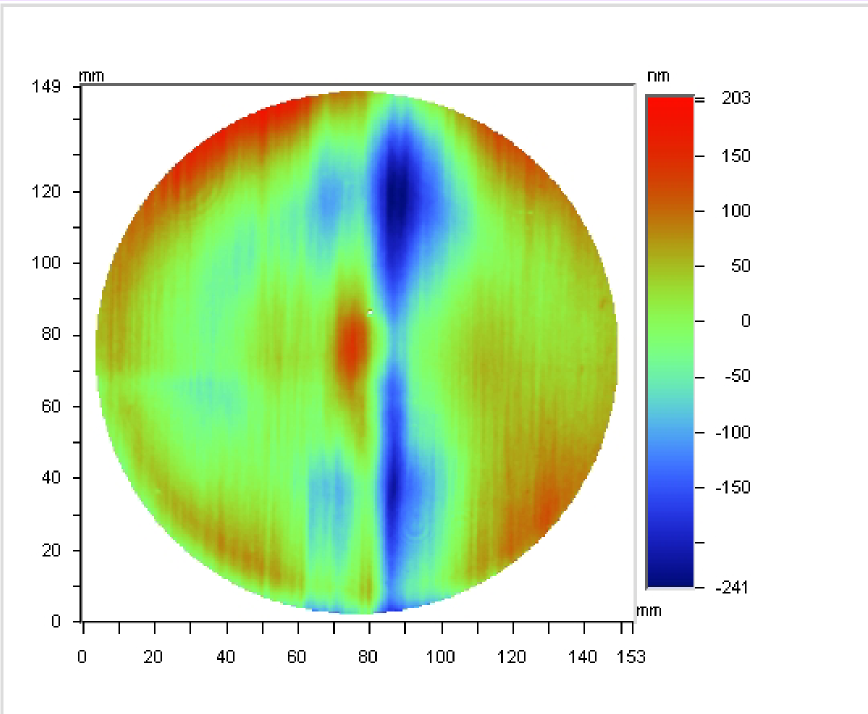
Advanced Laser – One Concept



Advanced Core Optics R&D (OPT)

- A key optical and mechanical element of design
  - » Substrate absorption, homogeneity, birefringence
  - » Ability to polish, coat
  - » Mechanical (thermal noise) performance, suspension design
  - » Mass – to limit radiation pressure noise: ~30-40 Kg required
- Two materials under study, both with real potential
  - » Fused Silica: very expensive, very large, satisfactory performance; familiar, non-crystalline
  - » Sapphire: requires development in size, homogeneity, absorption; high density (small size), lower thermal noise
- Caltech LIGO Lab leads effort, strong LSC input on materials/tests
- Schedule highlights:
  - ✓ 3Q00: m-axis birefringence measured
  - ✓ 3Q00: Initial sapphire refraction index homogeneity measurement
  - » 4Q01: Order LASTI SUS prototype sapphire & fused silica blanks
  - » 2Q02: Selection of test mass material
  - » 3Q03: Dedicated coating chamber installed and commissioned

Sapphire substrate homogeneity



Date: 11/08/2000
Time: 13:14:17
Wavelength: 1.064 um
Pupil: 100.0 %
PV: 444.0355 nm
RMS: 65.7678 nm
Rad of curv: 28.13 km

X Center: 287.00
Y Center: 240.00
Radius: 274.00 pix
Terms: Tilt
Filters: None
Masks: Detector Mask
Ref Sub: No

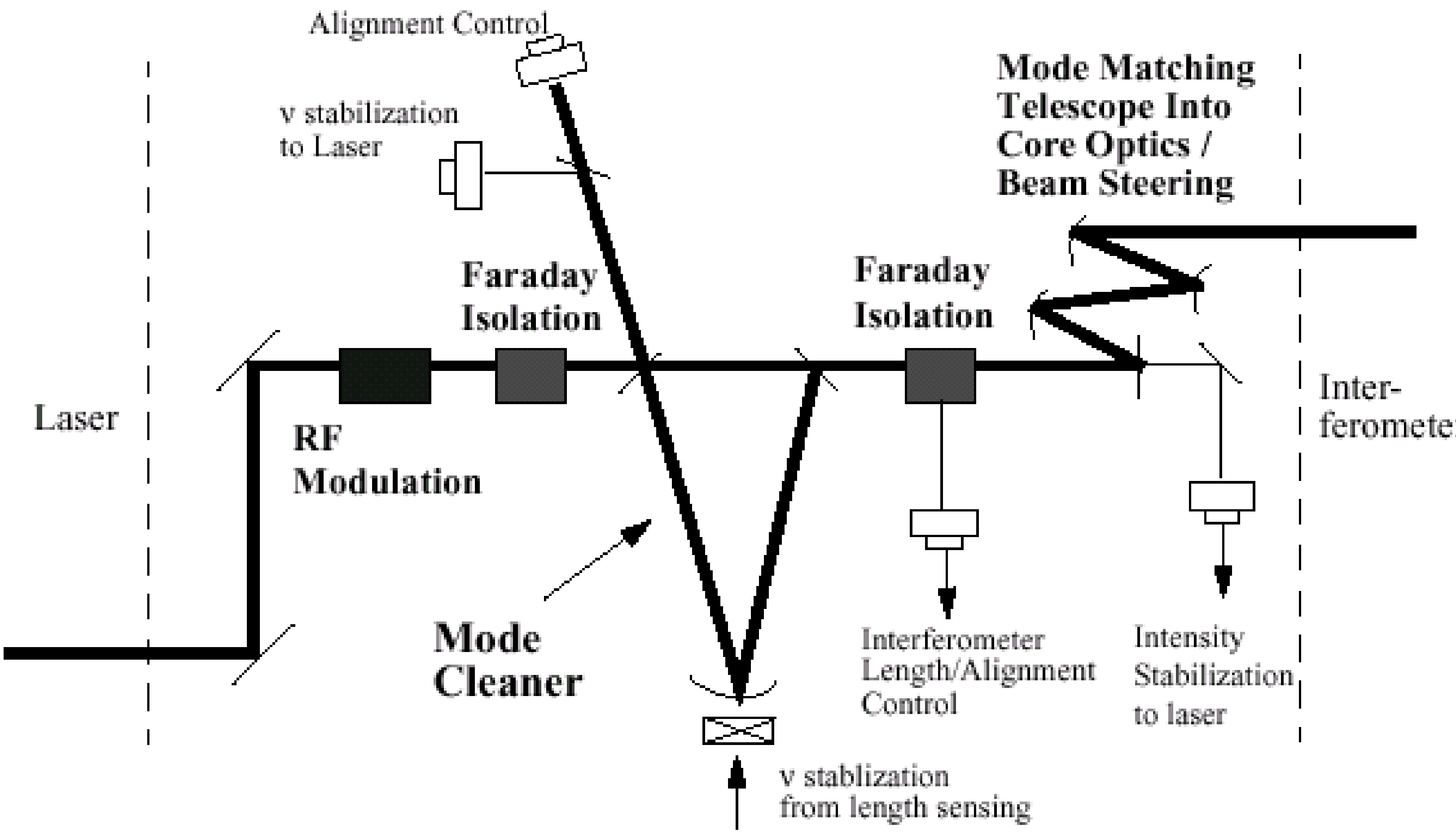
Averages: 8

- CIT measurement of a 25 cm m-axis sapphire substrate, showing the central 150mm.
- The piece is probed with a polarized beam. The structure is related to small local changes in the crystalline axis.
- Plan to apply a compensating polish to side 2 of this piece and reduce the rms variation in bulk homogeneity to roughly 10-20 nm rms

Input Optics System R&D (IOS)

- Subsystem interfaces laser light to main interferometer
  - » Modulation sidebands applied for sensing system
  - » Beam cleaned and stabilized by transmission though cavity
  - » Precision mode matching from ~0.5 cm to ~10 cm beam
- Challenges in handling high power
  - » isolators, modulators
  - » Mirror mass and intensity stabilization (technical radiation pressure)
- University of Florida takes lead, GEO suspensions, LIGO controls
- Schedule highlights:
  - ✓ 3Q00: Isolator demonstrated: >35 dB @ 50 W
  - » 2Q02: Demonstration of prototype phase modulation method
  - » 4Q02: Thermal lensing compensation results, optical layout chosen
  - » 1Q04: Install advanced LIGO IO components at LASTI
  - » 1Q05: PSL-Mode Cleaner integrated performance test completed

Input Optics

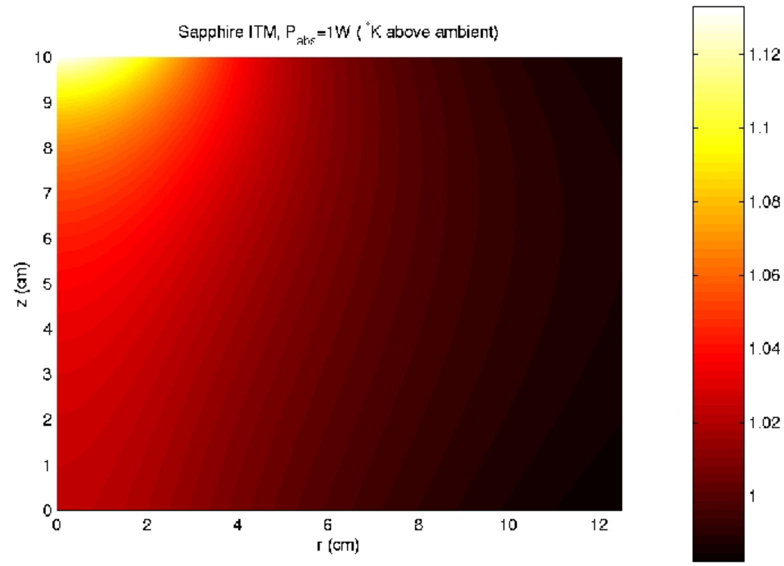


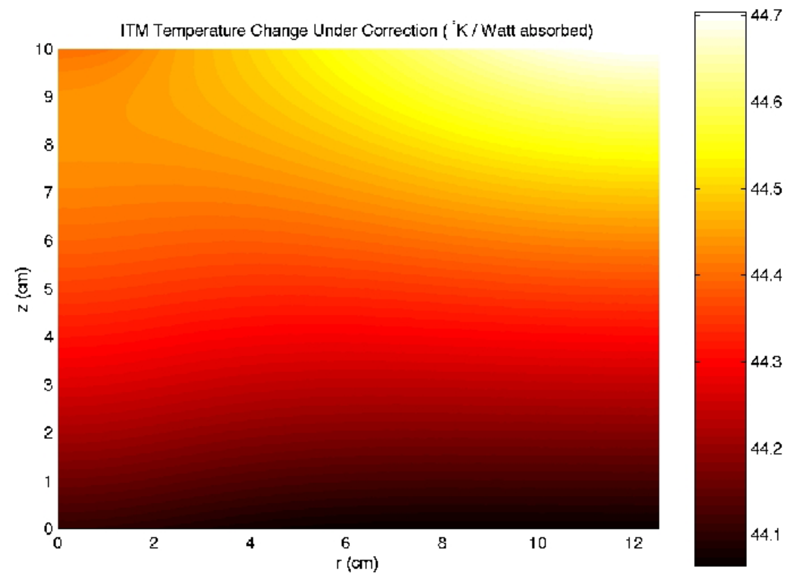
Auxiliary Optics R&D (AOS)

- Subsystem handles output beams from interferometer
  - » Desired beams matched into photodetectors
  - » Undesired beams ‘dumped’ with negligible backscatter
- Two new challenges requiring R&D:
  - » Substrate thermal focus compensation
  - » Photon actuator for test mass
- LIGO Lab activity
- Thermal focus Schedule Milestones
  - » 1Q01: Proof-of-concept, scaled experiments initial results
  - » 3Q02: Full Scale Radiative Compensator
  - » 4Q04: Full scale Directed Beam Actuation tests complete
- Photon actuator Schedule Milestones
  - » 2Q02: Initial demonstration system assembled
  - » 2Q03: Preliminary test results completed
  - » 2Q04: Final test results on iterated design completed

Thermal Compensation

- Model temperature maps for sapphire, 1 W deposited by laser, with and without ring-heater compensation
- At 4 cm dia, factor 10 reduction in optical path distortion
- Good experimental agreement





Lasers & Optics R&D

(LAS, OPT, IOS, AOS)

FY02

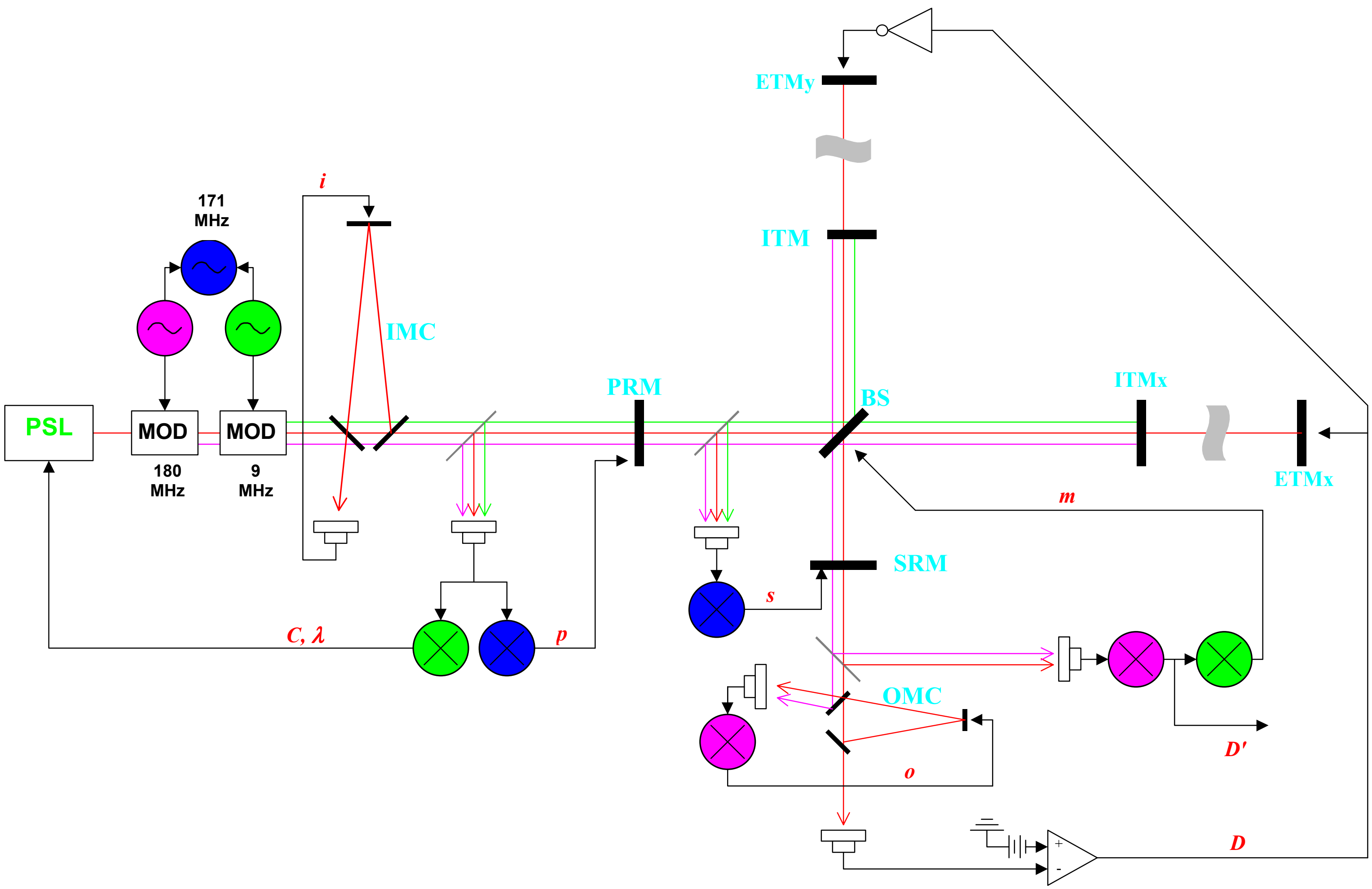
Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE, $K)	
LASERS & OPTICS						
Sci & PD	MIT	0	0	0.1	0.1	3.3
	CIT	1	0	2.3	3.3	
UG & Grads	MIT	1	0	0.0	1.0	2.0
	CIT	1	0	0.0	1.0	
Eng & Techs	MIT	0	0	0.0	0.0	2.0
	CIT	0.5	0	1.5	2.0	
	Totals (FTE):	3.5	0	3.8	**7.3**	
	Equip. & Supplies	$755	$1,706	0.0	**$2,461**	

N.B.: Does not include LSC research staff.

Advanced Interferometer Sensing & Control (ISC)

- Responsible for the GW sensing and overall control systems
- Addition of signal recycling mirror increases complexity
  - » Permits 'tuning' of response to optimize for noise and astrophysical source characteristics
  - » Requires additional sensing and control for length and alignment
- Shift to 'DC readout'
  - » Rather than RF mod/demod scheme, shift interferometer slightly away from dark fringe; relaxes laser requirements, needs photodiode develop
- Requires both proof-of-principle and precision testing (40m)
- LIGO Lab leads, with contributions from LSC, esp. GEO
- Schedule Highlights:
  - ✓ 4Q00: Tabletop configuration experiments concluded
  - » 2Q01: Design Requirements Review
  - » 2Q02: Tabletop DC readout test results
  - » 2Q03: GEO 10m prototype test results/review
  - » 4Q03: Final design complete
  - » DONE mason; delker?

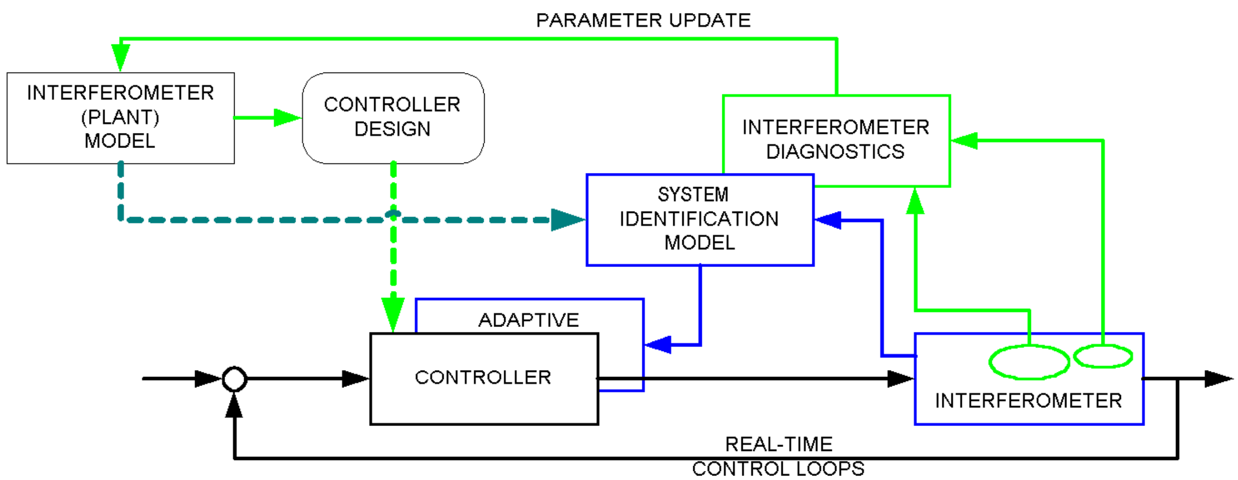
Interferometer layout



Advanced Controls & System Identification (SID)

- Modern controls approach to optimization of system
- Interfaces to existing infrastructure
- Allows both noise performance and robustness to be explored
- Can be static, or apply Adaptive Control techniques if proven
- Schedule Highlights
  - » 4Q02: System identification for the initial LIGO detector
  - » 4Q03: Adaptive control for the initial LIGO detector
  - » 1Q04: Application to 40m configuration testbed
  - » 2Q05: System identification for the advanced LIGO configuration

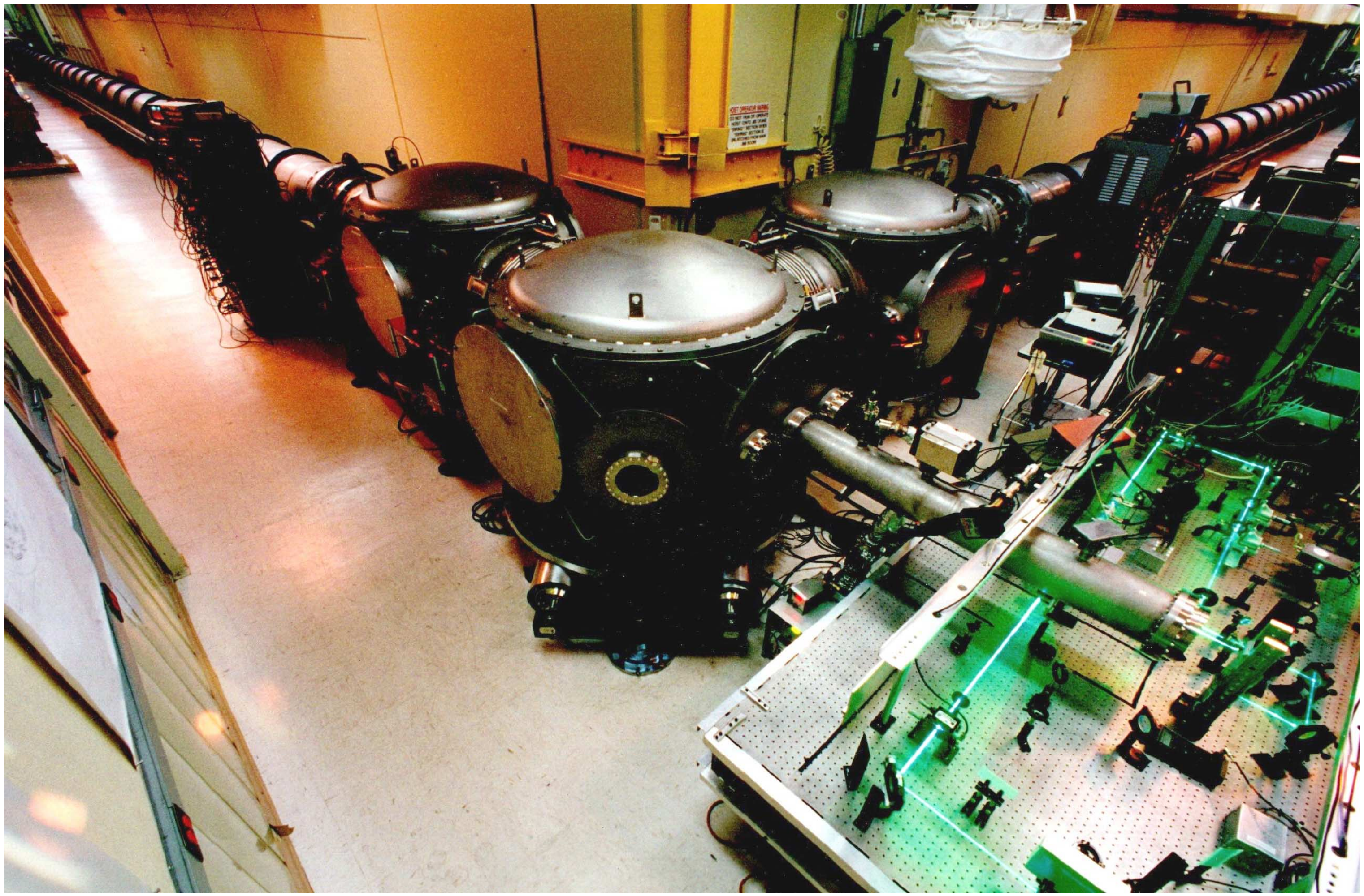
System Identification



40 m RSE Experiment (40m)

- Precision test of selected readout and sensing scheme
  - » Employs/tests final control hardware/software
  - » Dynamics of acquisition of operating state
  - » Frequency response, model validation
- Utilizes unique capability of Caltech 40 meter interferometer --- long arms allow reasonable storage times for light
- Schedule Highlights
  - ✓ 4Q00: LIGO 40 m Lab expansion completed
  - ✓ 1Q01: LIGO 40 m active isolation systems installed
  - » 2Q01: LIGO 40 m Vacuum Envelope commissioned
  - » 2Q01: LIGO 40 m PSL installed
  - » 4Q02: LIGO 40 m suspensions installed
  - » 2Q04: LIGO 40 m configurations research completed; further characterization studies & ISC prototype testing continues

40m Interferometer



Advanced Interferometer Systems, Sensing & Control (ISC, 40m, SID, SYS)

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE, $K)	
Advanced Interferometer Systems, Sensing & Control (ISC)						
Sci & PD	MIT	0	0	1.7	1.7	6.9
	CIT	2	0	3.2	5.2	
UG & Grads	MIT	1	0	1.0	2.0	5.0
	CIT	3	0	0.0	3.0	
Eng & Techs	MIT	0	0	0.8	0.8	10.2
	CIT	0	0	9.5	9.5	
Totals (FTE):		6	0	16.1	**22.1**	
Equip. & Supplies		$313	$0	0.0	**$313**	

N.B.: Does not include LSC research staff.

Total LIGO Lab R&D

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE, $K)	
TOTAL for advanced LIGO R&D (including CRY)						
Sci & PD	MIT	1	0	4.2	5.2	20.3
	CIT	8	0	7.2	15.2	
UG & Grads	MIT	5	0	1.0	6.0	13.0
	CIT	7	0	0.0	7.0	
Eng & Techs	MIT	0	0	3.5	3.5	26.4
	CIT	0.5	0	17.9	18.4	
	LLO	0	0	4.5	4.5	
Totals (FTE):		21.5	0	38.2	**59.7**	
Equip. & Supplies		$1,139	$3,301	0.0	**$4,440**	
				MIT	14.7	
				CIT	40.5	
				LLO	4.5	

N.B.: Does not include LSC research staff.

LIGO R&D Program

- Focussed on Advanced LIGO Conceptual Design
  - » Exciting astrophysical sensitivity
  - » Challenging but not unrealistic technical goals
  - » Advances the art in materials, optics, lasers, servocontrols
- A tight and rich collaboration
  - » NSF-funded research
  - » International contributors
- Program planned to mesh with fabrication of interferometer components leading to installation of new detectors in 2006
  - » Lessons learned from initial LIGO
  - » Thorough testing at Campus Labs to minimize impact on LIGO observation
  - » Coordination with other networked detectors to ensure continuous global observation

LIGO R&D Program

- With the initial LIGO commissioning, operation, and observation plan, the R&D program forms a blueprint for the LIGO mission:

- operate the LIGO facilities to support the national and international scientific community;
- support scientific education and public outreach related to gravitational wave astronomy.
- develop advanced detectors that approach and exploit the facility limits on interferometer performance;
- **observe gravitational wave sources.**