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

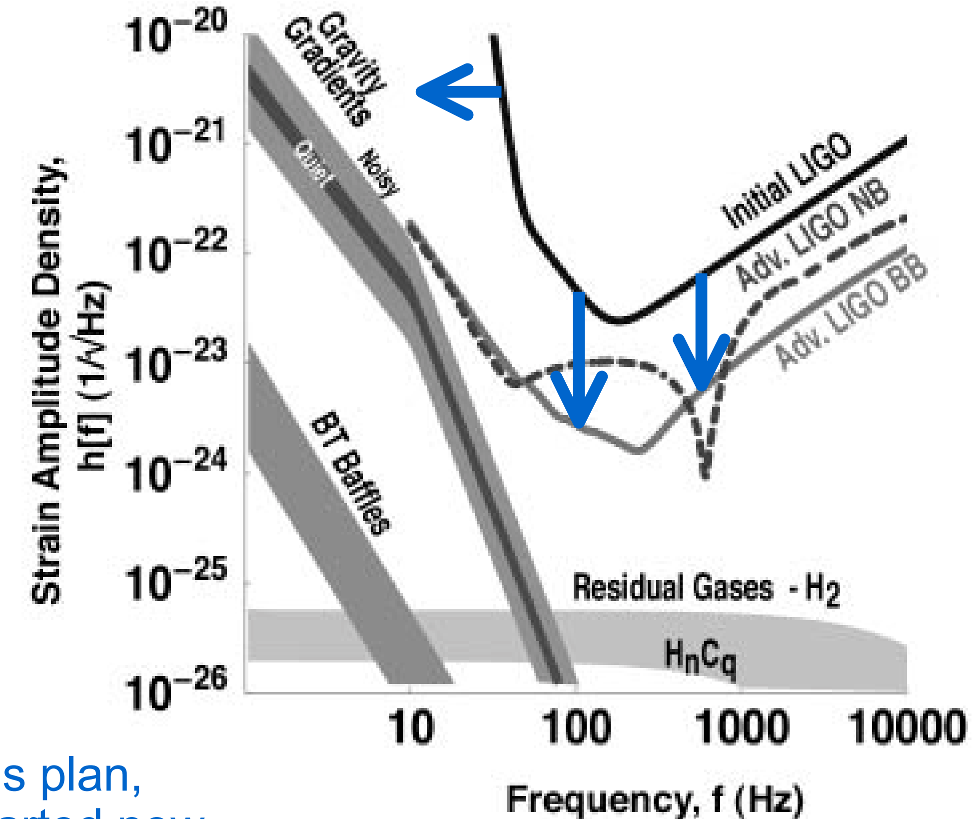
- Organization of presentations:
  - » Astrophysics within reach of Advanced LIGO
  - » Limits to sensitivity
  - » Overall development plan, organizational principles
  - » System designs and trades, Interferometer Sensing and Control
  - » Mechanical aspects of design: Isolation, Suspension, Thermal noise, and system tests
  - » Optics: Laser, Test Masses, Input Optics, Auxiliary Optics
  - » Major Research Equipment (MRE) Proposal plan and status

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!)

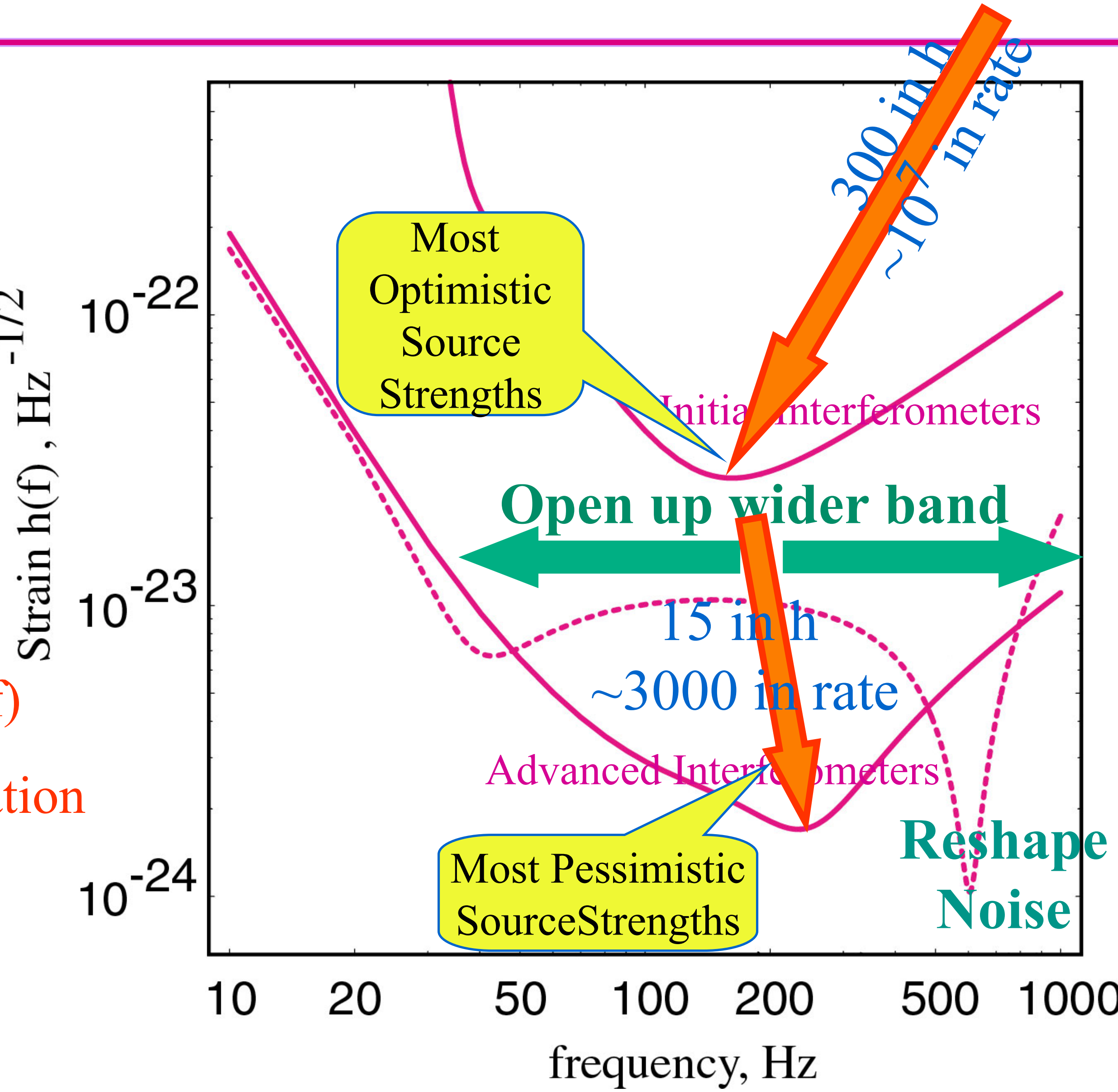
Present and future technical limits to sensitivity

- 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, e.g., cooling of test masses
  - » Quantum noise, e.g., quantum non-demolition
  - » Not the central focus of this plan, but exploration must be started now



From Initial Interferometers to Advanced

Astrophysics transparencies from Kip Thorne



$h_{rms} = h(f)\sqrt{f} \Rightarrow 10\, h(f)$

Assume 4 mos. Integration for periodic sources

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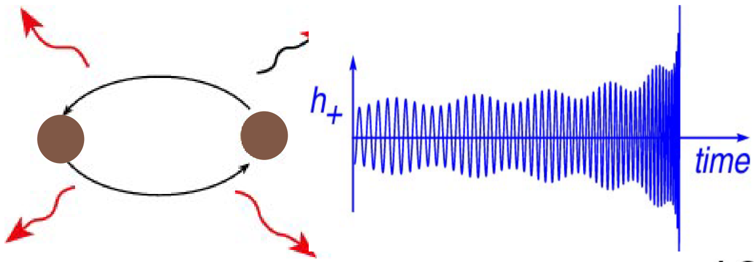
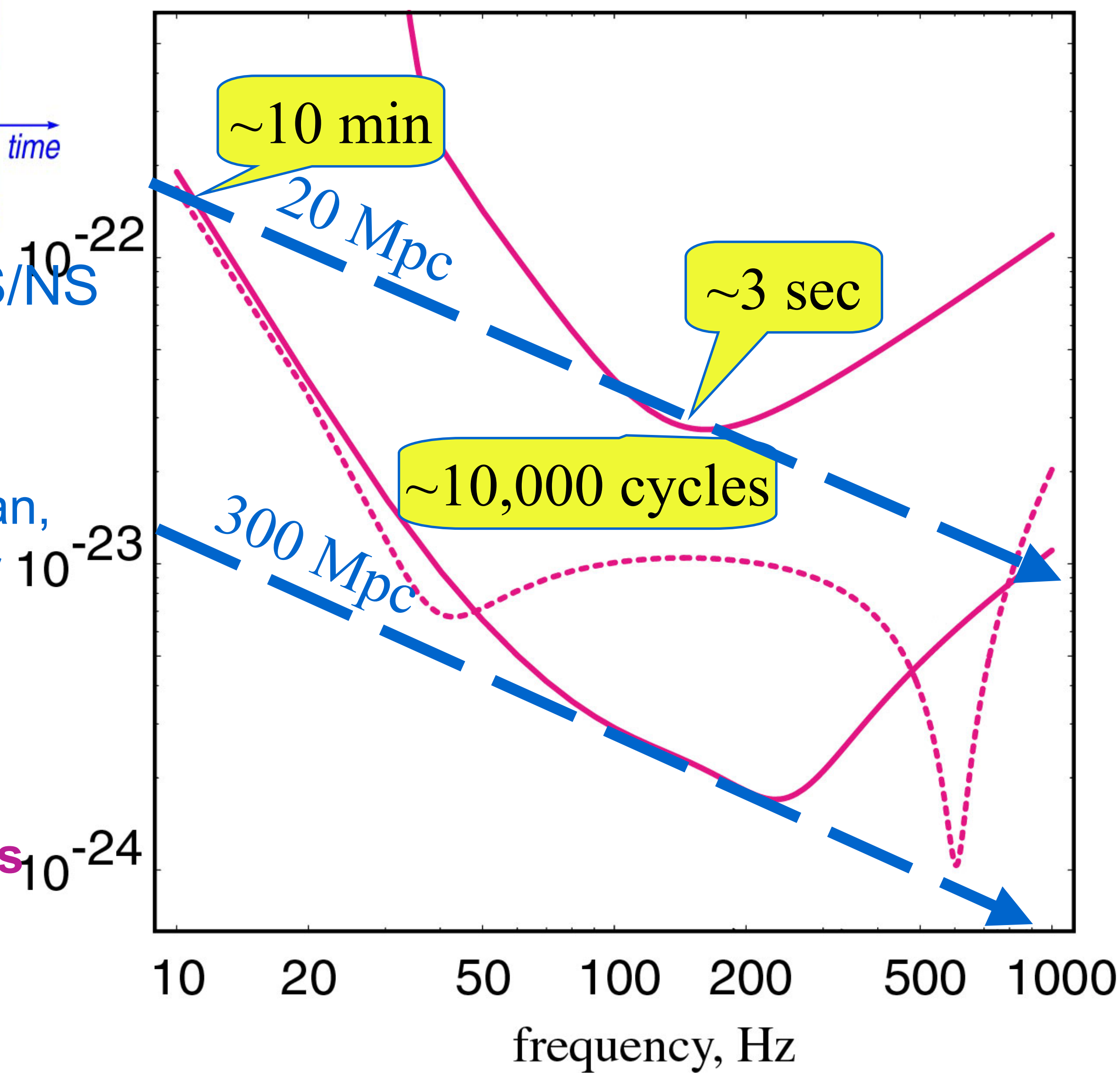
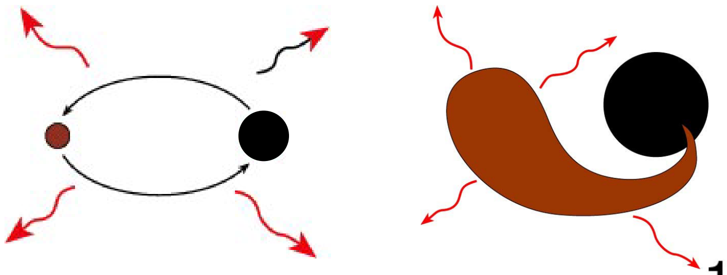
Neutron Star / Neutron Star Inspiral
(our most reliably understood source)



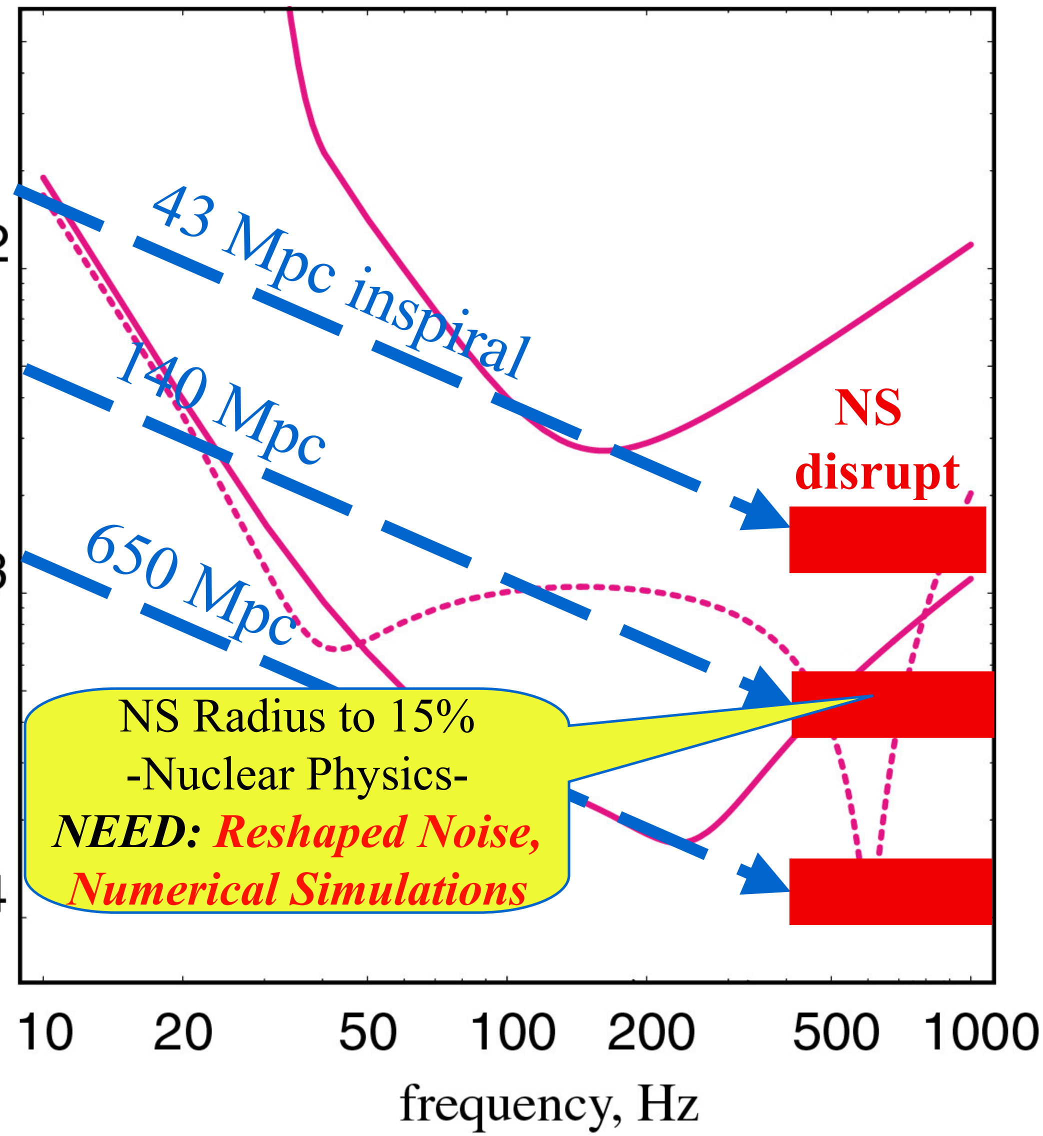
- 1.4 Msun / 1.4 Msun NS/NS Binaries
- Event rates
  - » V. Kalogera, R. Narayan, D. Spergel, J.H. Taylor astro-ph/0012038
- Initial IFOs
  - » Range: 20 Mpc
  - » 1 / 3000 yrs to **1 / 3yrs**
- Advanced IFOs -
  - » Range: 300Mpc
  - » **1 / yr to 2 / day**



Neutron Star / Black Hole Inspiral and NS Tidal Disruption

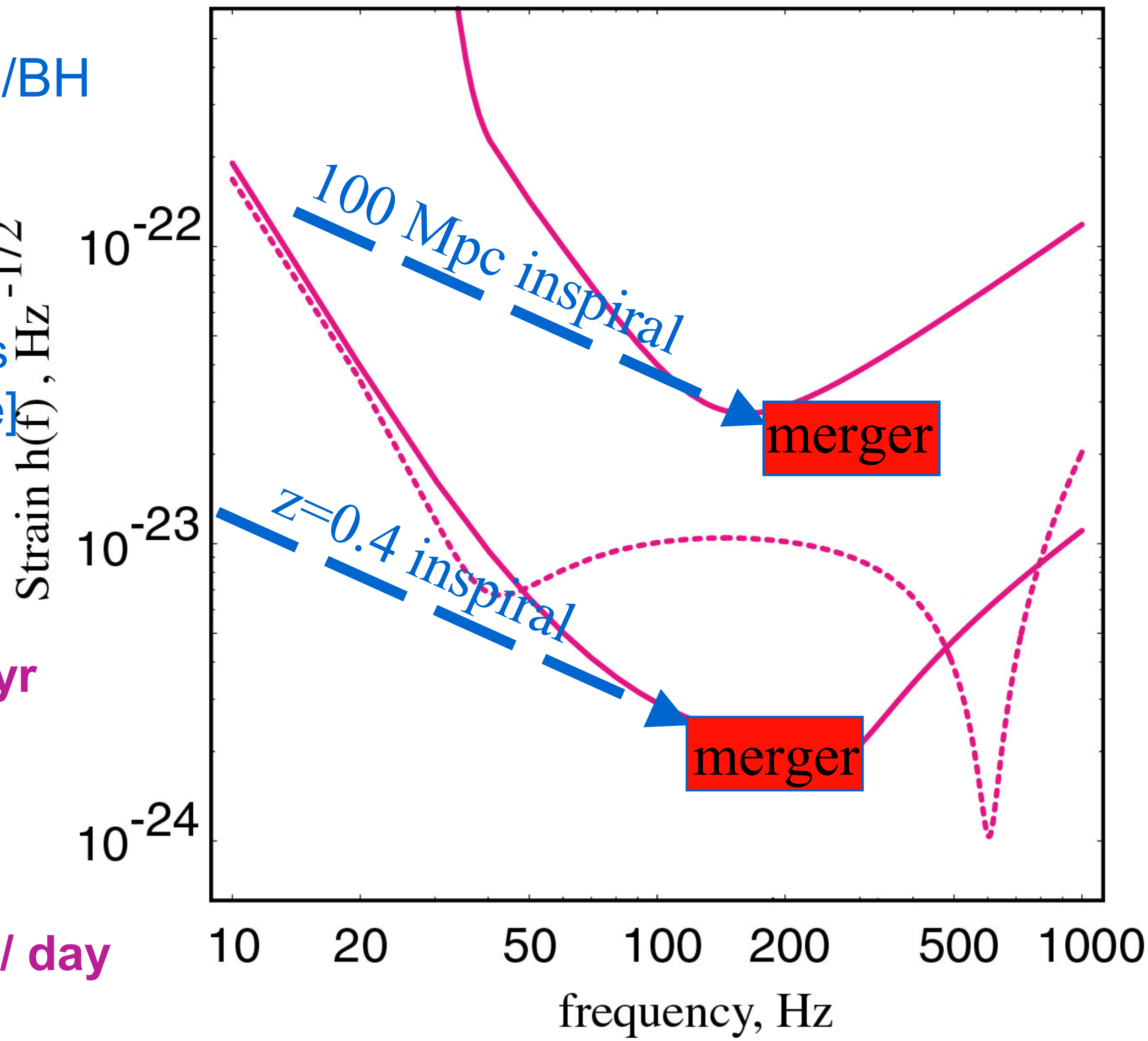


- 1.4Msun / 10 Msun NS/BH Binaries
- Event rates
  - » Population Synthesis [Kalogera's summary]
- Initial IFOs
  - » Range: 43 Mpc
  - » ≲1 / 2500 yrs to **1 / 2yrs**
- Advanced IFOs
  - » Range: 650 Mpc
  - » **≲1 / yr to 4 / day**

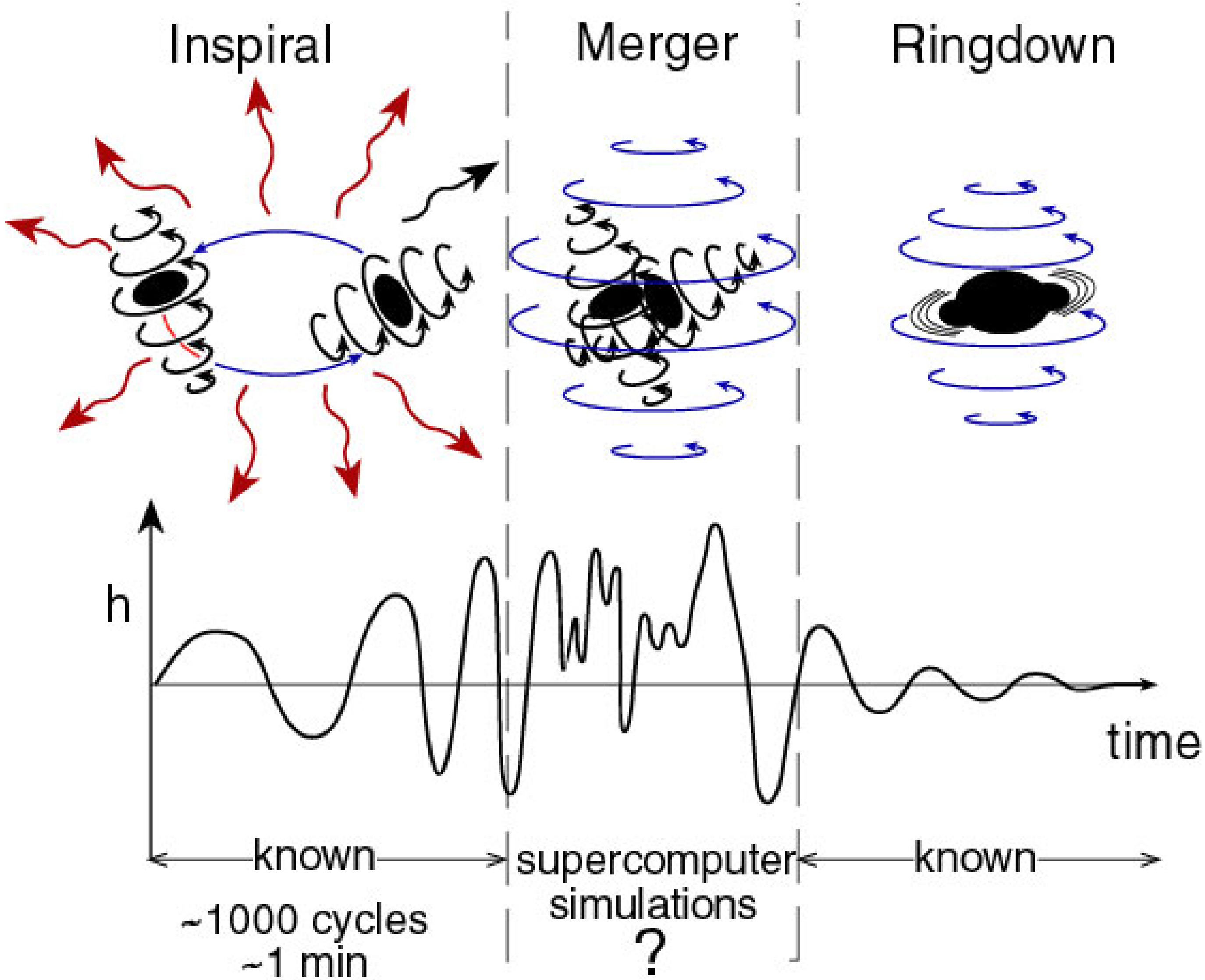


Black Hole / Black Hole Inspiral and Merger

- 10Msun / 10 Msun BH/BH Binaries
- Event rates
  - » Based on population synthesis [Kalogera's summary of literature]
- Initial IFOs
  - » Range: 100 Mpc
  - » ≲ 1 / 300yrs to **~1 / yr**
- Advanced IFOs -
  - » Range: z=0.4
  - » **≲ 2 / month to ~10 / day**



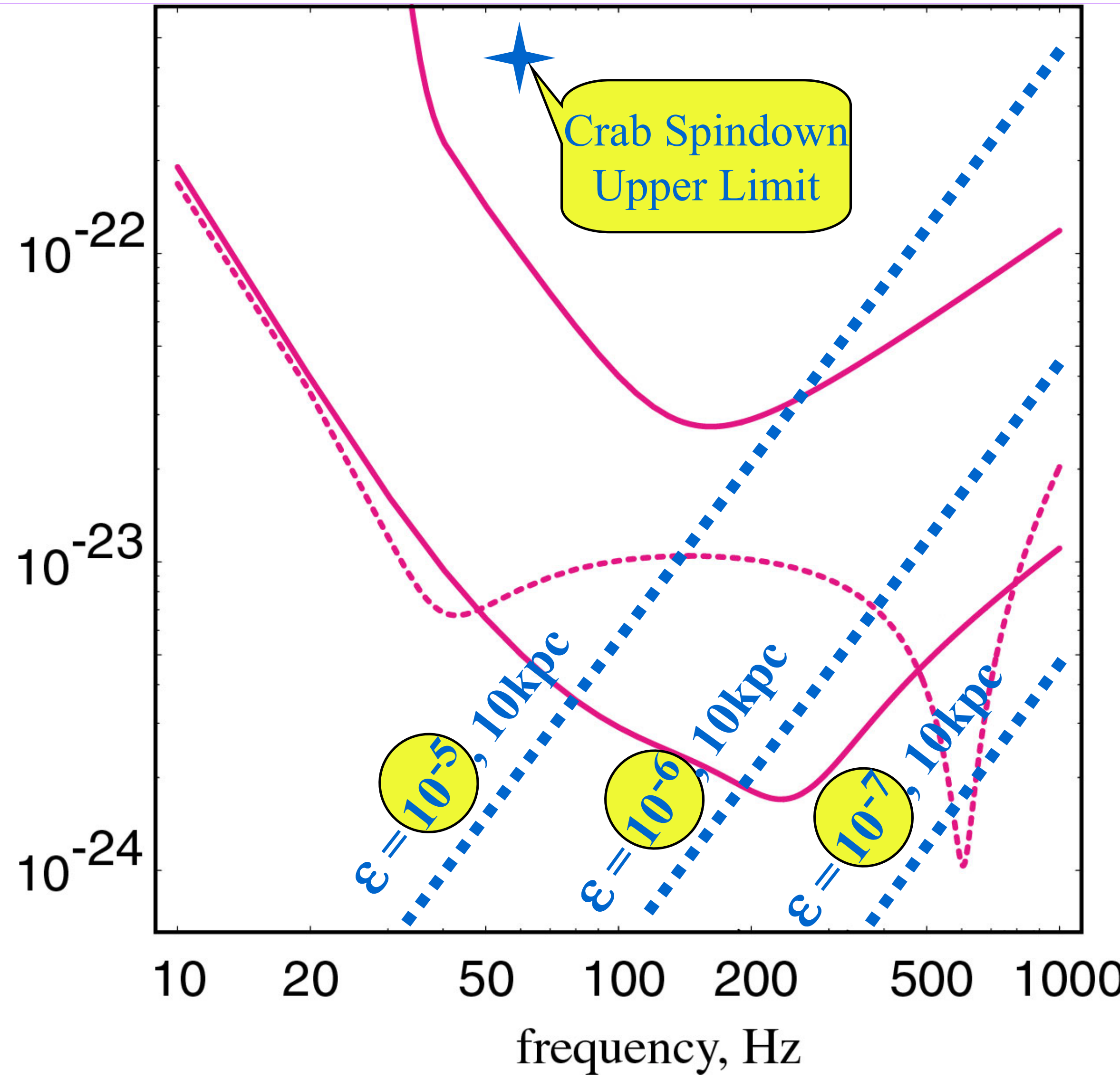
BH/BH Mergers: Exploring the Dynamics of Spacetime Warpage



Numerical Relativity Simulations Are Badly Needed!

Spinning NS's: Pulsars

- **NS Ellipticity:**
  - » Crust strength
    ε ❾ 10^{-6}; possibly 10^{-5}
- **Known Pulsars:**
  - » First Interferometers:
    ε ≳ 3×10^{-6} (1000Hz/f) x (distance/10kpc)
  - » Narrowband Advanced
    ε ≳ 2×10^{-8} $(1000\text{Hz}/f)^2$ x (distance/10kpc)



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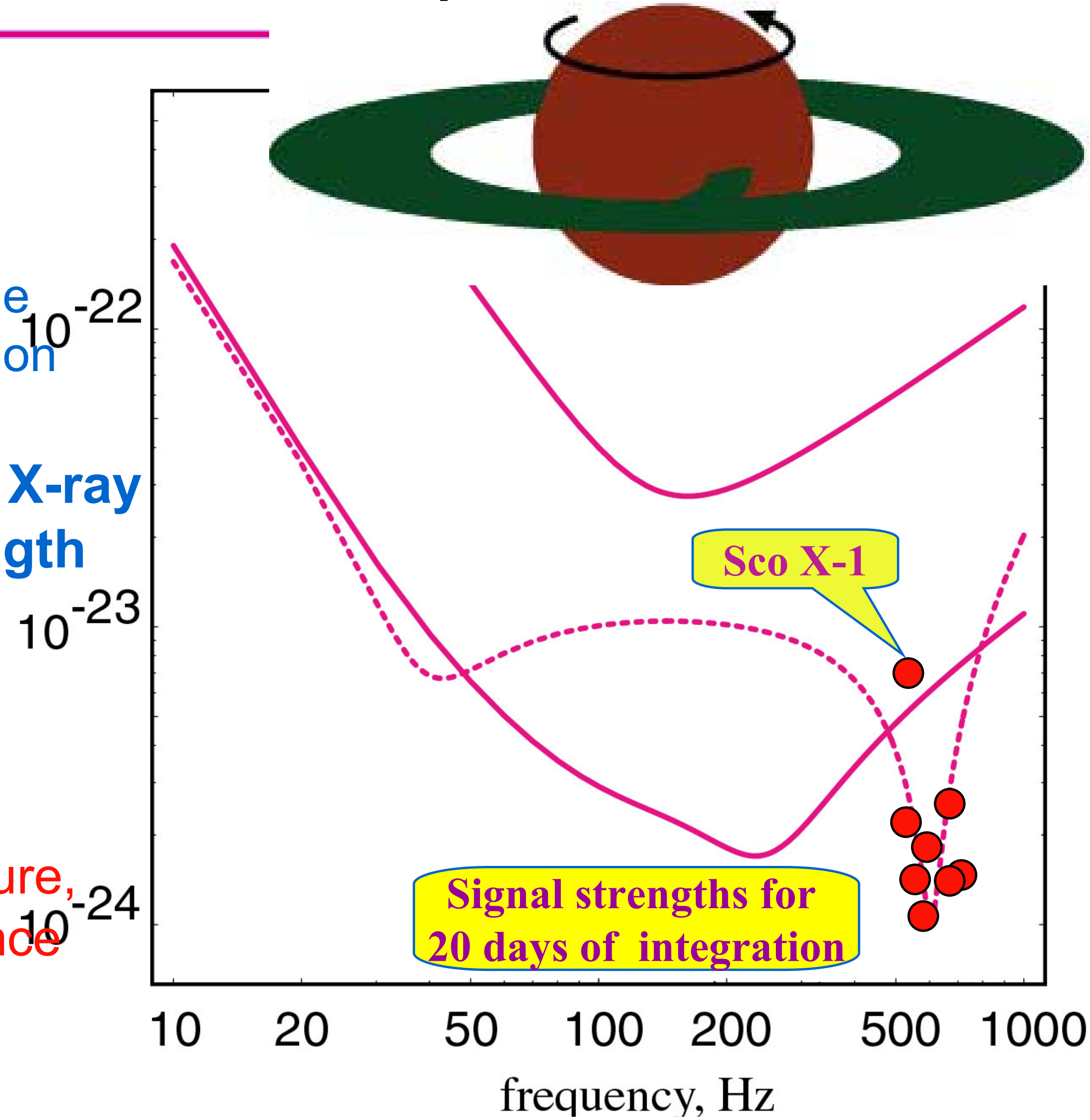
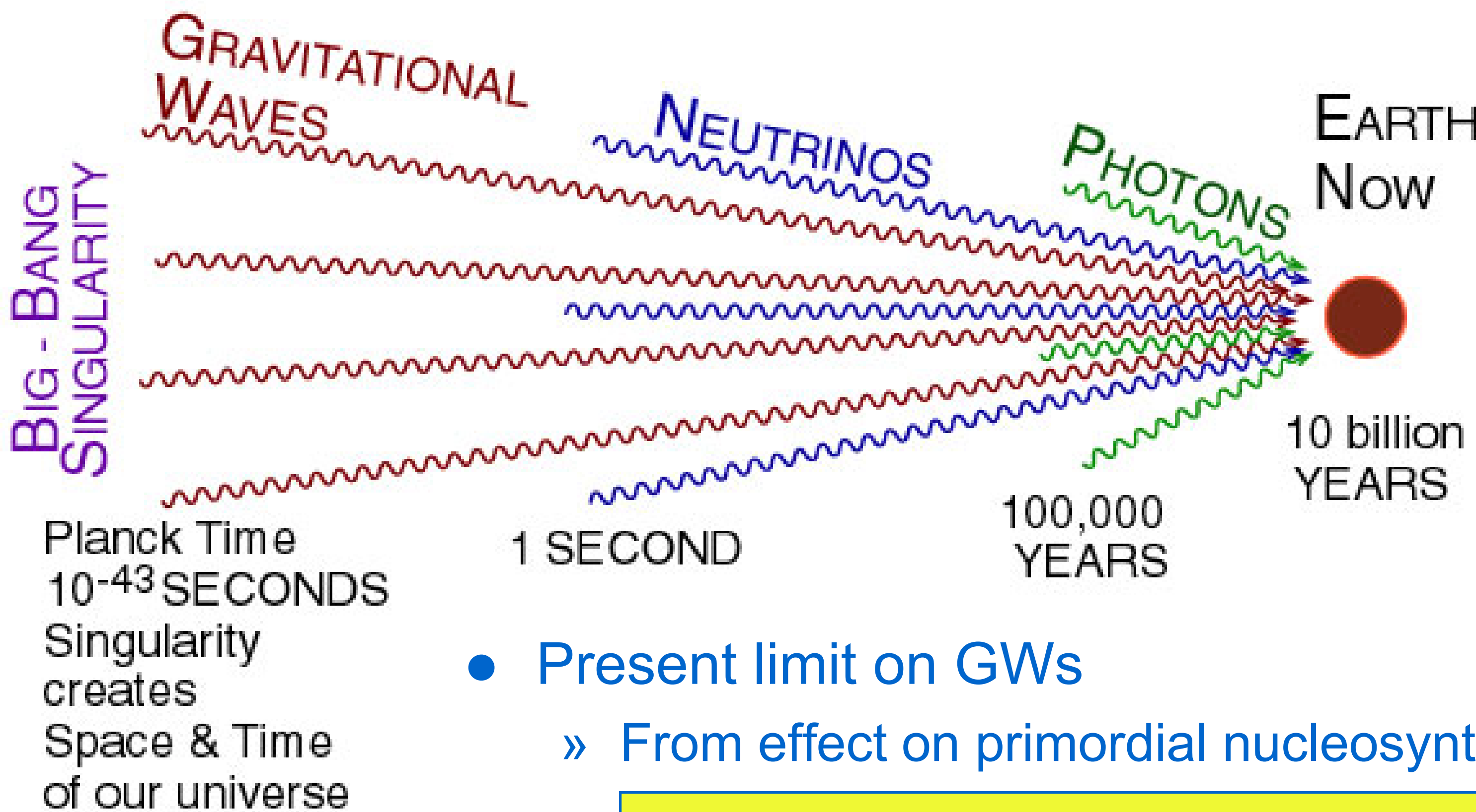
Spinning Neutron Stars: Low-Mass X-Ray Binaries

- **Rotation rates ~250 to 700 revolutions / sec**
  - » Why not faster?
  - » **Bildsten**: Spin-up torque balanced by GW emission torque
- **If so, and steady state: X-ray luminosity → GW strength**
- **Combined GW & EM obs's → information about:**
  - » crust strength & structure, temperature dependence of viscosity, ...



Stochastic Background from Very Early Universe

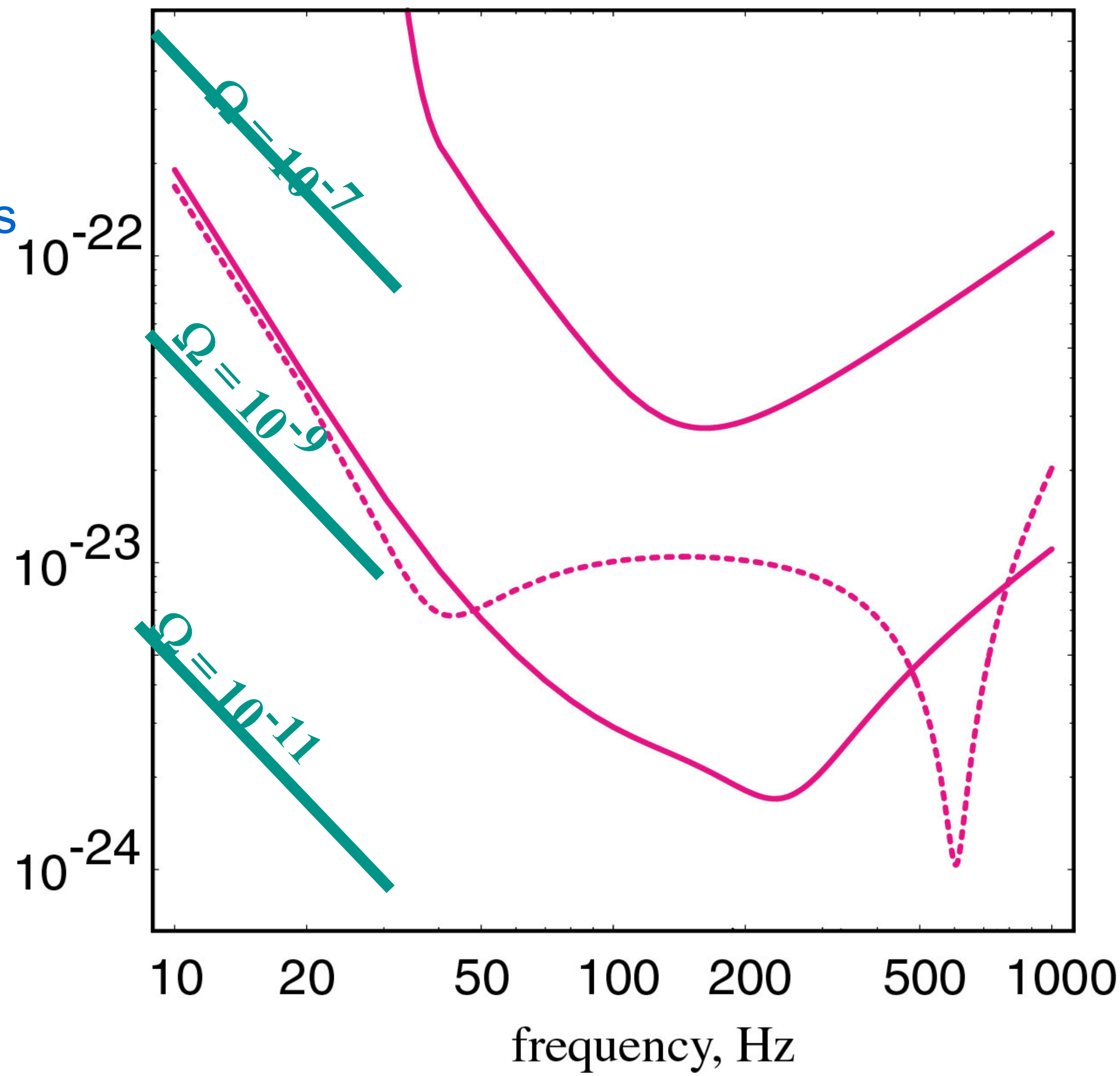
- GW's are the ideal tool for probing the very early universe



- Present limit on GWs
  - » From effect on primordial nucleosynthesis
  - Propo » Ω = (GW energy density)/(closure density) $\lesssim 10^{-5}$

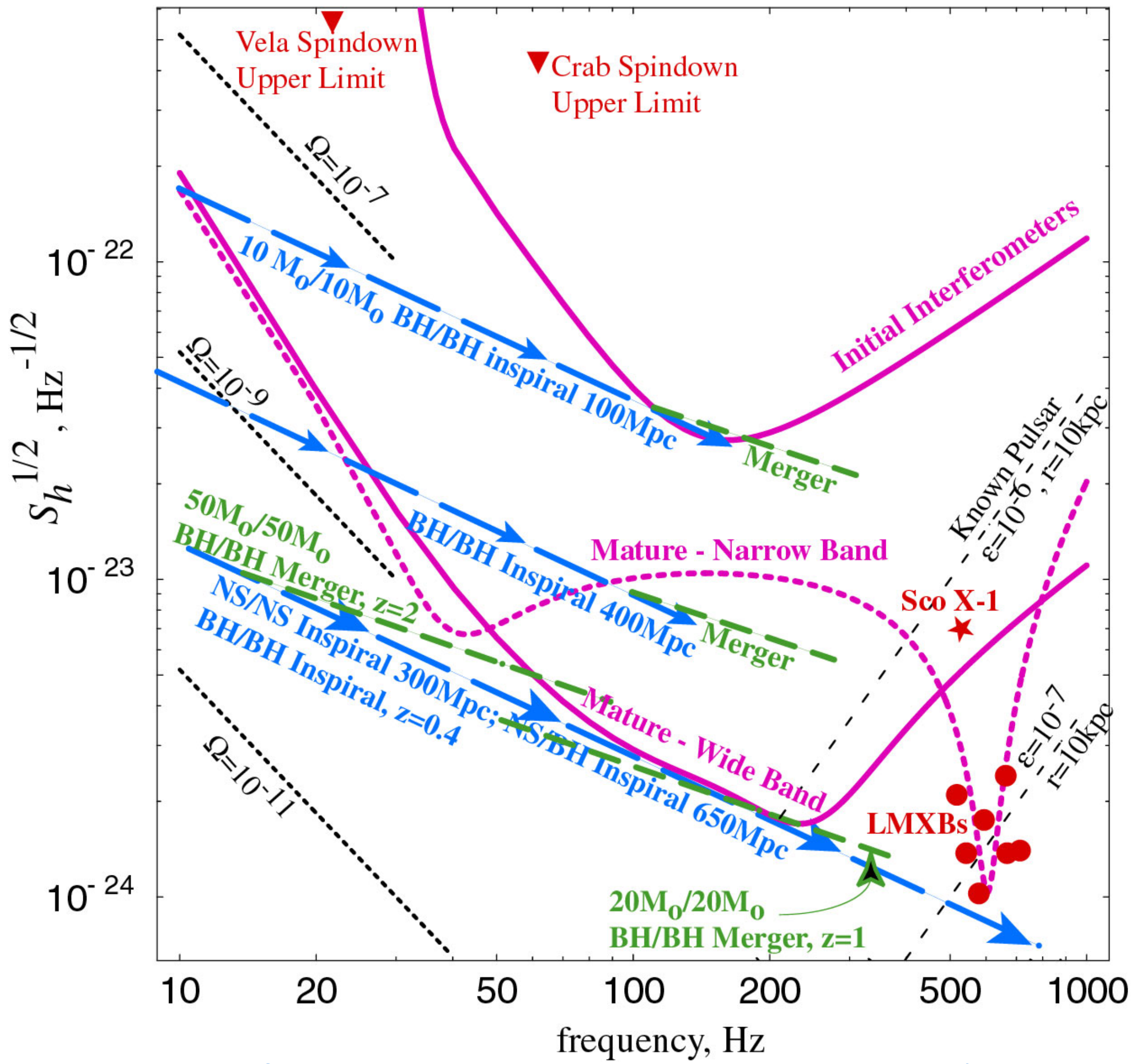
Stochastic Background from Very Early Universe

- Detect by
  - » cross correlating output of Hanford & Livingston 4km IFOs
- Good sensitivity requires
  - » (GW wavelength) $\gtrsim$ **2x**(detector separation)
  - » f $\lesssim$ 40 Hz
- Initial IFOs detect if
  - » $\Omega \gtrsim 10^{-5}$
- Advanced IFOs:
  - » $\Omega \gtrsim 5\times10^{-9}$



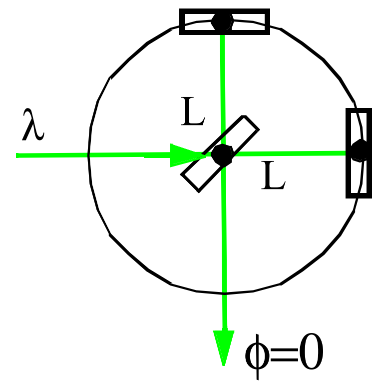
Overview of Sources

- LIGO's Initial Interferometers bring us into the realm where it is plausible to begin detecting cosmic gravitational waves.
- With LIGO's Advanced Interferometers we can be confident of:
  - » detecting waves from a variety of sources
  - » gaining major new insights into the universe, and into the nature and dynamics of spacetime curvature, that cannot be obtained in any other way

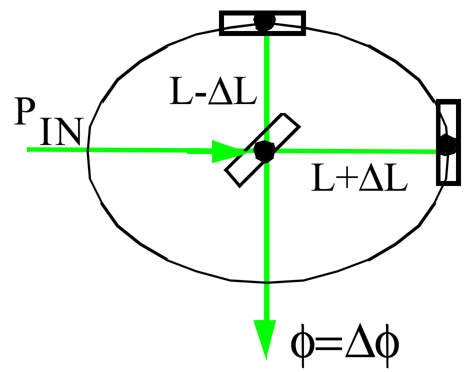


Introduction to the detector

- 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)

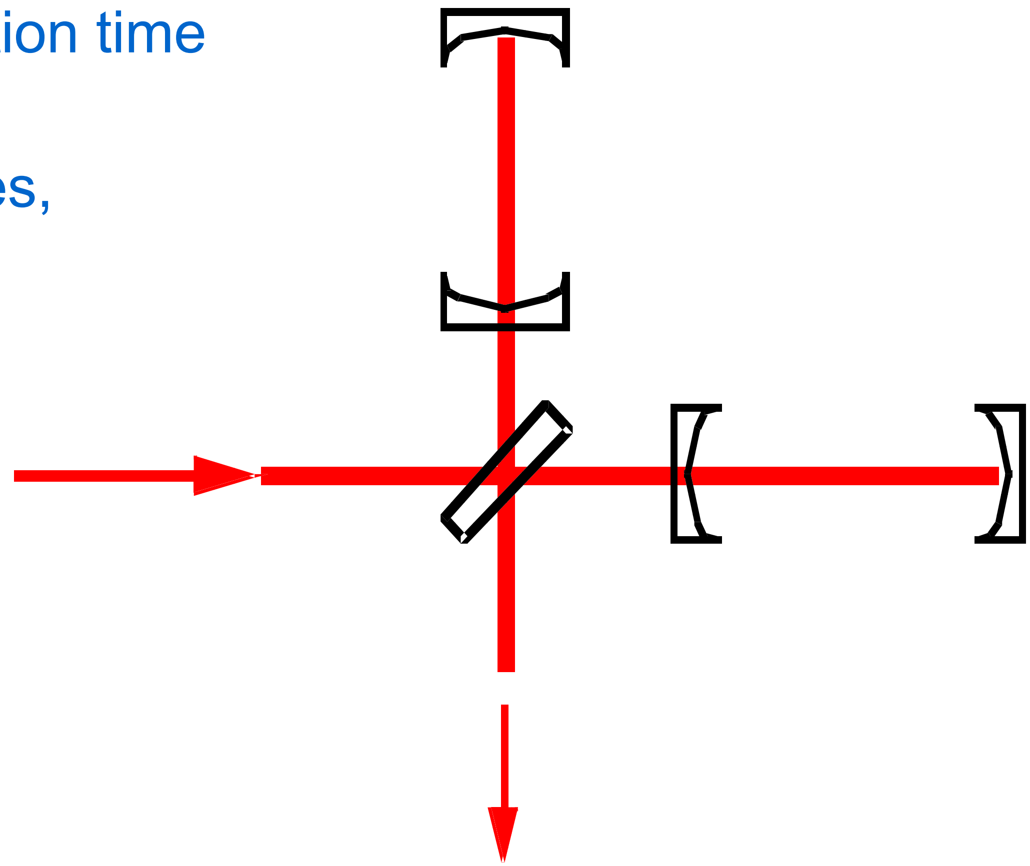


$$\Delta L = h\,L$$



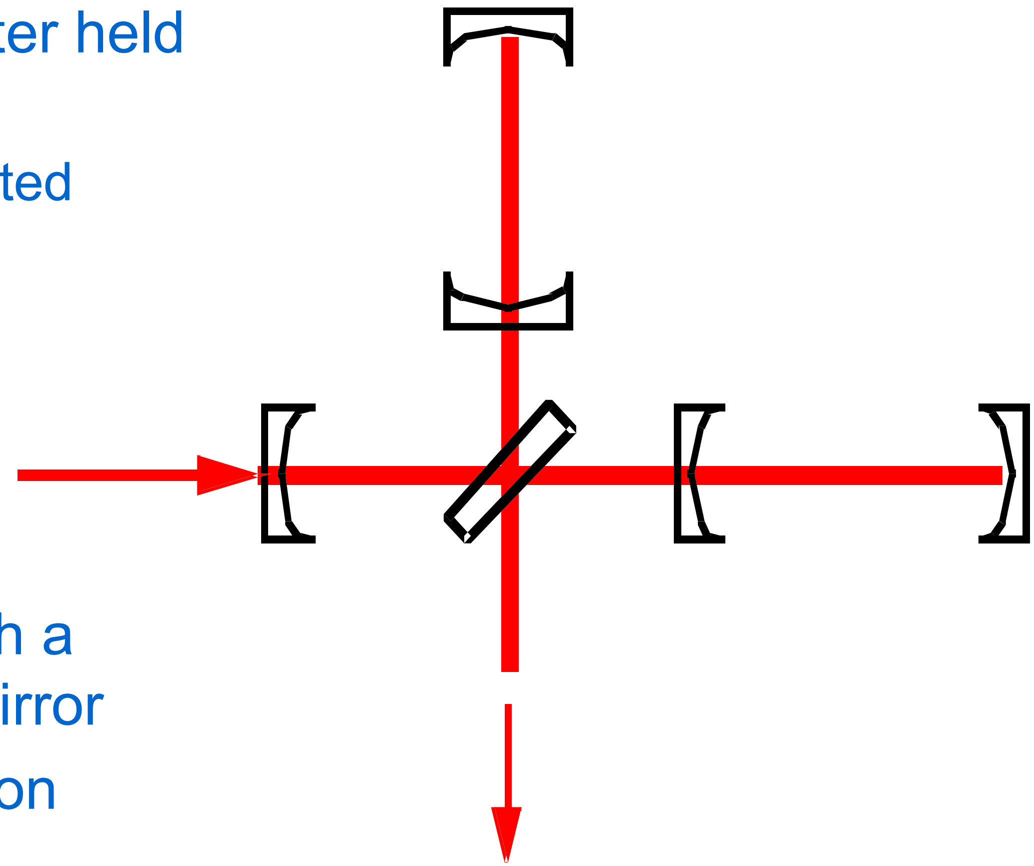
Increasing the interaction time

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



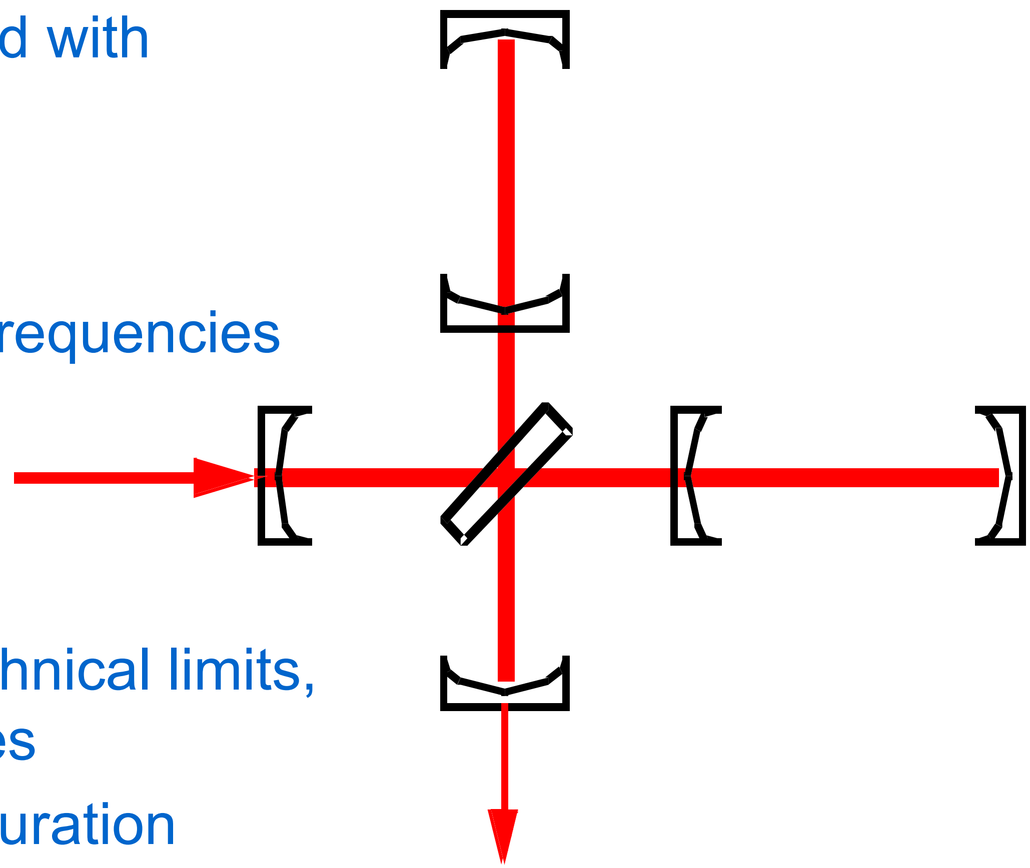
Increasing the circulating power

- 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

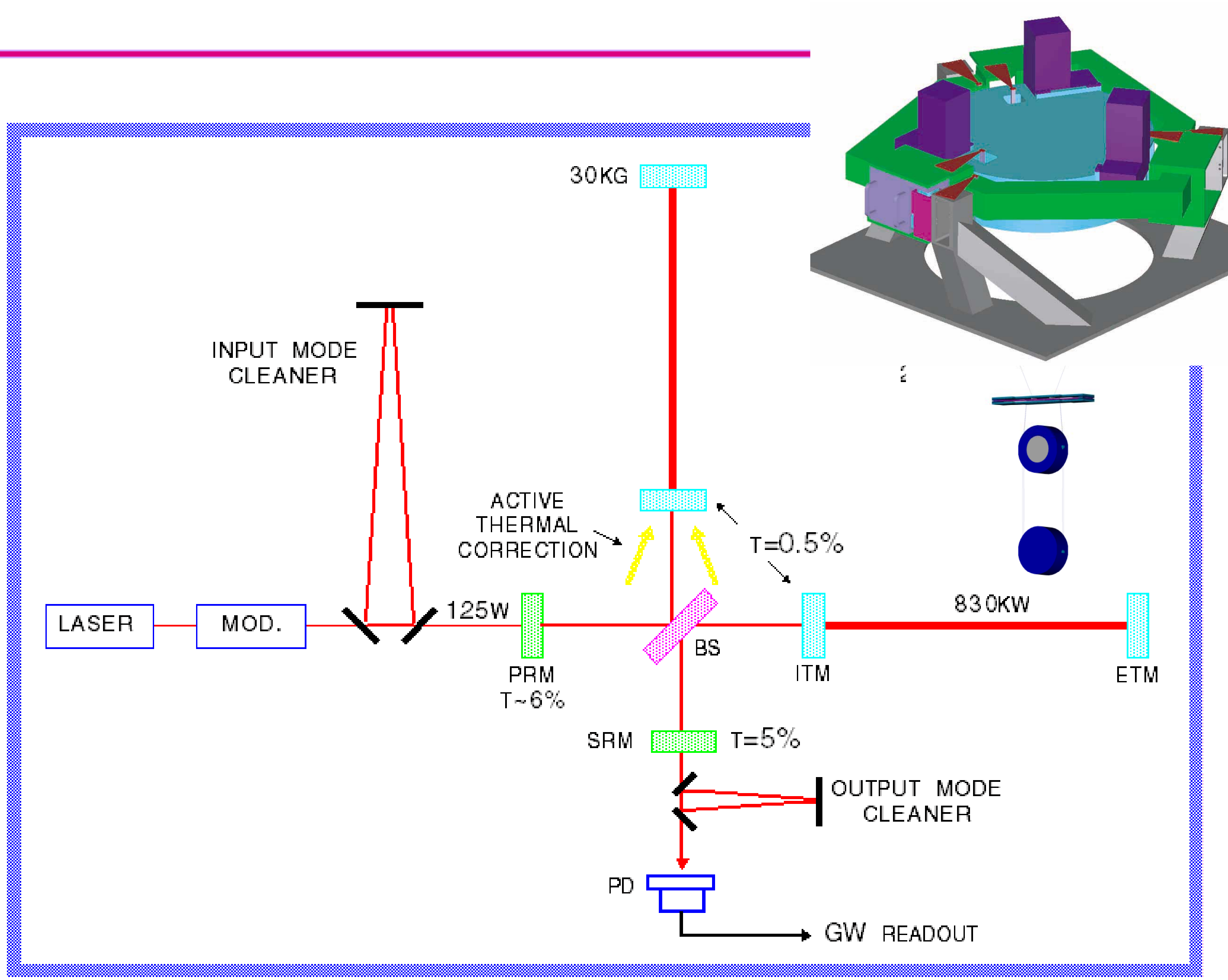


- Allows optimum for technical limits, astrophysical signatures
- Advanced LIGO configuration

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

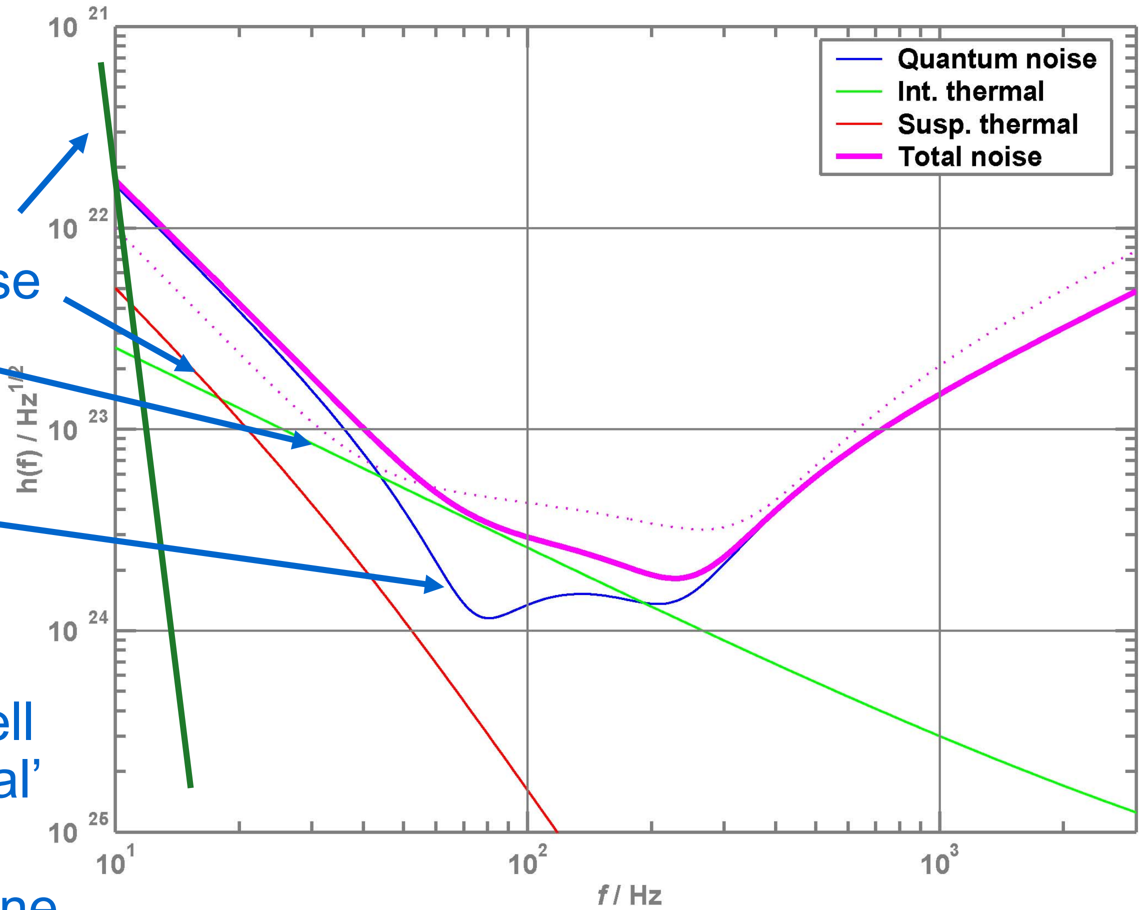


System trades

- 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

- Broadband mode
- 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



LIGO

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

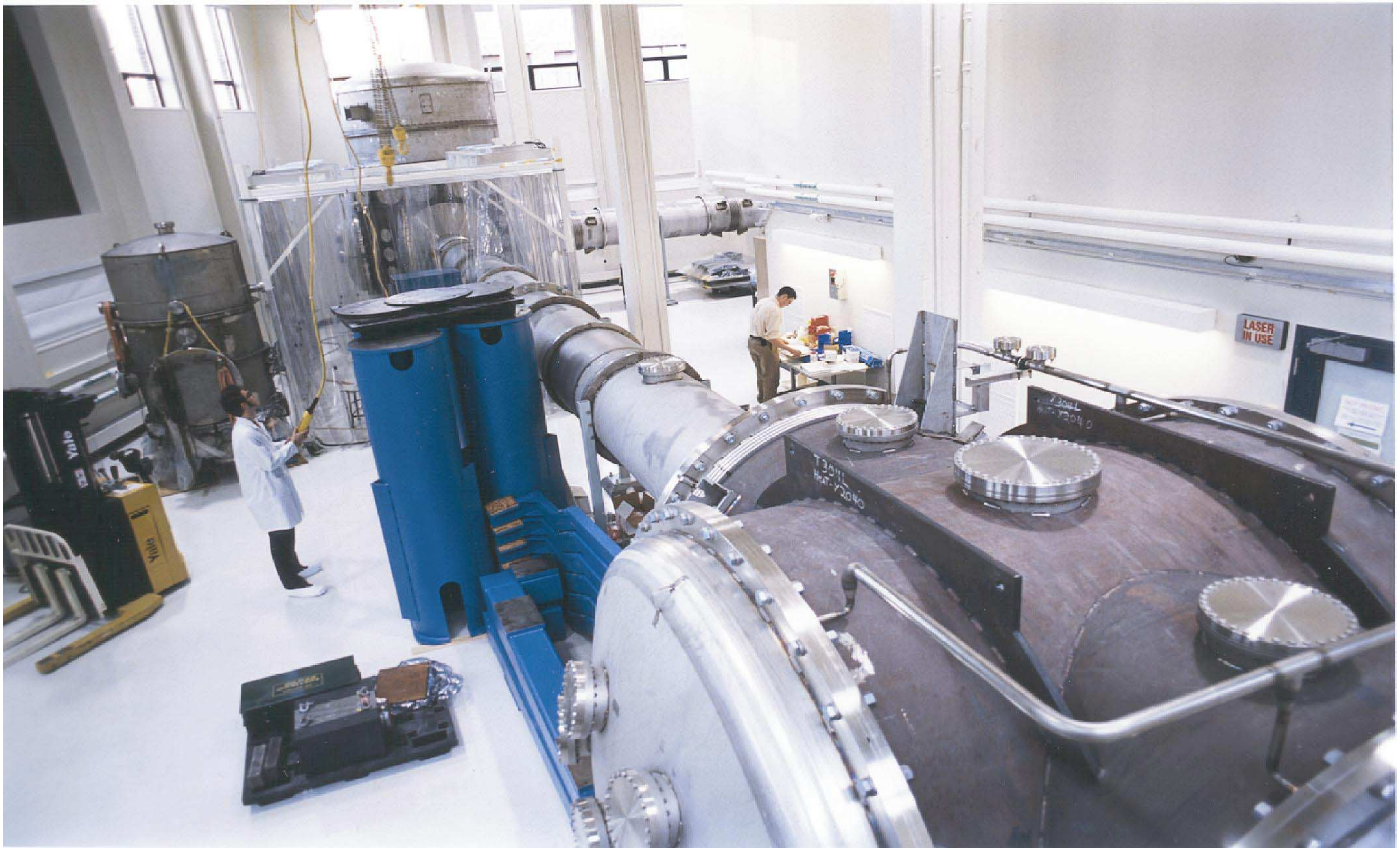
Development plan

- Inputs:
  - » Single significant upgrade
  - » Reasonable/exciting extrapolations of technical developments
  - » Test and installation practice necessary
- Outputs:
  - » Sensitivity as described above
  - » Timing: Initial LIGO observations until 2006, then change to Advanced LIGO
  - » Subsystems to be described below
  - » Testbeds for integrated subsystems on University Campuses
- Goal: Eliminate the work which formed the first year of commissioning of Initial LIGO by subsystem testing and installation practice

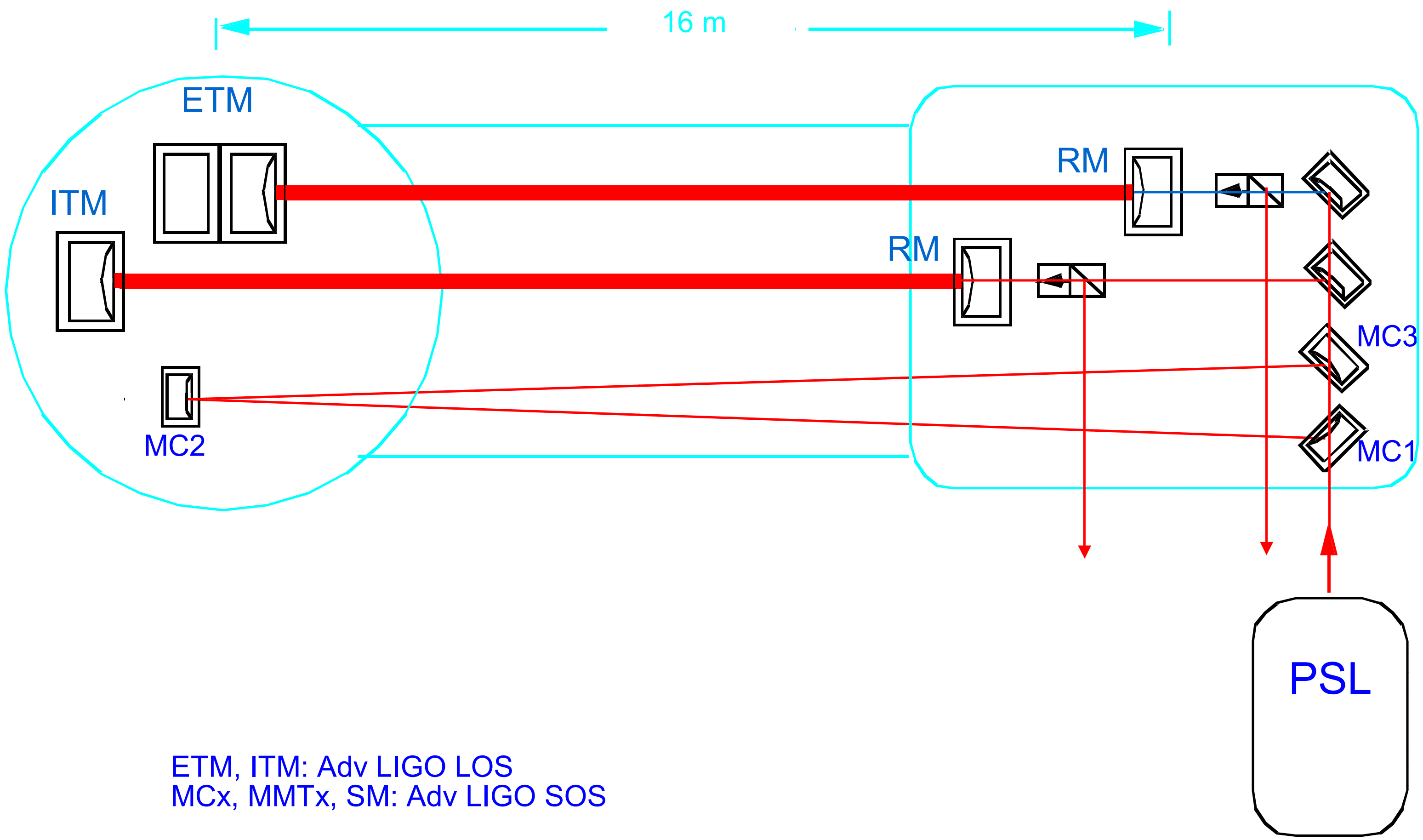
Stochastic noise system tests: LASTI

- 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. to be 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



LASTI Layout

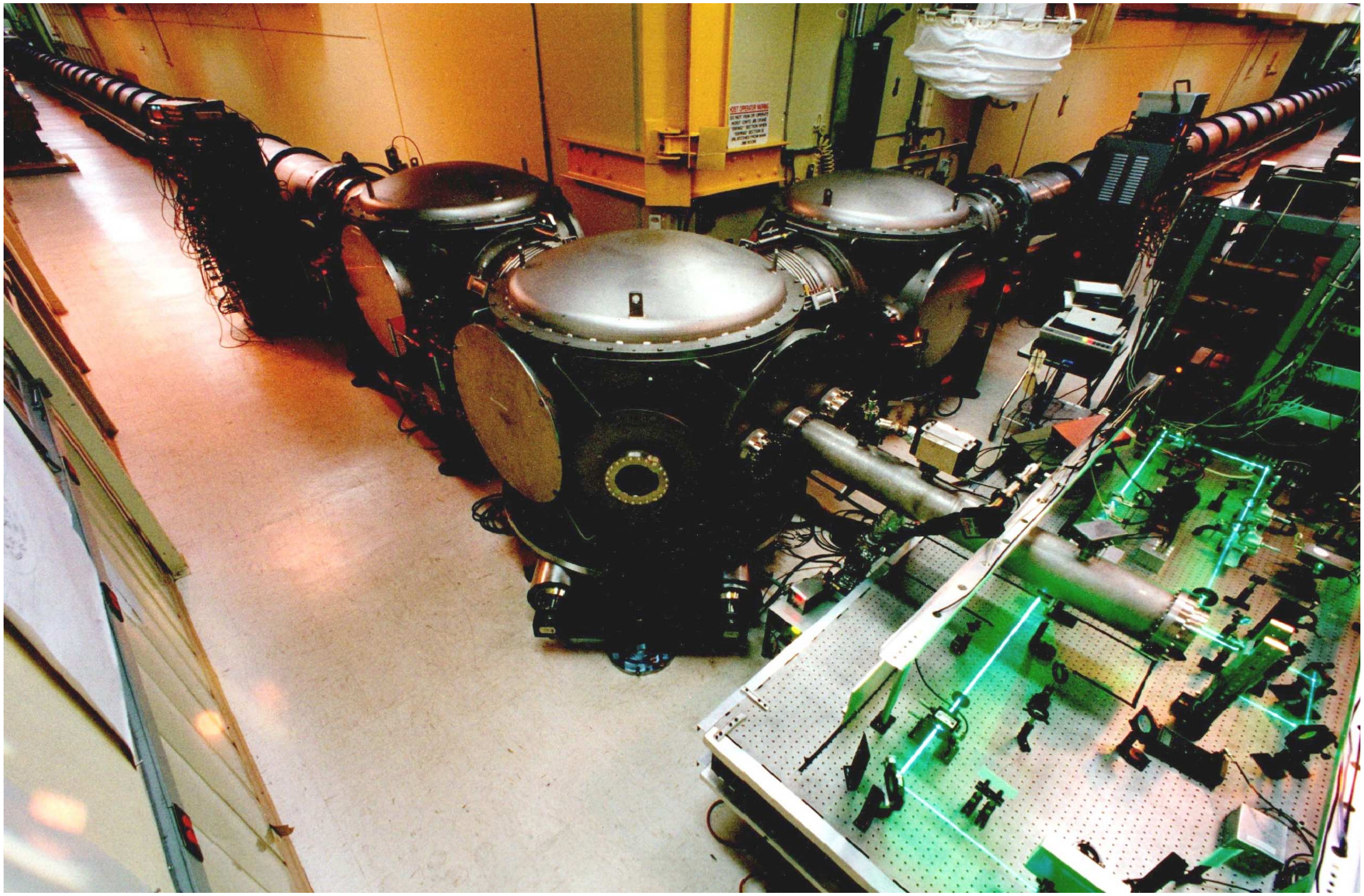


ETM, ITM: Adv LIGO LOS
MCx, MMTx, SM: Adv LIGO SOS

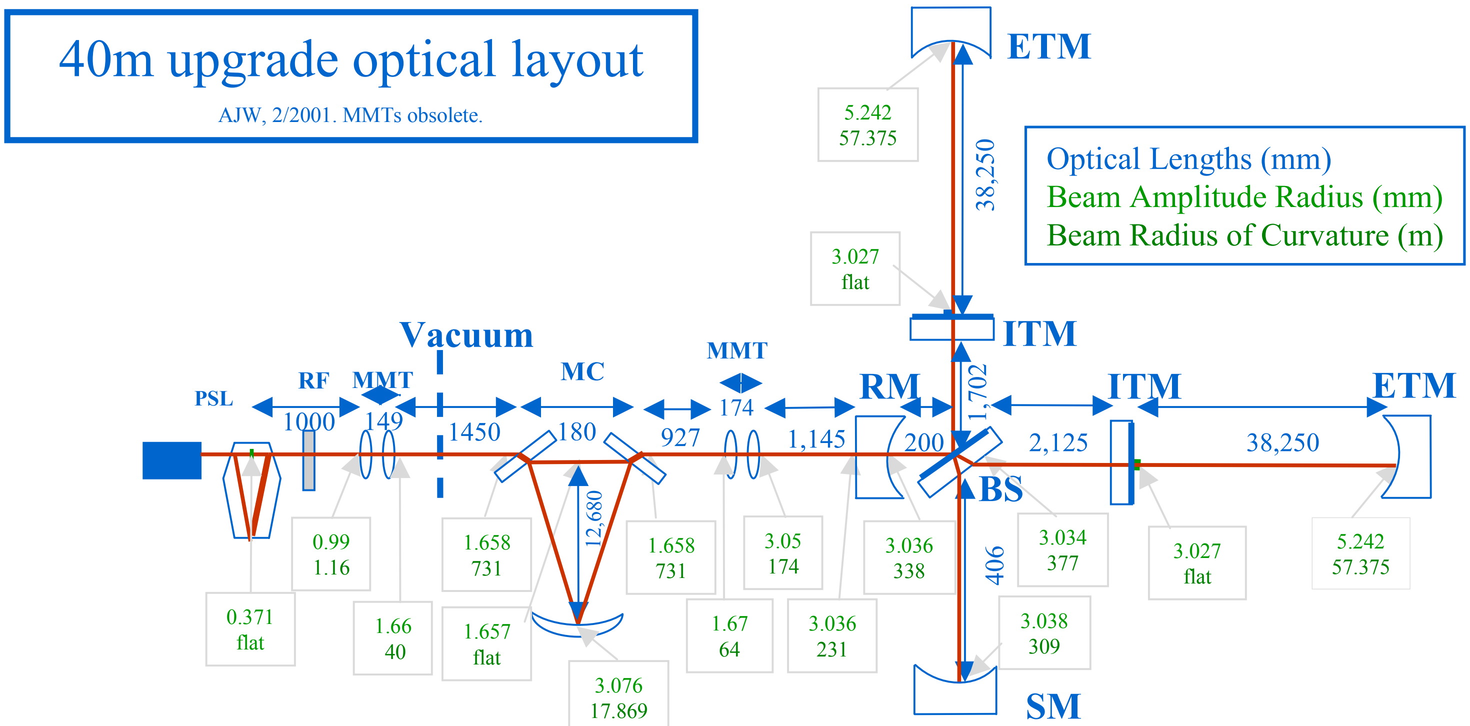
40 m RSE Experiment (40m)

- 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 to be installed
  - » 4Q02: LIGO 40 m suspensions installed
  - » 2Q04: LIGO 40 m configurations research completed; further characterization studies & ISC prototype testing continues

40m Interferometer



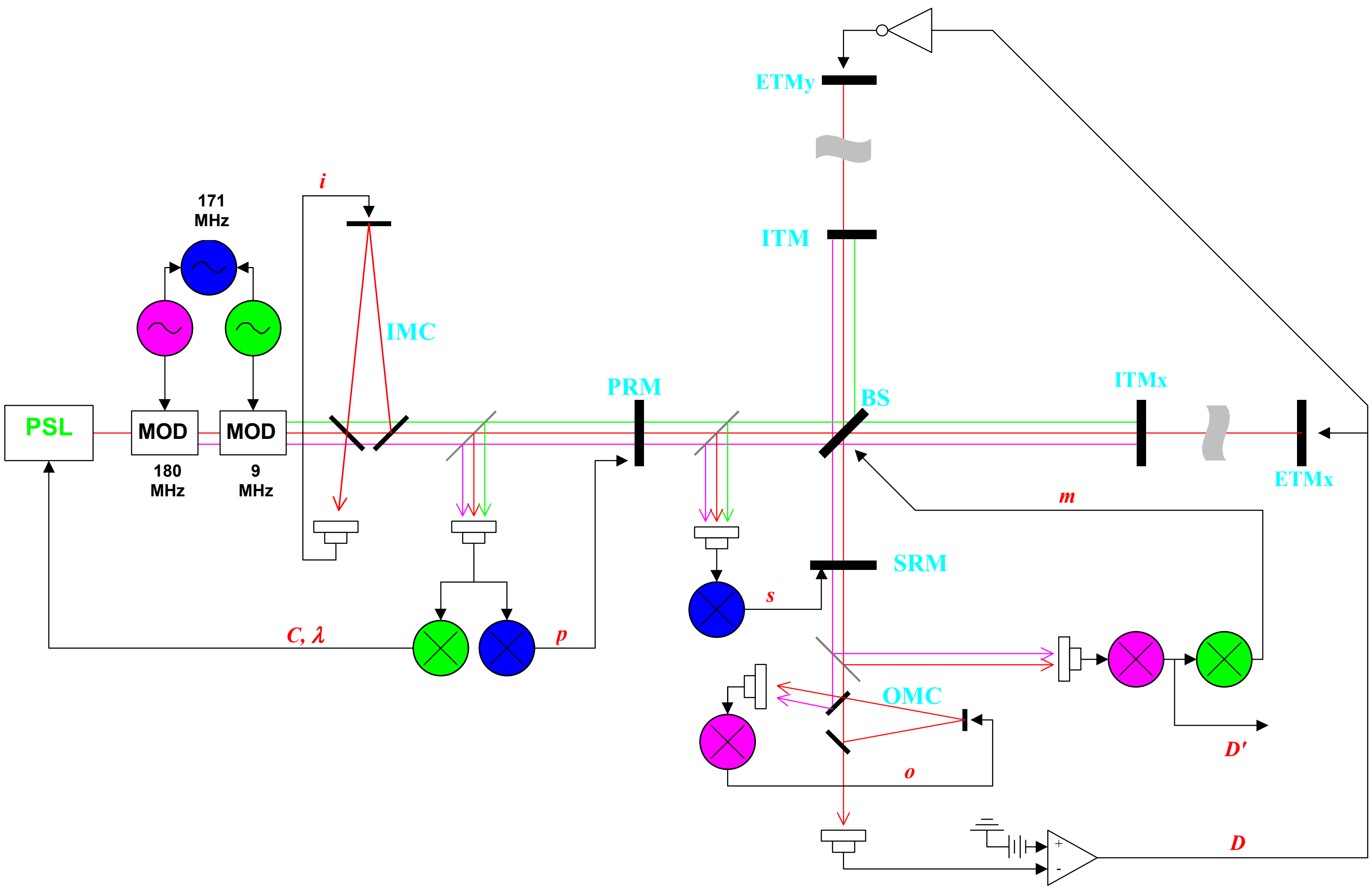
40m Interferometer Layout



Advanced Interferometer Sensing & Control (ISC)

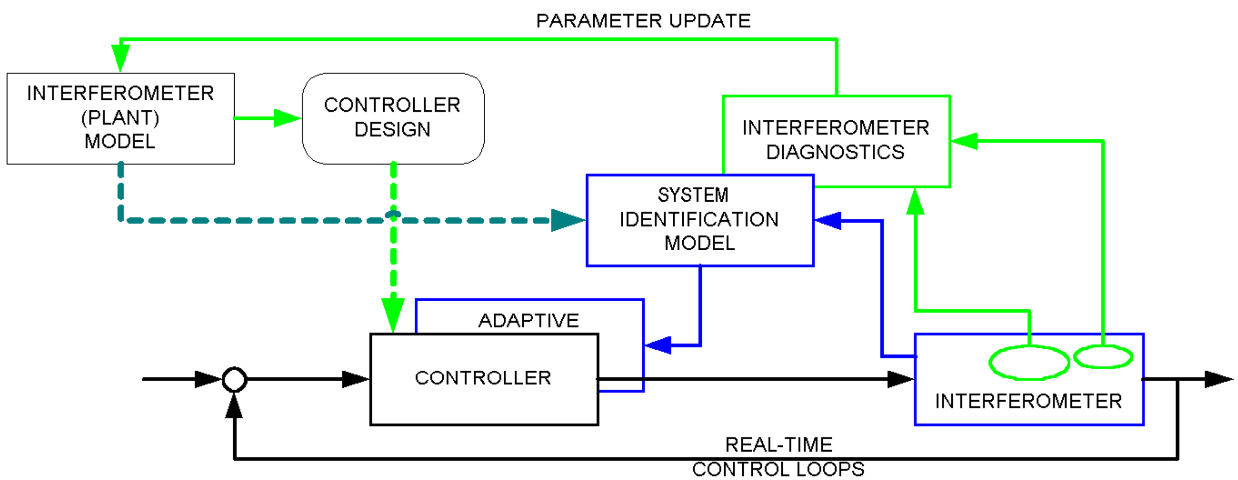
- Responsible for the GW sensing and overall control systems
- Addition of signal recycling mirror increases complexity
  - » Permits ‘tuning’ of response to optimize for noise and astrophysical source characteristics
  - » Requires additional sensing and control for length and alignment
- Shift to ‘DC 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

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



Systems and Interferometer Sensing and Control Organization

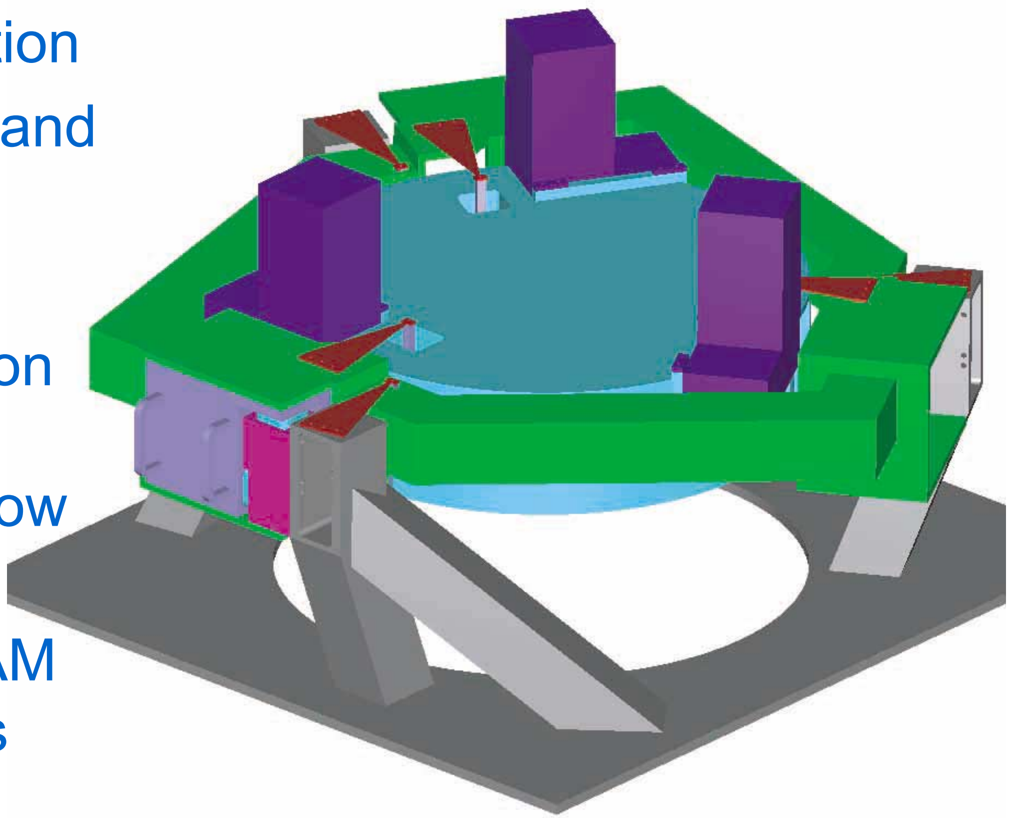
- Systems flows naturally into the controls problem, similar skills and overview needed
- Peter Fritschel and Dennis Coyne at LIGO east/west leading, distributed team in Lab
- Strong coupling to Ken Strain (U Glasgow)
- Strong coupling to experiments at U. Glasgow, and small tabletop proof-of-principle experiments at the two campuses
- Effort leads to Caltech 40m tests for validation

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

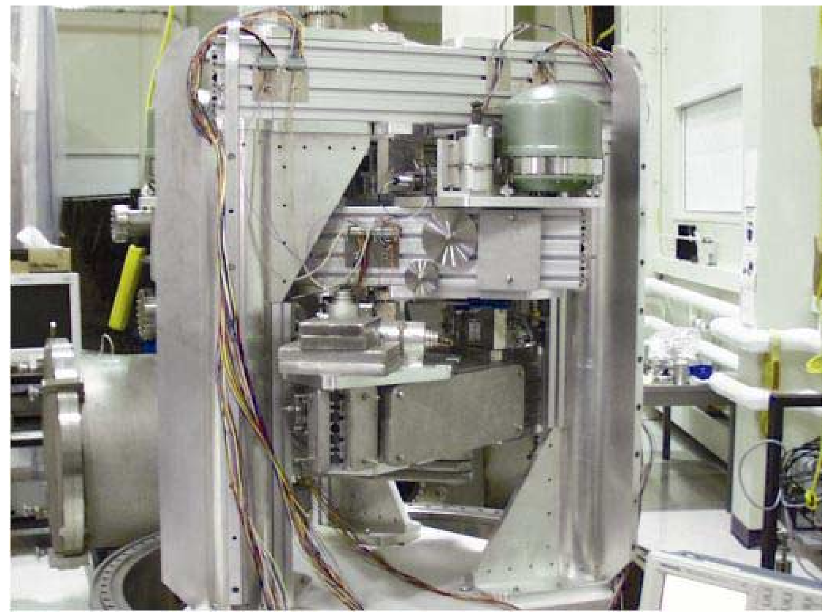


SEI: Organization

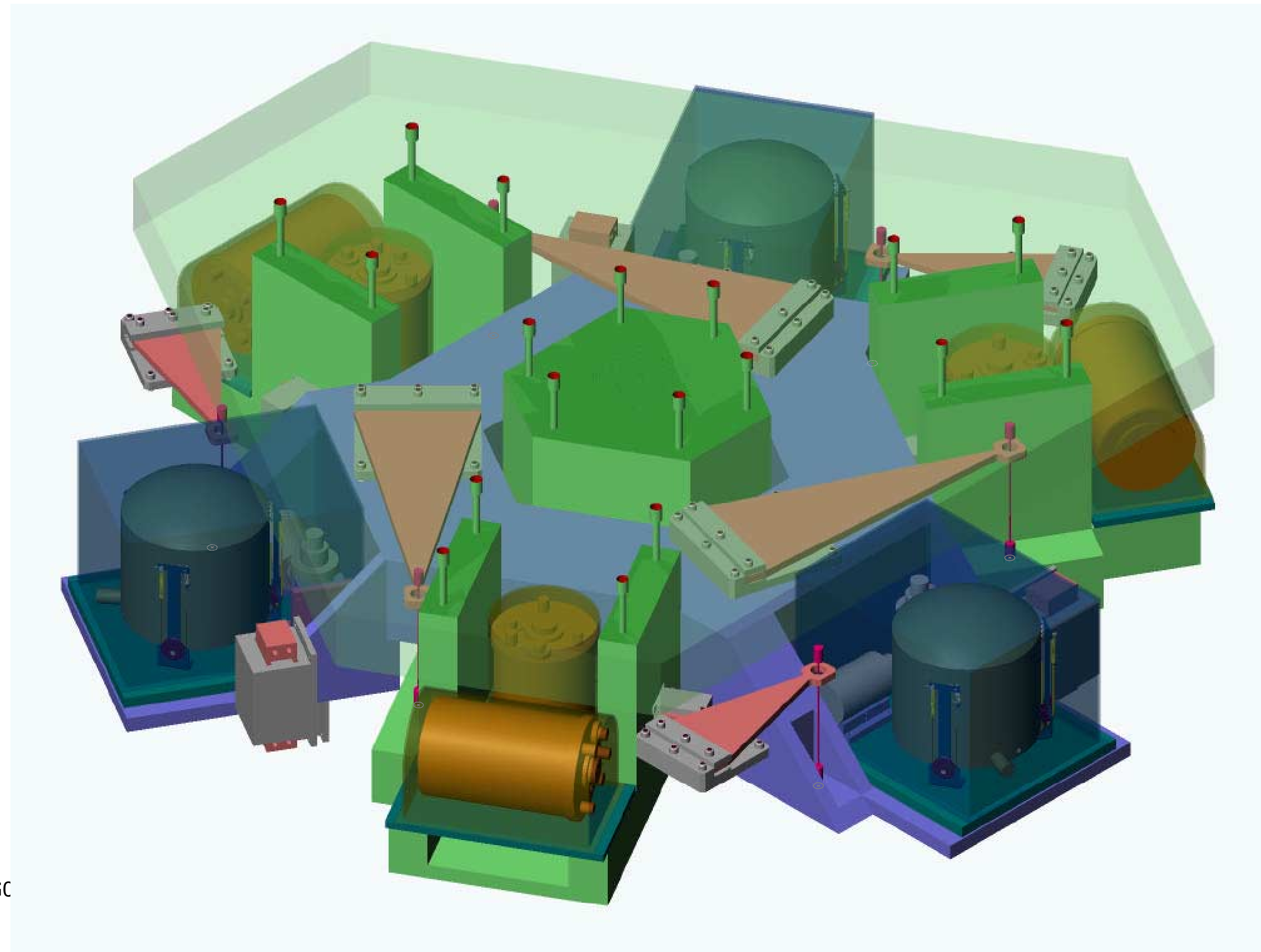
- Initial work done by teams at Caltech, MIT, Stanford, LSU, JILA – significant input from LSC teams, suspension working group
- Strategic organization by Lab of continued development at LLO, with continued LSC scientific leadership (Giaime/LSU)
- Engineering effort and prototype fabrication managed 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

- Prototyping and test of active systems
  - ✓ 3Q00: proof of principle prototype
  - ✓ 4Q00: demonstrator bid package
  - ✓ 1Q01: demonstrator fabrication contract let (HPD, Boulder)
  - ✓ 2Q01: design requirements review (first one for Advanced LIGO!)
  - » 4Q01: demonstrator test to be complete (at Stanford)
  - » 1Q02: Hydraulic prototype test on LIGO I system (Stanford/MIT)
  - » 3Q02: HAM prototype standalone testing completed (MIT LASTI)
  - » 1Q03: BSC prototype standalone testing completed (MIT LASTI)

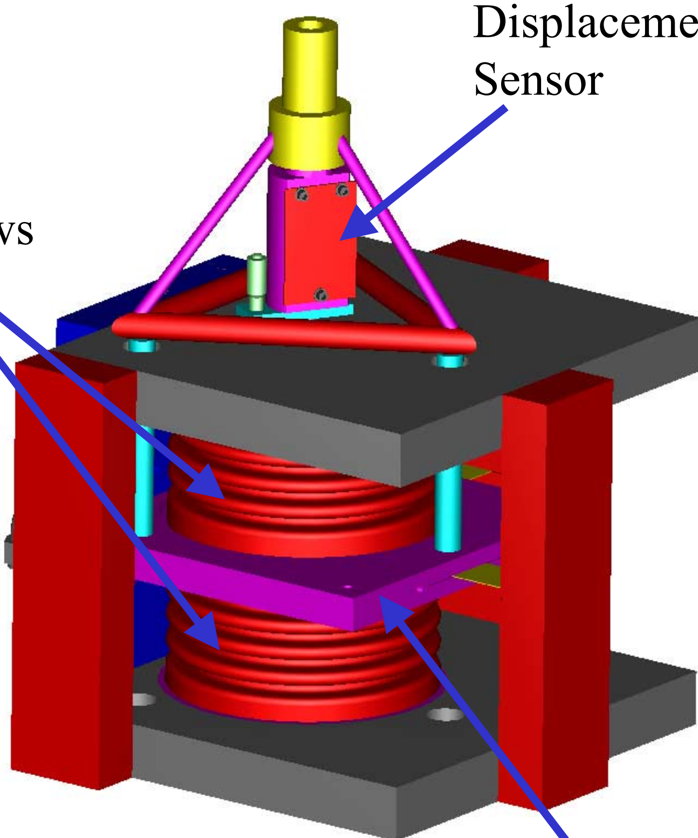


Design work on Demonstrator
(early draft)

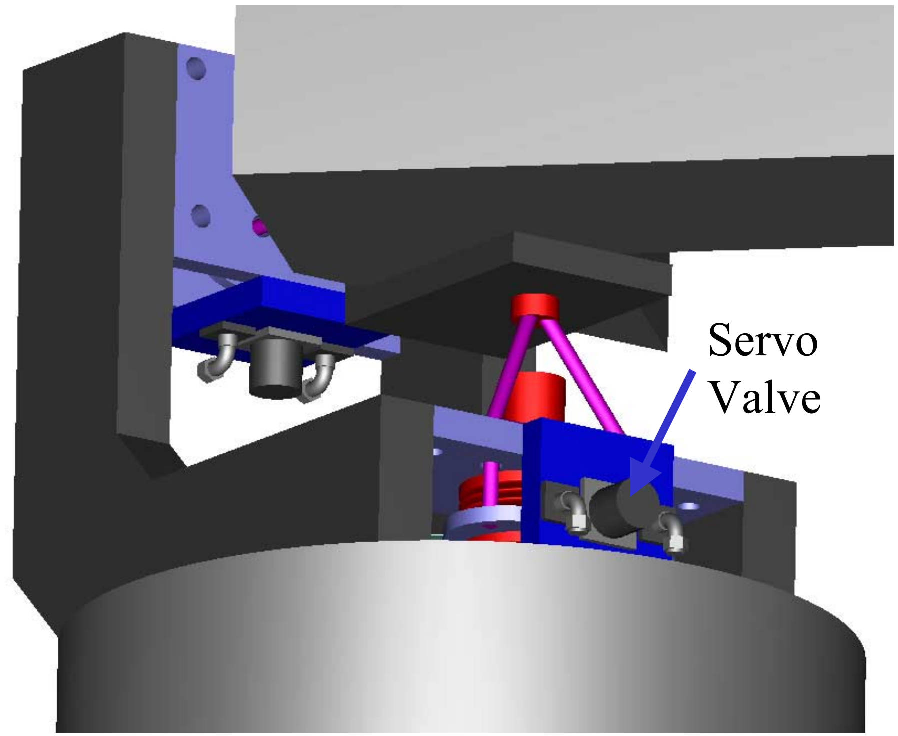


GC

The Quiet Hydraulic Actuator



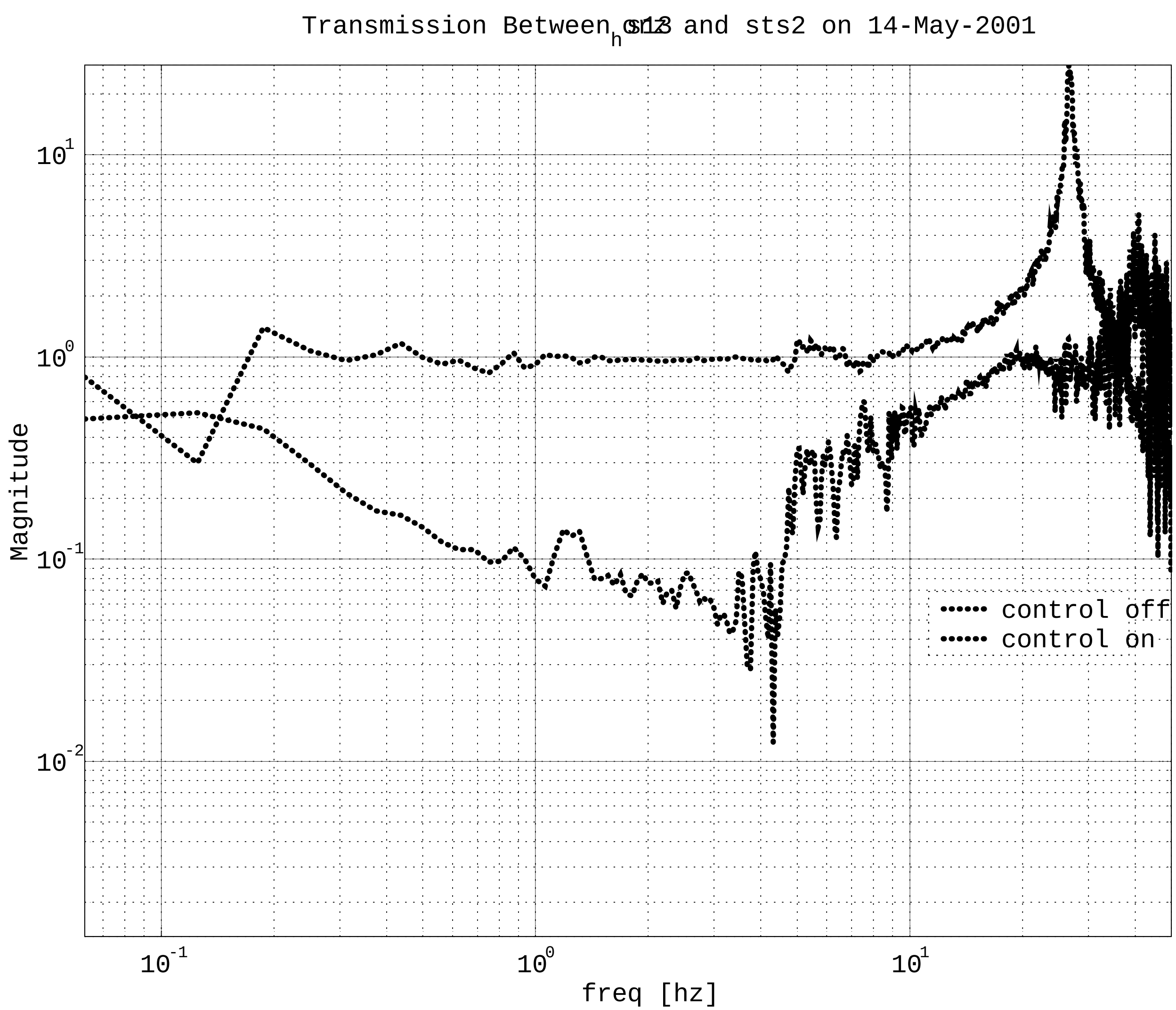
Current Design



Current Design Implemented On LIGO Pier

Hydraulic prototype test results

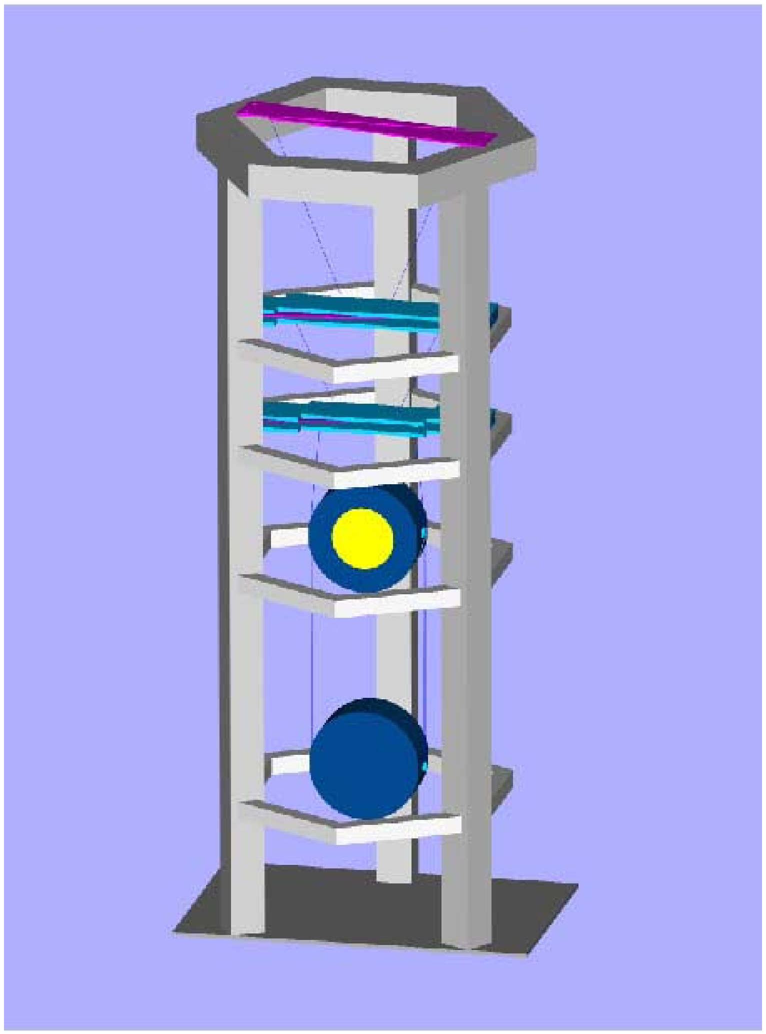
- 2-DOF system
- Feedforward and feedback
- Potential to reduce ambient seismic noise also for initial LIGO if indicated



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, potentially with Birmingham (Cruise) group
- Schedule highlights:
  - » 2Q01: Fabricate and test quad pendulum
  - » 2Q01: Install first fused silica GEO-600 suspension
  - » 2Q02: Controls prototypes complete, in testing
  - » 2Q03: Noise prototypes complete, in testing

GEO suspension – Quad pendulum prototype



Parallel effort: Thermal Noise Issues

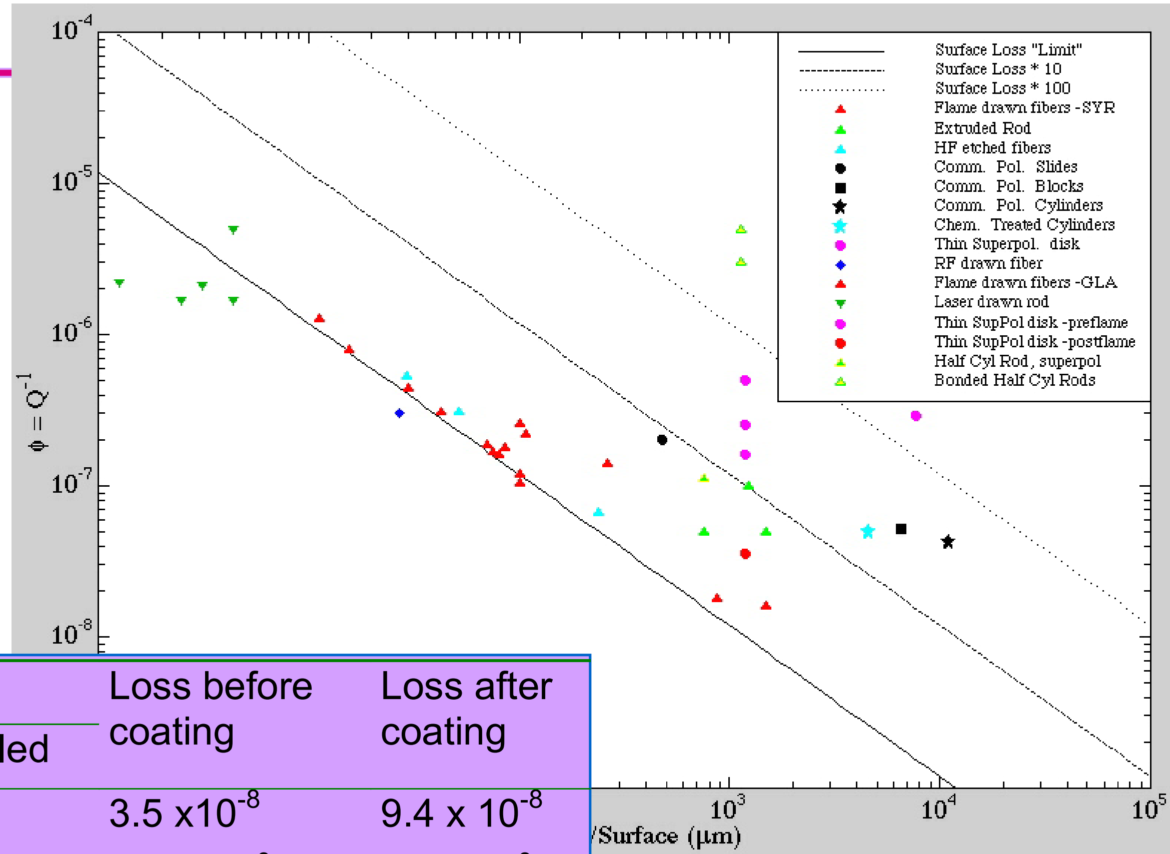
- Choice of substrates – sapphire, fused silica
  - » Modeling, measurements of thermophysical properties, measurements of Q and anelastic aftereffect
- Coating and polishing mechanical losses
  - » Modeling, specialized coating and before/after coating, polishing Q measurements, flame/chemical processing
- Assembly techniques
  - » Hydroxy-catalysis bonding with various solutions, welding, ribbon and cylindrical fiber development

LIGO

Surface losses, coating losses

Left: Volume/surface ratio for fused silica;

Below: losses of sapphire before and after dielectric coating



Mode	Frequency (Hz) measured	Frequency (Hz) modelled	Loss before coating	Loss after coating
'Clover (4) leaf'	35674	35085	3.5×10^{-8}	9.4×10^{-8}
Asymmetric drum	54850	53074	4.5×10^{-8}	15×10^{-8}
Bending	68633	66657	11×10^{-8}	14×10^{-8}
Fundamental	82980	82296	1.9×10^{-8}	6.4×10^{-8}
'Clover (6) leaf'	87267	88292	3.7×10^{-8}	9.4×10^{-8}

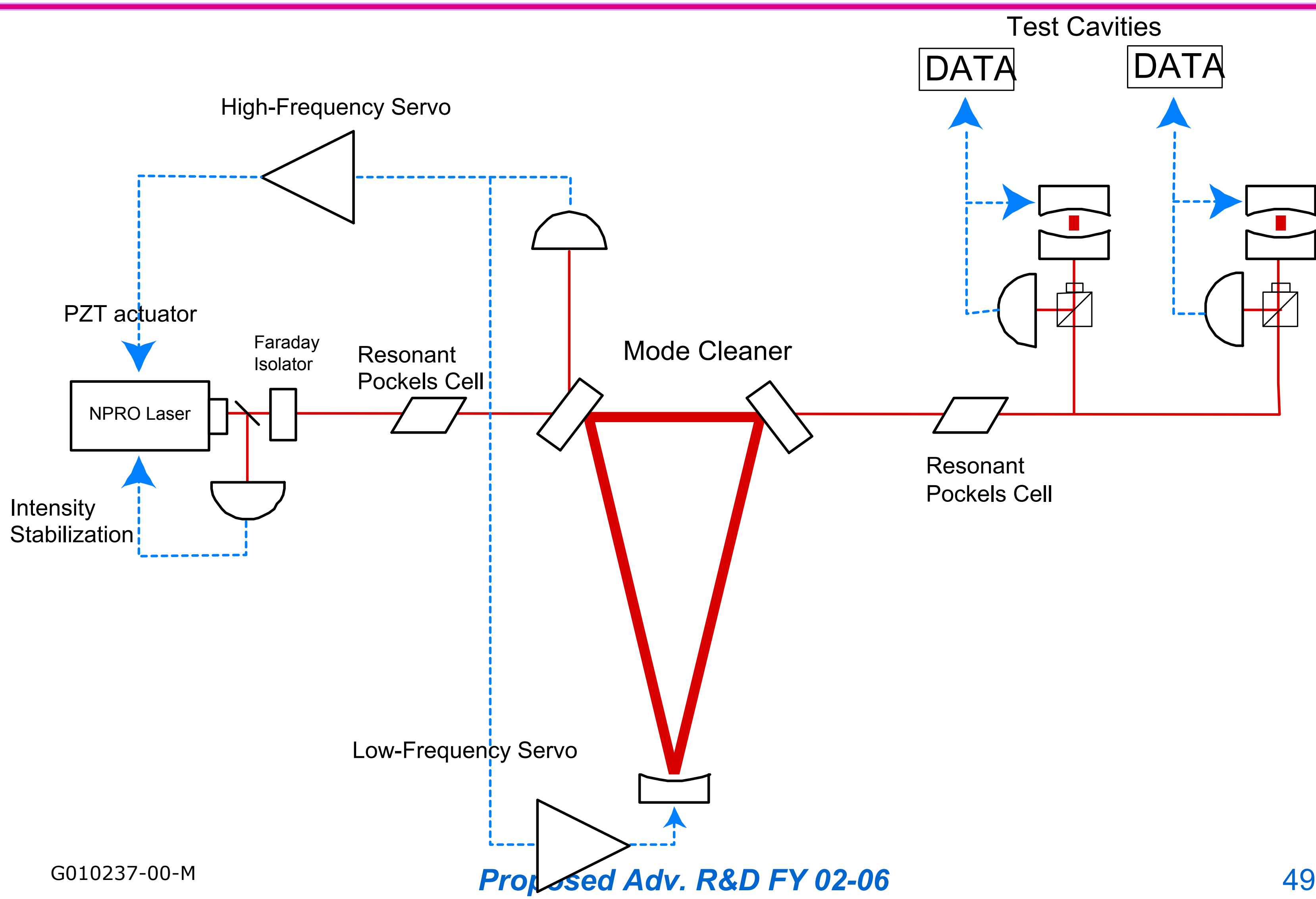
Suspension effort organization

- Thermal noise research pursued by a wide range of institutions, with some (intentional) duplication: Syracuse, Stanford, Glasgow, Iowa State, LIGO Lab, SMA/Lyon/Virgo
- Suspension initial design through the initial prototypes and the design rules: GEO (University of Glasgow, Norna Robertson), potential involvement of University of Birmingham in electronics and integration
- Suspension final design and production of final ‘performance’ prototypes, ultimately final articles: LIGO Lab Caltech (Phil Willems)

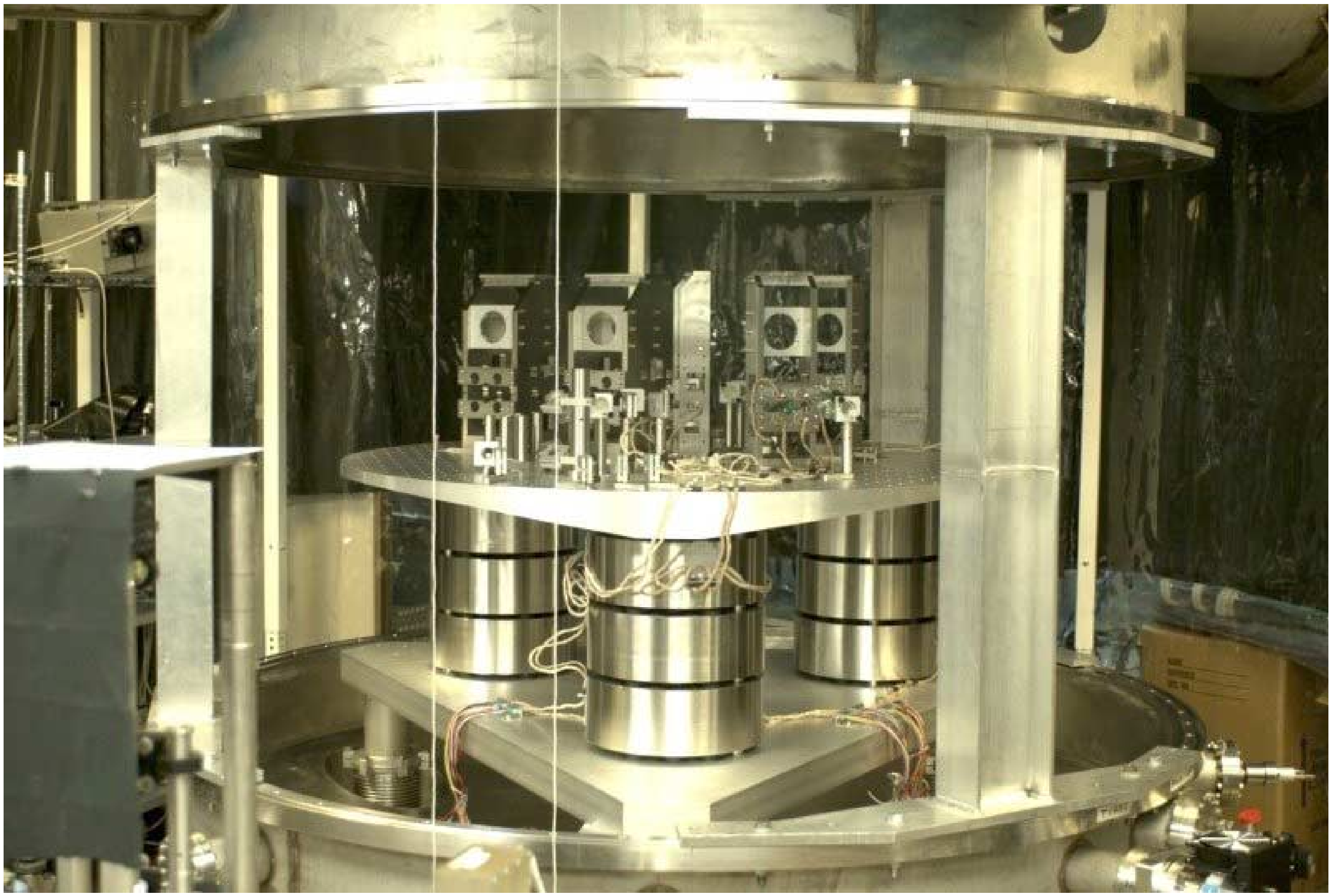
Thermal Noise Interferometer (TNI)

- 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
- All system components in place, in ‘commissioning’
- Schedule highlights:
  - ✓ 4Q00: TNI mode cleaner cavity locks
  - » 2Q01: TNI studies for initial LIGO to be completed
  - » 2Q02: Sapphire substrates installed
  - » 1Q03: TNI final Sapphire/fused silica results

Thermal Noise Interferometer



Thermal Noise Interferometer



Advanced R&D: Optics & Laser

- Core Optics Components (COC)
- Input Optics (IO)
- Core Optic Active Thermal Compensation (ATC)
- Pre-Stabilized Laser (PSL)

Advanced R&D: Optics
Core Optics

- Sapphire Material Development
- Sapphire Polishing
- Coating

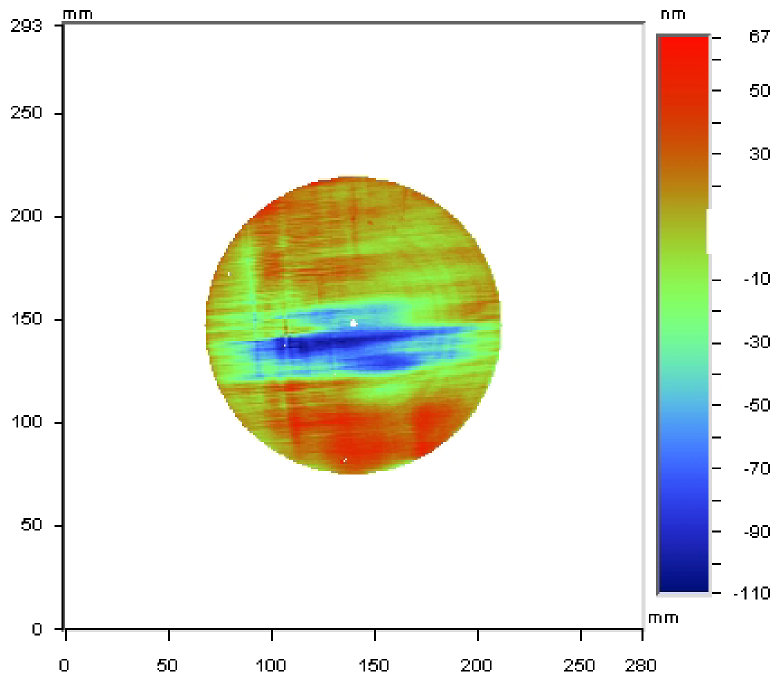
Advanced R&D: Core Optics Material Development

- Why Sapphire?
  - » Increased detection range
    - – 200 Mpc range for NS inspiral for sapphire vs 165 Mpc for fused silica
    - – Sapphire has higher Q (2×10^8 vs 3×10^7 for fused silica), but is thermoelastic noise limited
  - » Improved high power performance
    - – Thermal conductivity is 30 x higher than fused silica
    - – Rayleigh scattering is ~ 30x lower than fused silica
- Material R&D Effort
  - » Effect of coating, bonding, polishing on thermal noise
    - – jointly performed with the Suspensions group
  - » R&D to produce large (40 kg, 32 cm diameter), high quality sapphire:
    - – Crystal Systems Inc.
    - – Shanghai Institute for Optics and Fine Mechanics (SIOM)
  - » Measure thermophysical, optical and mechanical properties
  - » Reduce bulk absorption

Advanced R&D: Core Optics Material Development Status

- Mechanical Q (Stanford, U. Glasgow)
  - » Q of 2 x 10^8 confirmed for a variety of sapphire substrate shapes
- Thermoelastic damping parameters (Caltech)
  - » Measured room temperature values of thermal expansion and conductivity by 2 or 3 methods with agreement
  - » Provides better basis for advanced LIGO thermoelastic noise floor
- Optical Homogeneity (Caltech, CSIRO)
  - » Characterized by CIT & CSIRO
    - – two a- or m-axis, 15 cm dia. x 8 cm thick sapphire optic
    - – One m-axis, 25 cm dia. Sapphire optic
  - » 100's nm p-v, 24 to 58 nm rms
  - » Need to reduce the optical homogeneity by a factor of 5 to 10
    - – Compensation by polishing or coating
    - – Investigating homogeneity of other crystal orientations

Advanced R&D: Core Optics
Sapphire Optical Inhomogeneity



Title: Difference File name: saphah0a

Note:

Zernike Coefficients

09 wv	Zernike_15[01]: 0.000201 wv
	Zernike_15[02]: -0.000163 wv
	Zernike_15[03]: 0.041291 wv
	Zernike_15[04]: -0.039196 wv
	Zernike_15[05]: -0.009541 wv
Zernike_8[2]: 0.00032 wv	Zernike_15[06]: 0.004158 wv
Zernike_8[3]: 0.04148 wv	Zernike_15[07]: -0.017952 wv
	Zernike_15[08]: -0.027253 wv
Zernike_8[4]: -0.03831 wv	Zernike_15[09]: 0.002337 wv
Zernike_8[5]: -0.00947 wv	Zernike_15[10]: 0.015170 wv
	Zernike_15[11]: 0.040536 wv
Zernike_8[6]: 0.00355 wv	Zernike_15[12]: -0.000247 wv
Zernike_8[7]: -0.01699 wv	Zernike_15[13]: -0.007035 wv
Zernike_8[8]: -0.02689 wv	Zernike_15[14]: 0.043106 wv
	Zernike_15[15]: 0.013823 wv

Date: 08/04/2000
Time: 15:43:44
Wavelength: 690.700 nm
Pupil: 100.0 %
PV: 176.8397 nm
RMS: 30.1551 nm
Rad of curv: 45.53 km

X Center: 280.00
Y Center: 280.00
Radius: 144.00 pix
Terms: Tilt
Filters: None
Masks:
Ref Sub:

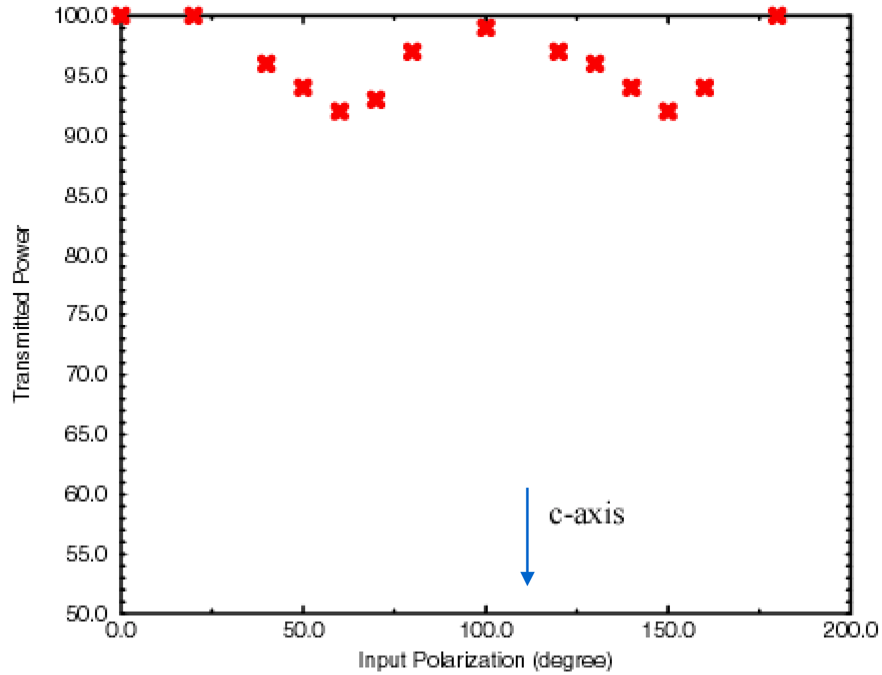
Averages:

Seidel Aberrations (8 Term Fit)

	Coeff (per radius)	Rms	Angle
Tilt	0.0350 wv		101.8 deg
Power	0.0830 wv	0.024 wv	
Focus	0.2048 wv		
Astig	0.0789 wv	0.020 wv	-83.1 deg
Coma	0.0521 wv	0.018 wv	-78.2 deg
Sa3	-0.1613 wv	0.048 wv	

Advanced R&D: Core Optics
Material Development Status

- Birefringence (Caltech)
  - » Monitored transmission of high finesse Fabry-Perot cavity as a function of input light polarization
  - » Alignment of input polarization within 10 degree of c-axis gives recycling gain loss of < 5% in advanced LIGO

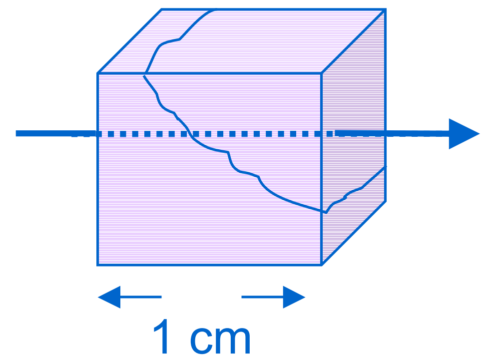


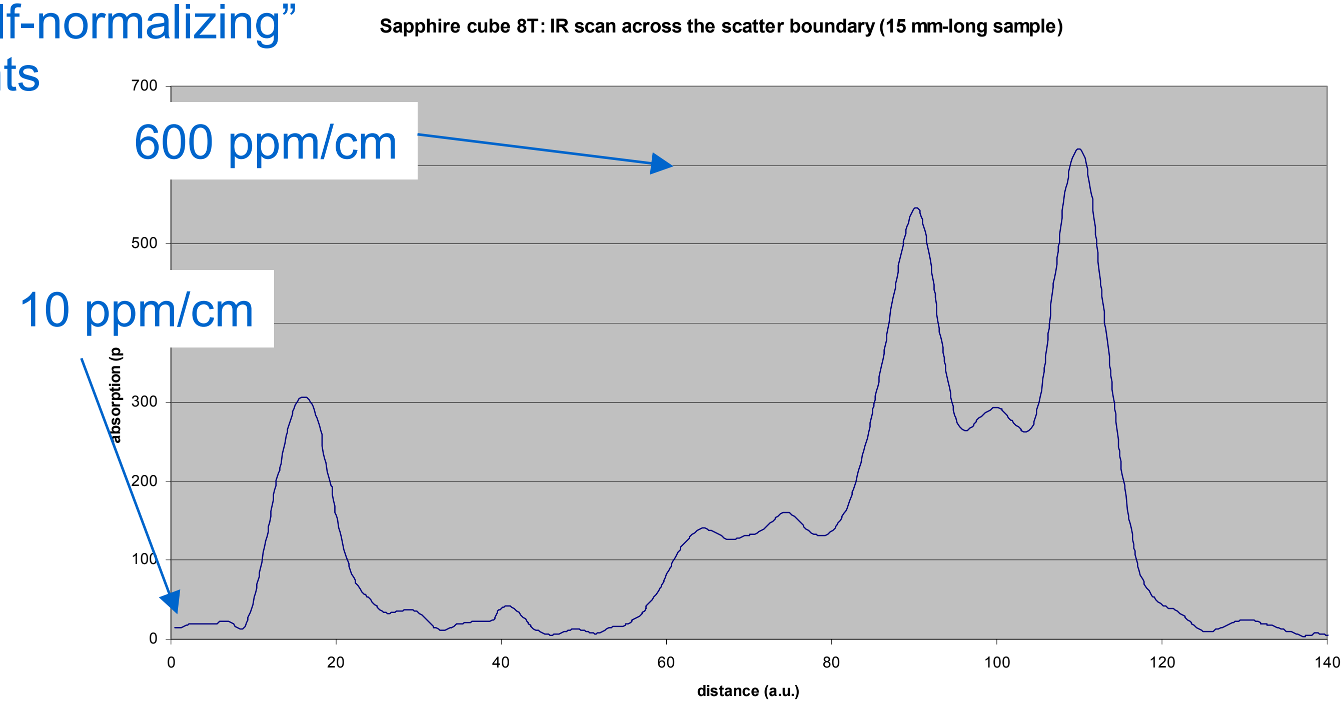
Advanced R&D: Core Optics Material Development Status

- Reduce bulk absorption (Stanford, Southern University, CS, SIOM, Caltech)
  - » LIGO requirement is <10 ppm/cm
  - » Current material ~60 ppm/cm
  - » 15 ppm/cm seen at one boule locatiion with a high purity starting material
  - » 1600C air bake gives 20 ppm/cm uniformly through sample
  - » Vary starting material, boule location
  - » Identify impurities
  - » Vary annealing atmosphere, temperature to reduce absorption

Curious observation (Rosetta Sapphire)

- Single 1 cm sample
  - » region with 10 ppm/cm
  - » region with 600 ppm/cm
  - » abrupt boundary between
- Preparation unexceptional
- Tantalizing existence proof
- Mechanism not yet clear
  - » suggests “self-normalizing” measurements

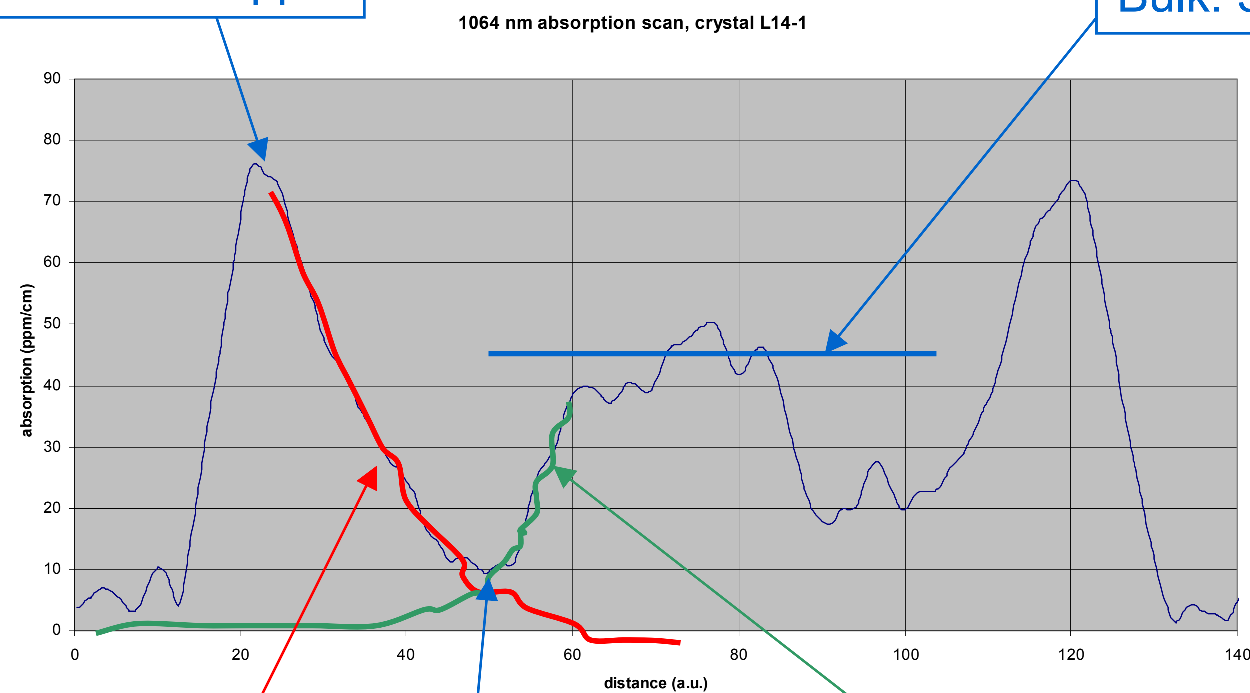




Complicated Annealing Phenomena

Maximum: 80 ppm

Bulk: 50 ppm



surface contamination?

Minimum: 10 ppm

oxidation

1064 nm absorption through cross-section of a cube

Composition Analysis (GDMS): ppm's of everything

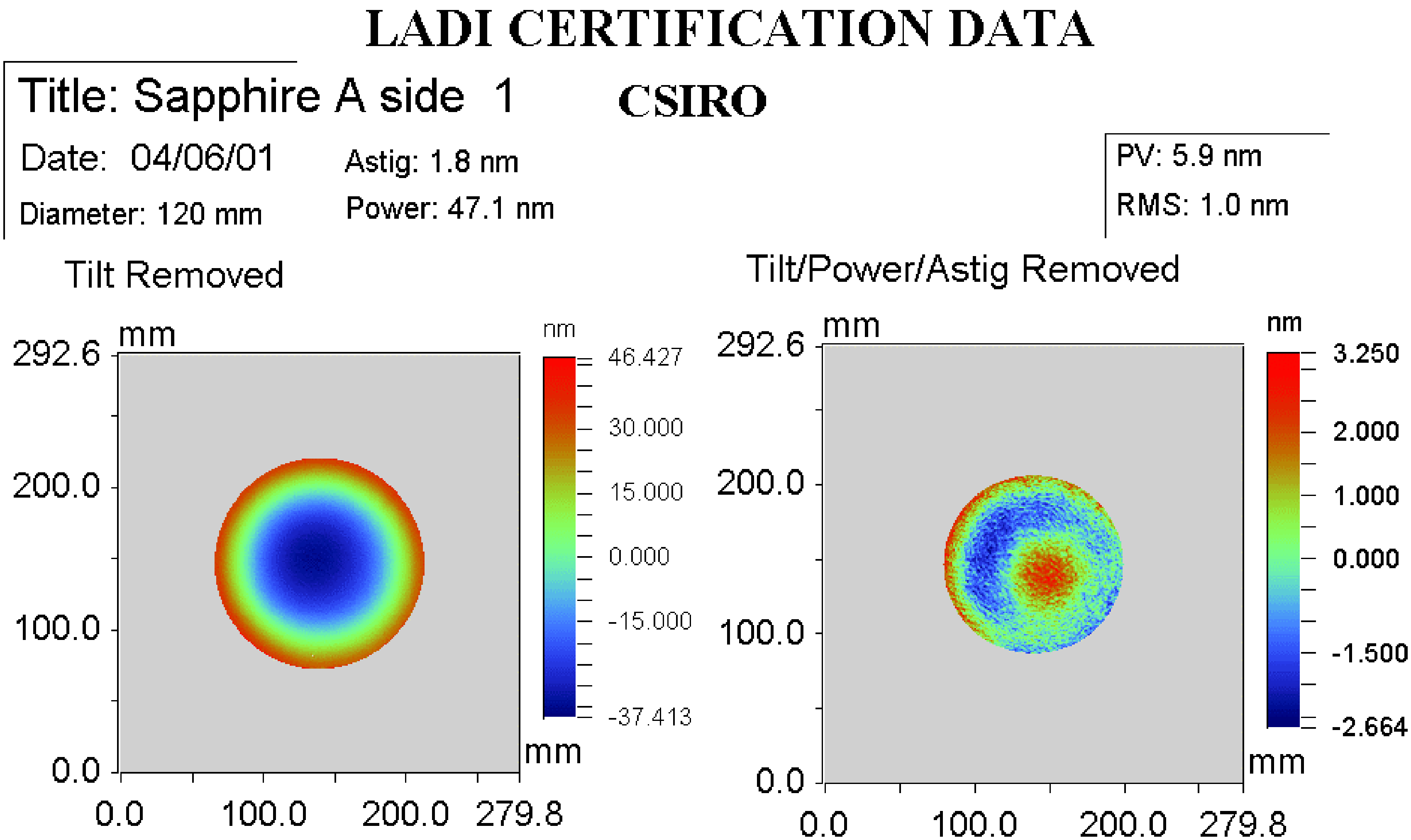
	LIGO #1T Sample #10 ppmw	LIGO #1M Sample #11 ppmw	LIGO #1B Sample #12 ppmw	LIGO #2T Sample #07 ppmw	LIGO #2M Sample #08 ppmw	LIGO #2B Sample #09 ppmw	LIGO #3T Sample #04 ppmw	LIGO #3M Sample #05 ppmw	LIGO #3B Sample #06 ppmw	LIGO #4T Sample #01 ppmw	LIGO #4M Sample #02 ppmw	LIGO #4B Sample #03 ppmw	LIGO #5T Sample #13 ppmw	LIGO #5M Sample #14 ppmw	LIGO #5B Sample #15 ppmw	LIGO #6T Sample #16 ppmw
Li	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Be	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
O	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major
F	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Na	0.21	0.42	0.40	0.25	0.75	0.35	0.36	0.44	0.81	0.82	3.2	0.95	0.20	0.26	0.26	0.46
Mg	0.16	0.27	0.30	0.22	0.29	0.18	0.19	0.25	0.25	0.53	0.39	0.20	0.15	0.15	0.10	0.065
Al	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major
Si	12	8.5	10	8.5	7.5	9.5	4.2	5.9	9.5	10	15	8.5	15	7.5	6.9	11
P	0.1	0.053	0.20	0.11	0.11	0.11	0.1	0.15	0.15	0.21	0.19	0.1	0.045	0.045	0.13	0.14
S	1.1	1.5	1.8	0.79	1.2	1.6	1.5	1.5	0.21	1.5	1.8	1.1	0.88	0.60	1.6	1.1
Cl	1.2	5.5	4.2	1.5	2.5	2.5	2.6	2.9	3.1	4.7	6.0	1.0	2.5	1.7	1.5	3.9
K	0.29	0.25	0.39	0.33	0.33	0.35	0.23	0.35	0.33	1.1	1.2	0.40	0.25	0.23	0.21	0.38
Ca	1.1	1.2	1.1	1.1	1.1	1.5	1.2	0.63	0.75	1.7	1.4	0.75	0.80	0.86	1.0	0.82
Ti	0.37	0.11	0.45	0.12	0.36	0.45	0.089	0.39	0.27	0.22	0.14	0.12	0.11	0.19	0.081	0.25
V	0.10	0.037	0.026	0.12	0.23	0.37	0.026	0.021	0.04	0.11	0.086	0.095	0.056	0.072	0.066	0.086
*Cr	2.5	1.1	1.5	1.2	1.1	1.5	1.0	1.4	1.4	1.3	1.0	1.1	1.0	1.0	1.0	1.6
Mn	0.10	0.088	0.065	0.021	0.083	0.15	0.033	0.055	0.068	0.073	0.065	0.03	0.034	0.036	0.017	0.093
*Fe	2.5	2.2	5.5	1.8	1.4	1.5	2.1	1.8	1.8	1.5	1.3	1.5	2.7	3.3	1.8	3.3
Co	0.10	0.018	0.02	0.02	0.01	0.012	0.01	0.018	0.06	0.01	0.01	0.01	0.01	0.01	0.01	0.02
Ni	0.46	0.025	0.23	0.11	0.11	0.067	0.066	0.17	0.28	0.074	0.025	0.060	0.045	0.62	0.045	0.13
Cu	0.23	0.11	0.15	0.31	0.24	0.20	0.38	0.20	0.22	0.096	0.19	0.30	0.10	0.12	0.17	0.29
Zn	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ga	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
As	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Zr	0.14	0.02	0.15	0.12	0.050	0.22	0.048	0.13	0.15	0.38	0.12	0.14	0.045	0.025	0.025	0.10
Nb	0.027	0.13	0.11	0.047	0.037	0.041	0.065	0.092	0.025	0.019	0.045	0.045	0.021	0.021	0.014	0.019
Mo	0.25	0.24	0.24	0.18	0.37	0.29	0.29	0.29	0.15	0.18	0.26	0.29	0.15	0.25	0.23	0.29
Cd	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Sn	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Sb	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Ba	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
La	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Ce	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Hf	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
W	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.2	0.2	0.2
Pb	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Bi	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

LIGO

Advanced R&D: Core Optics Sapphire Polishing

- Demonstration of super polish of sapphire (150mm diameter, m-axis)
- Radius of Curvature
  - » Requirement: ROC 50 km +/- 10 km, OR sagitta of 52 nm +/- 10 nm
  - » Achieved: 47 nm sagitta
- Surface Error
  - » Requirement: $<$0.8 nm rms over the central 120mm
$<$0.4 nm rms over the central 80mm
  - » Achieved: 1 nm rms over the central 120mm
0.6 nm rms over the central 80mm
probably limited by metrology
will be measured by Caltech
- Microroughness
  - » Goal $<$0.1nm rms; Requirement $<$0.2 nm rms
  - » The average microroughness over the surface was 0.18 nm rms (though due to measurement noise expected to be actually 0.12 nm rms)

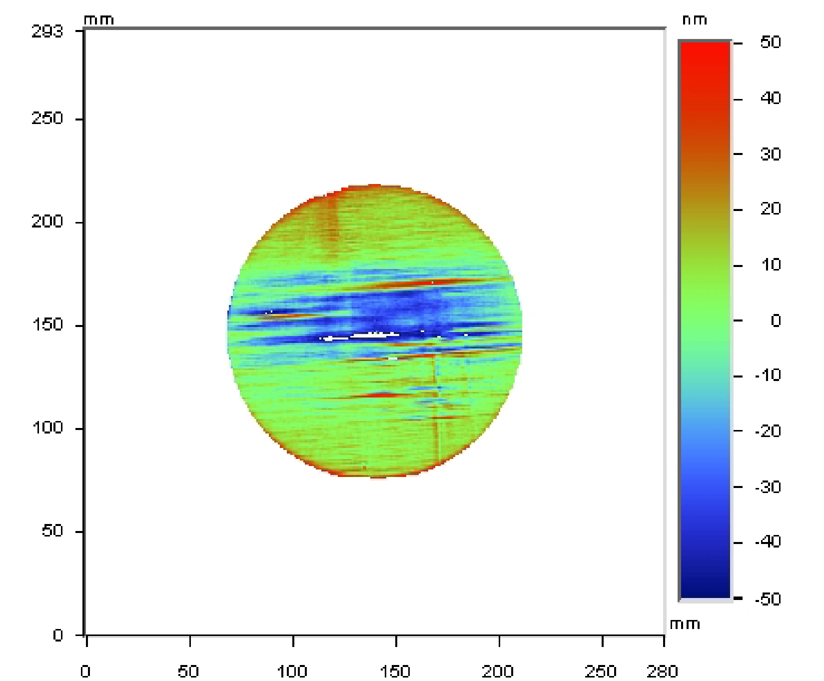
Advanced R&D: Core Optics
Sapphire Polishing



Advanced R&D: Core Optics Sapphire Polishing

- Optical Homogeniety compensation
  - » Need 5 to 10 x reduction of inhomogeneity
  - » Computer controlled 'spot' polish by Goodrich (formerly HDOS)
    - – has done compensating polish on a-axis sapphire, they have not seen the types of stria that we observe
    - – will spot polish the 25 cm dia. Piece
    - – expect to compensate for frequencies up to .08/mm or ~ 12mm/cycle
  - » Ion beam etching, fluid stream polish, compensating coating by CSIRO
    - – Have experience in ion beam etching and compensating coating
    - – Difficulty is high spatial frequency for correction
  - » Investigate a-axis and m-axis homogeneity (as alternative to c-axis)

Advanced R&D: Core Optics
Sapphire Polishing



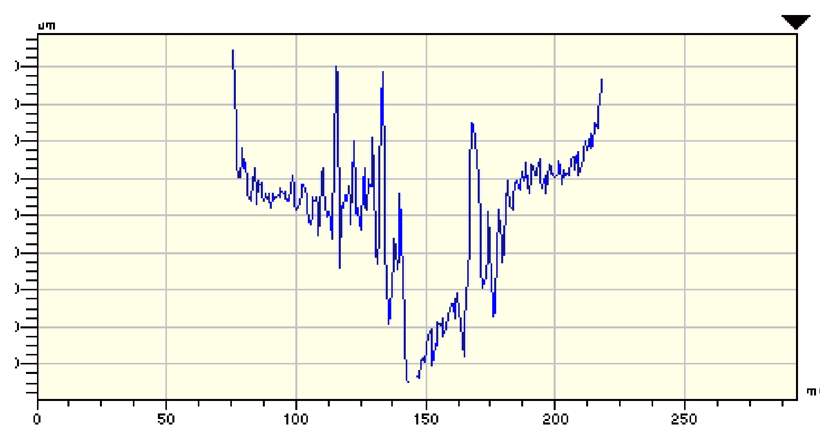
Date: 08/14/2000
Time: 16:48:14
Wavelength: 690.700 nm
Pupil: 100.0 %
PV: 100.4358 nm
RMS: 16.1115 nm
Rad of curv: 87.883 km

X Center: 280.00
Y Center: 279.00
Radius: 143.43 pix
Terms: Tilt
Filters: DHP (0.089/mm)
Masks: 3.0 Sigma Mask
Ref Sub:

Averages:

X Profile

Y Profile

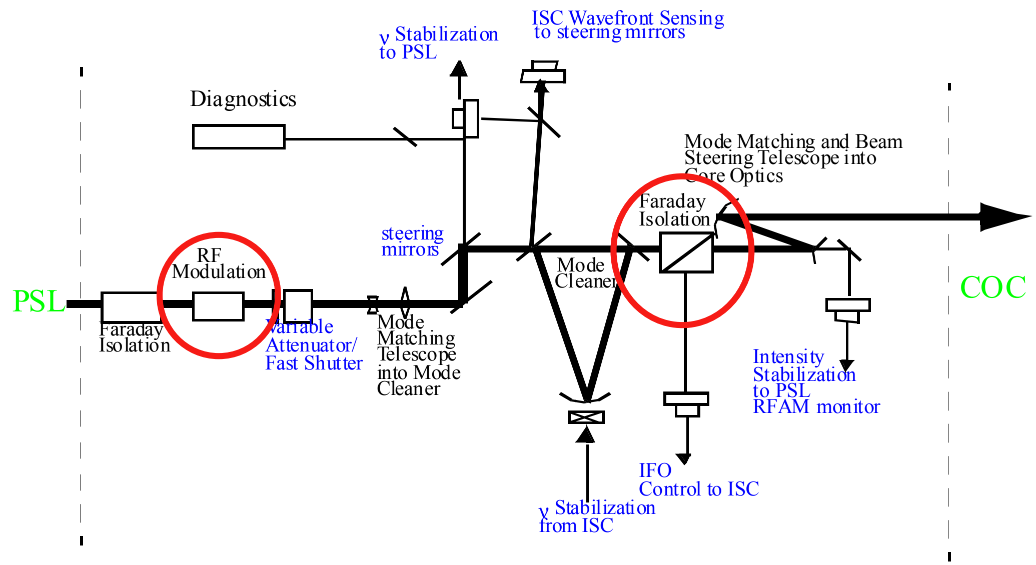


Advanced R&D: Optics
Coating Research

- Quote from Research Electro-Optics (REO, Boulder) for advanced LIGO fabrication phase was much higher than LIGO Lab anticipated based on initial LIGO experience
  - » $2,250,000 for coating development that included procurement of an Ion Beam Sputtering System
  - » fabrication phase was quoted as an additional $2,000,000
  - » high cost reflects a change in REO's business plan to emphasize telephony and communications and a concomitant de-emphasis on research
- LIGO Lab contacted other vendors with credible high performance, ion deposition, dielectric coating capability
  - » resulted in cooperative development with Virgo-SMA (Lyon, France) and MLD (Oregon)
  - » develop the required capability for advanced LIGO
  - » develop ultra-low loss coatings at Lyon (~0.1 ppm)
  - » Research effect of coating on Q (with the SUS group)
  - » Coating birefringence on sapphire substrates

Advanced R&D: Optics
Input Optics Layout & Functions

- **RF Modulation**
- **Mode Cleaning**
- **Mode Matching**
- **Optical Isolation**
- **Distribution of Control Beams**
- **Self Diagnostics**

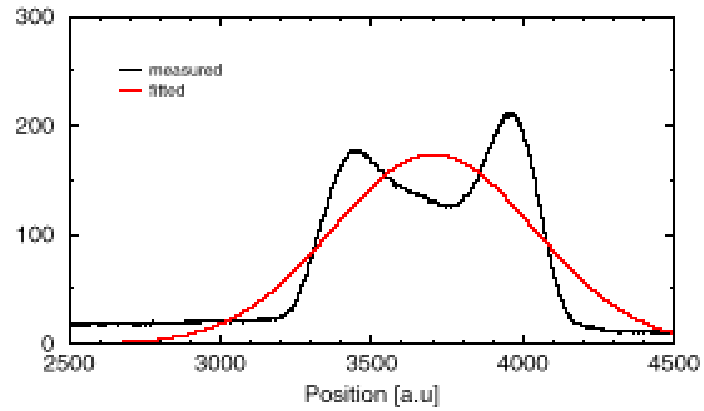


Conceptual layout of IO optical components

Parameter	*LIGO I*	*Advanced LIGO*
Laser Power	8.5 W	180 W (150 W)
Overall IO Efficiency (TEM_{00})	75%	66%
Optical Isolation	70 dB	(> 85 dB)

Advanced R&D: Input Optics R&D Issues

- Advanced LIGO will operate at 180W CW powers -- presents some “challenges”:
  - » Thermal Lensing --> Modal Degradation
  - » Thermally induced birefringence
    - – Faraday Isolator (FI): loss of isolation
    - – Electro-Optic Modulation (EOM): spurious amplitude modulation
  - » Damage
  - » Other (nonlinear) effects (SHG, PR)



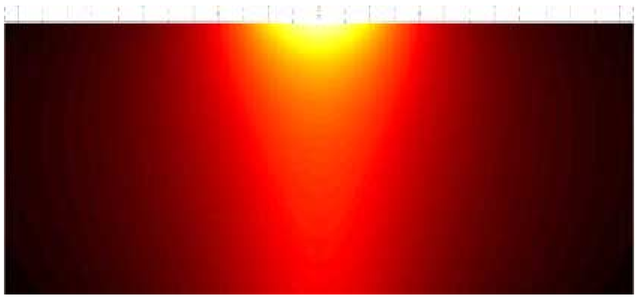
5 x 5 x 40 mm $LiNbO_3$ EOM - thermal lensing is:
i) severe
ii) position dependent

- Research Program:
  - » Modulator Development:
    - – RTA material performance (should be better than KTP)
    - – Mach Zehnder topology for modulation as an alternative
  - » Isolator Development:
    - – Full FI system test (TCFI, EOT)
    - – Possible thermal compensation (-dn/dT materials)
  - » Telescope Development:
    - – in-situ mode matching adjustment

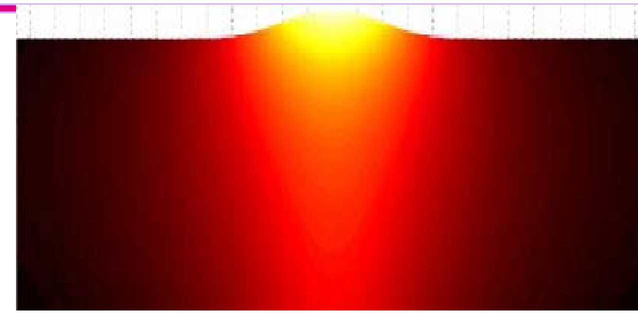
Advanced R&D: Optics Thermal Compensation

- Thermal lensing forces polished-in curvature bias on initial LIGO core optics for cavity stability at operating temperature
- LIGO II will have ~20X greater laser power, ~3X tighter net figure requirements
  - » higher order (nonspherical) distortions significant; prepolished bias, dynamic refocusing not adequate to recover performance
  - » possible bootstrap problem on cold start
- Test mass & coating material changes may not be adequate
  - » SiO_2 has low k_{th} , high dn/dT, but low bulk absorption
  - » Al_2O_3 has higher k_{th} , moderate dn/dT, but high bulk absorption (so far...)
  - » coating improvements still speculative

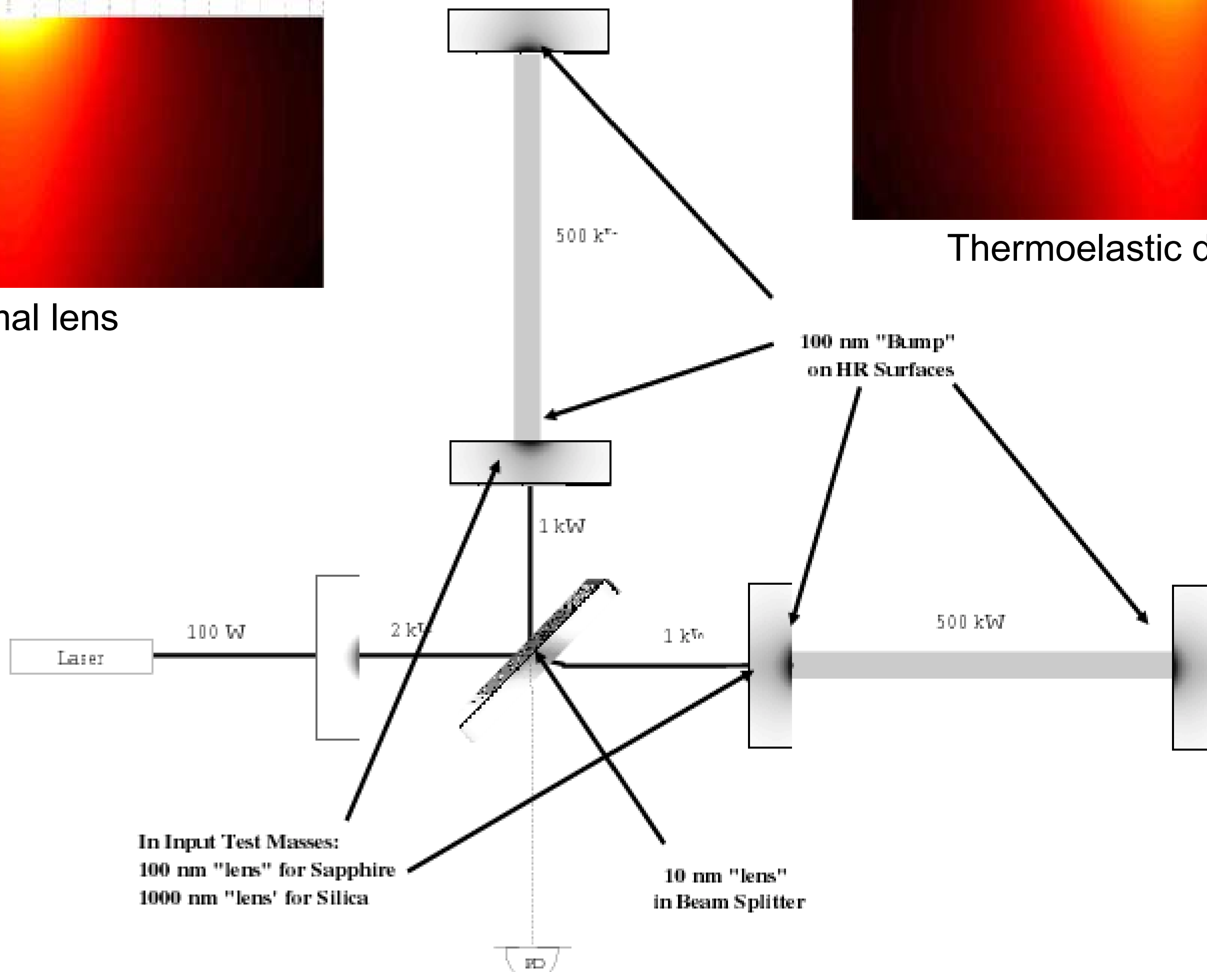
Advanced R&D: Optics
Thermal Compensation



Thermal lens



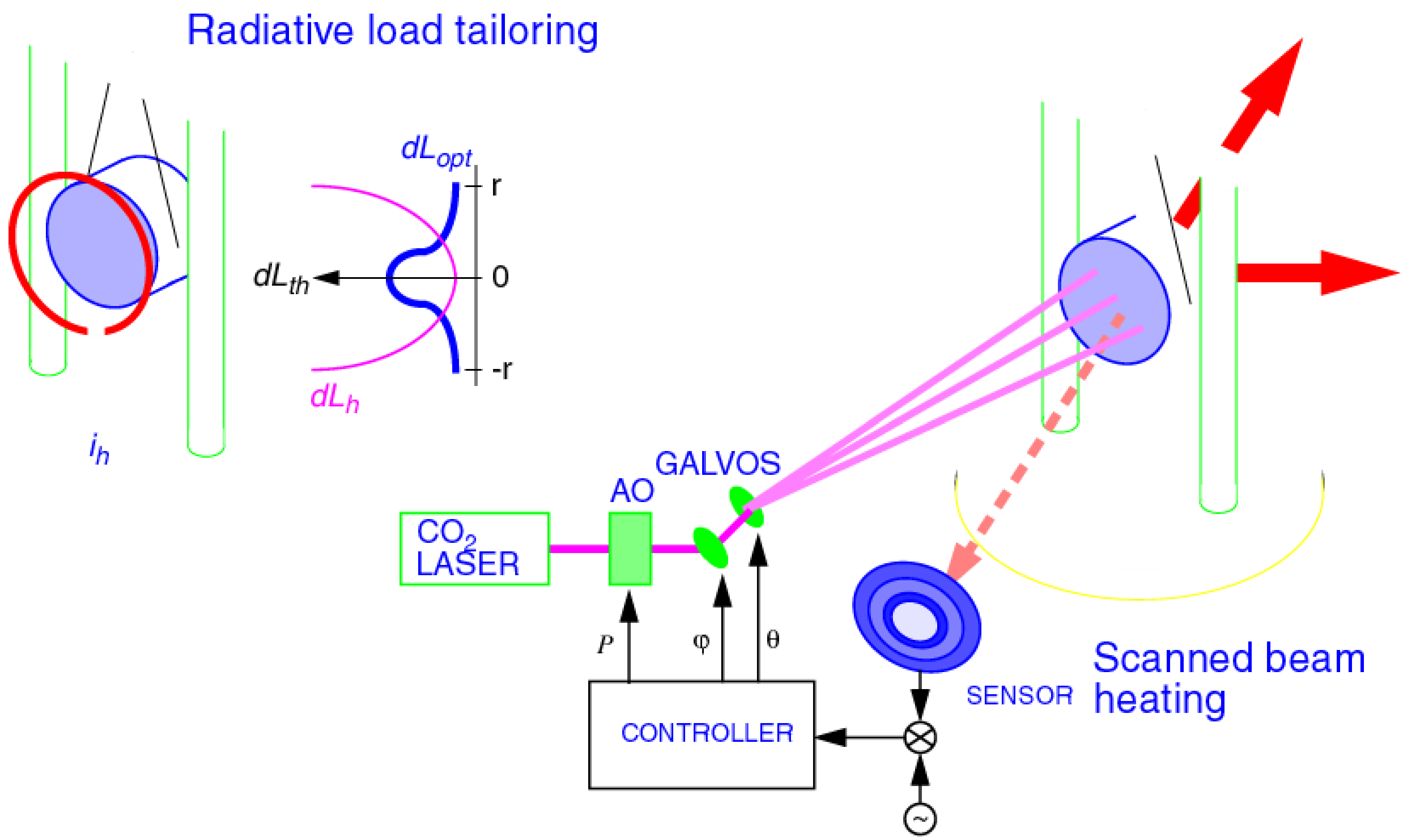
Thermoelastic deformation



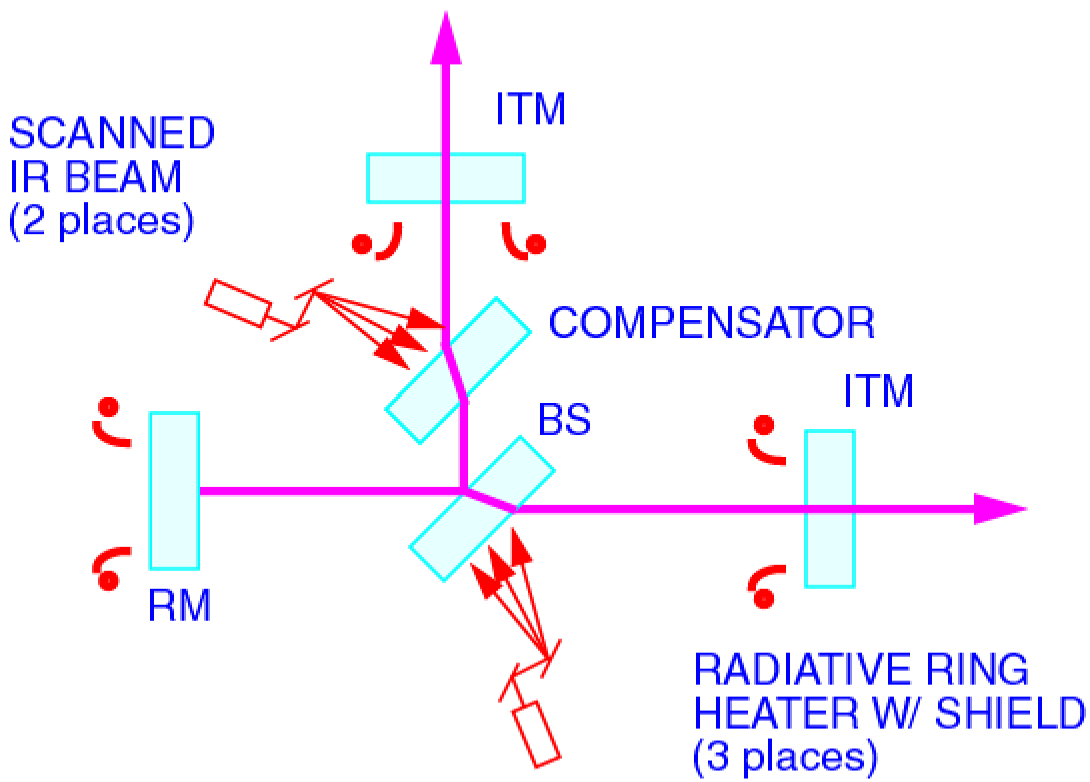
Advanced R&D: Optics
Thermal Compensation

- Extend LIGO I “WFS” to spatially resolve phase/ OPD errors
  - » scanning “Phase Camera” (MIT)
  - » staring “Bullseye WFS” (UF)
- Thermal actuation on core optics (MIT)
  - » Noncontact actuator with minimal spurious phase noise
  - » Time constants matched to disturbance timescales
- Two actuators in development
  - » passive radiative ring heater and low- emissivity shields
    - – Only copes w/axisymmetric errors, but minimal potential for spurious noise
  - » Scanned directed beam
    - – Arbitrary spatial correction, but induced thermoelastic noise is a concern

Compensation Actuators



Compensation Potential Implementation

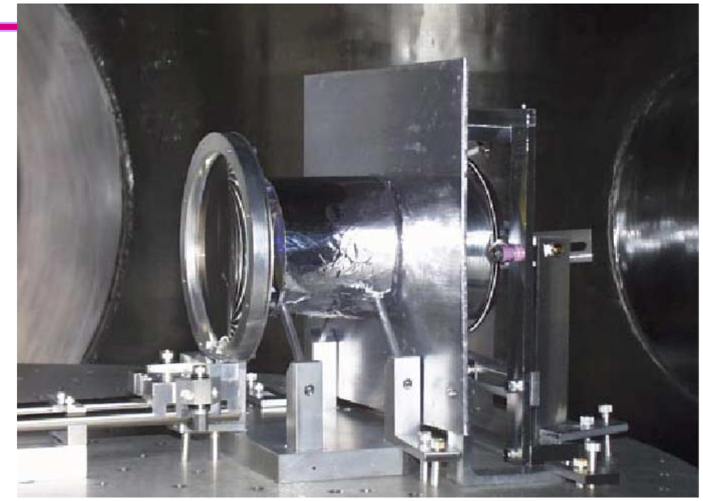


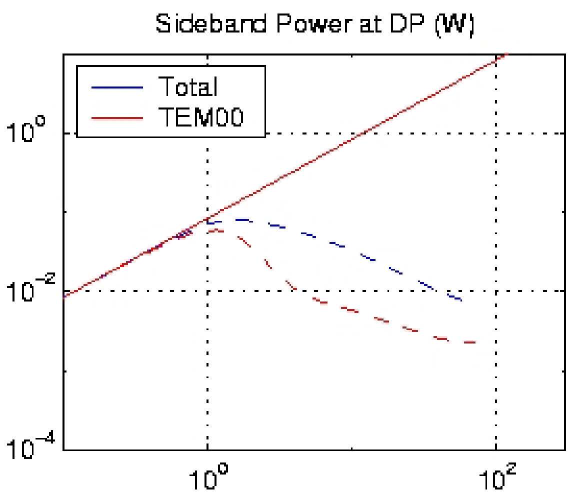
Compensation Issues

- Total heat deposited & net temperature rise
  - » “Efficient” compensation will ~ double net DT w.r.t. ambient
  - » 30K total rise plausible, would increase kT noise 5%
- Noise
  - » Thermoelastic response to varying beam intensity/position (for sapphire)
  - » Developing time-dependent thermal FEA to model better
- Absorption spatial inhomogeneity
  - » Determines pixellation, complexity/depth of compensation required
- Net efficacy & trade with optics/ material improvements
  - » Depends on sensitivity of IFO sensing to Þgure errors & their spatial scales

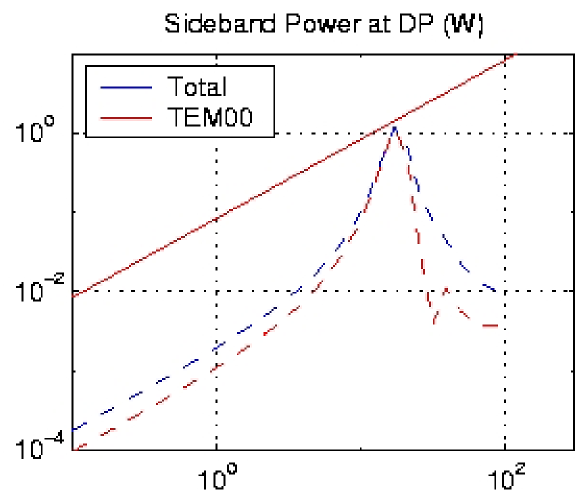
Compensation Verification

- Vacuum Chamber experiment on ring heater and scanned laser thermal compensation continues
- Finite element analyses of transient thermoelastic response
- Melody code analysis of the effect of the thermal compensation on the interferometer performance



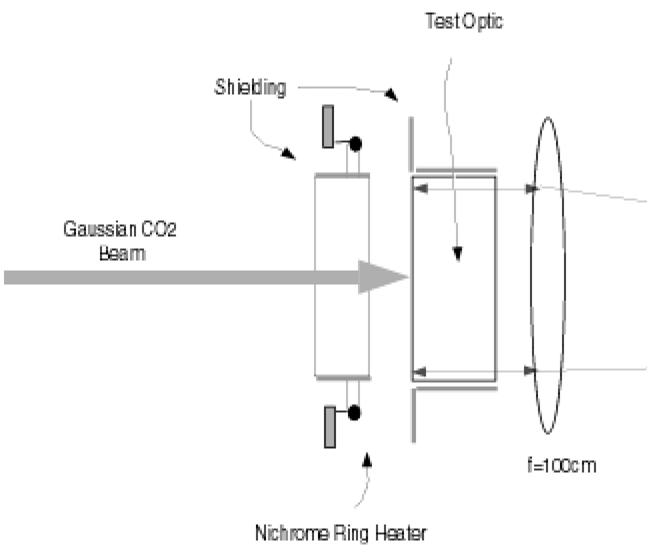


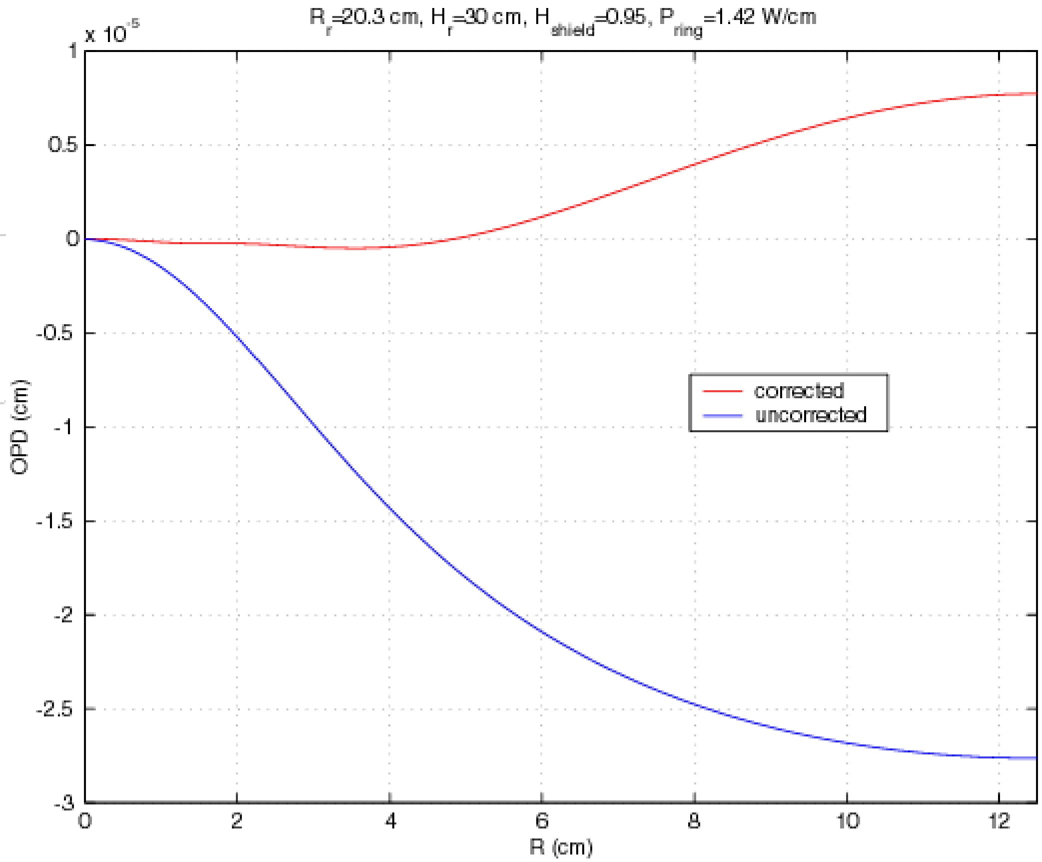
No compensation;
ROC cold matched



Ring heater compensation for
20W input power

Compensation
OPD Radial Variation

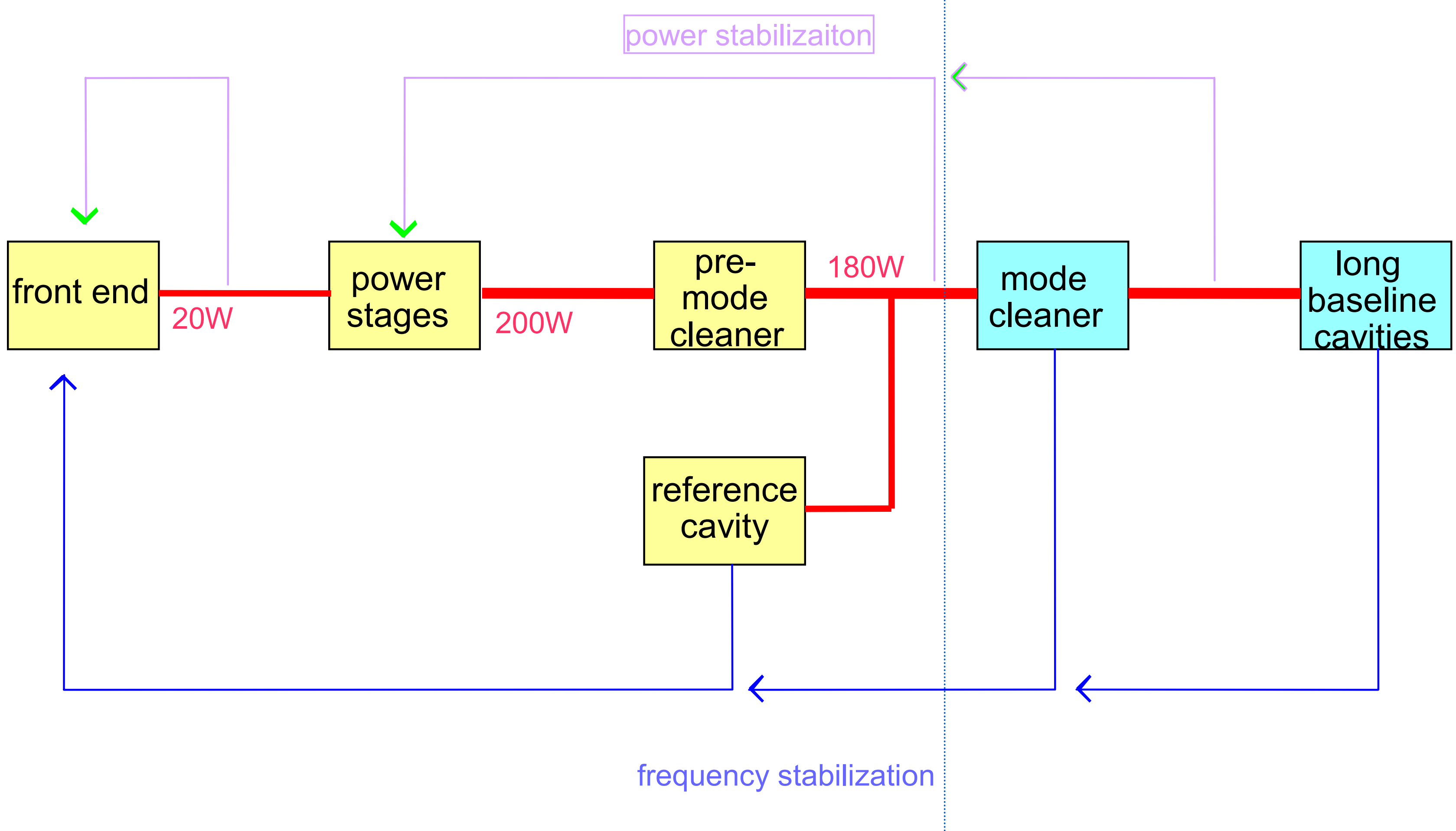




Compensation Plans

- 2Q01: Proof-of-concept experiment & IFO model results
  - » Improved requirements definition
  - » Performance figure of merit vs. COC losses, power, etc.
  - » Enables conceptual design for Advanced LIGO
- 3Q02: Full scale radiative compensator demonstration
  - » Engineering prototype at full mechanical scale (time constants, etc.)
  - » Also demo main parts of wavefront error sensing technology
- 4Q04: Full scale directed beam actuation demonstration

Advanced R&D: High Power Laser System Layout



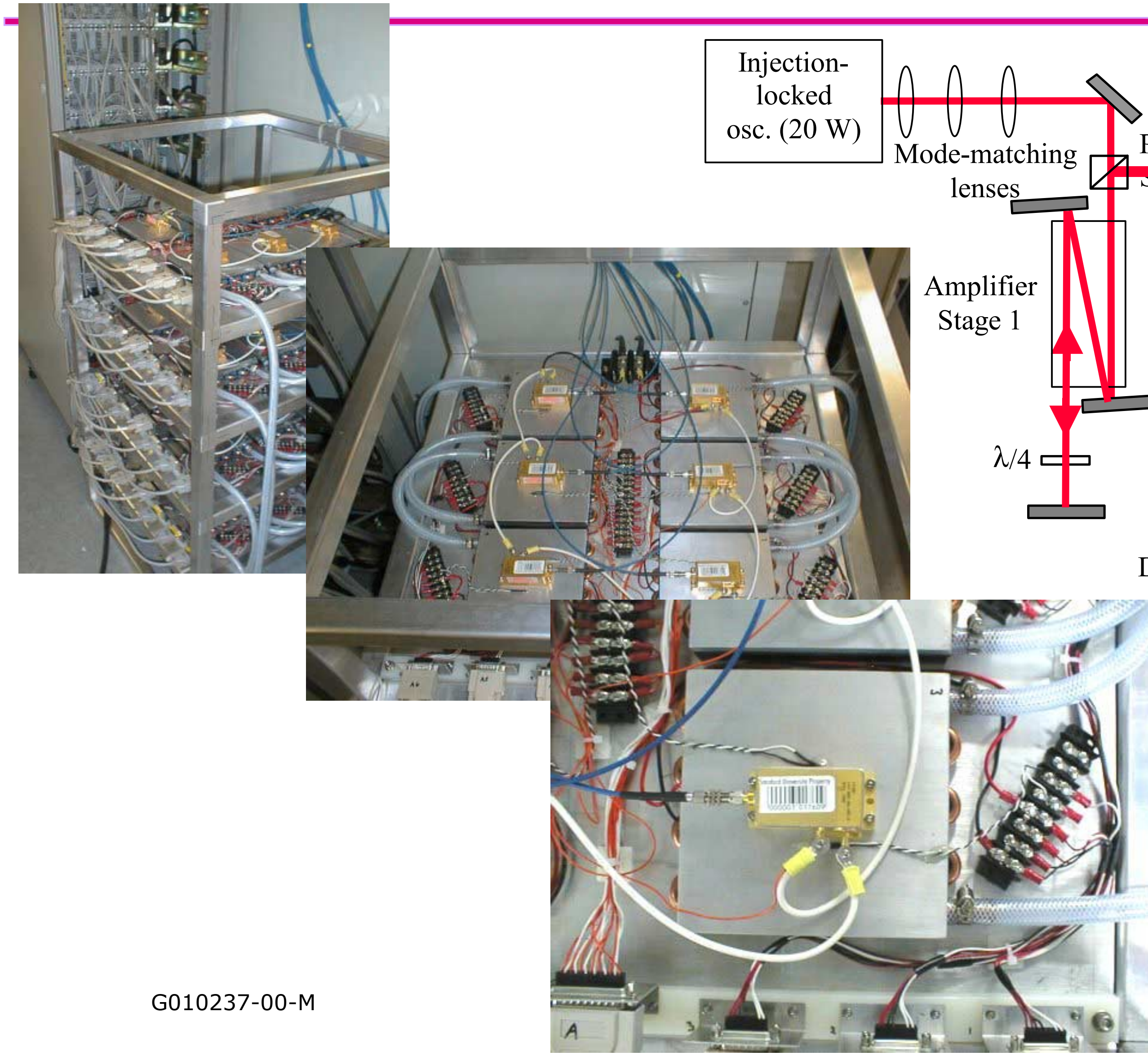
Advanced R&D: High Power Laser Research Stages

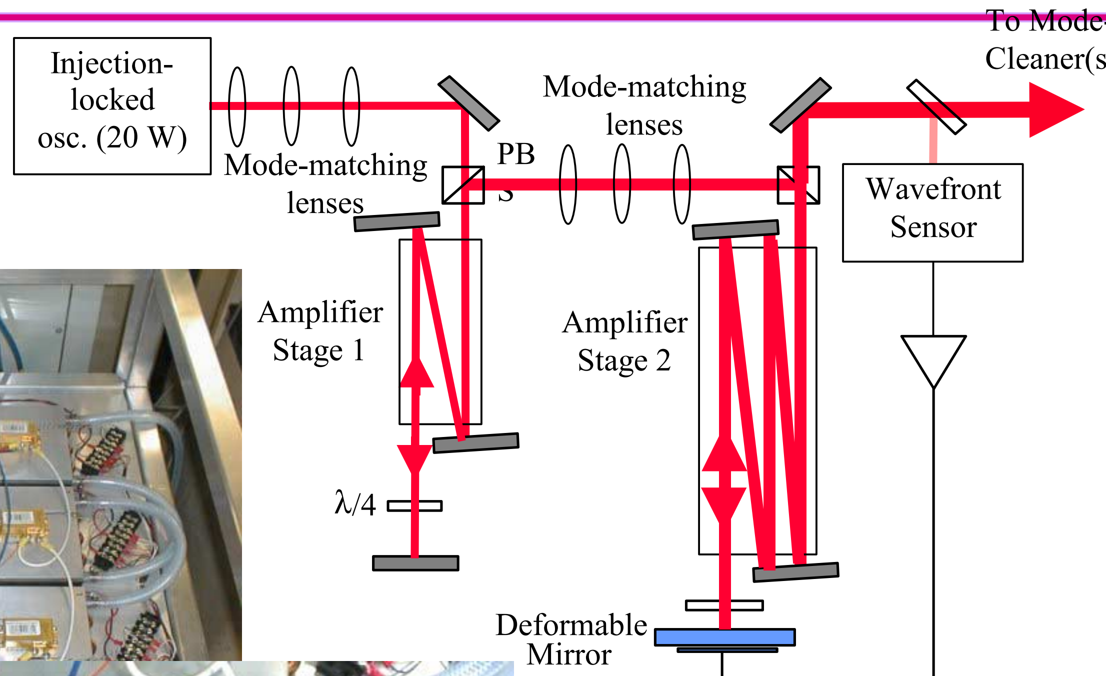
- Develop alternative concepts
- Design and build laboratory version
- Design, build and test final version in LASTI
- Team
- Key Milestones

Advanced R&D: High Power Laser Develop Concepts

- increase power of front-end
- evaluate high-power-stage concepts
  - » MOPA slab (Stanford)
    - – uses proven technology but expensive due to the large number of pump diodes required
  - » stable-unstable slab oscillator (Adelaide)
    - – typically the approach adopted for high power lasers, but not much experience with highly stabilized laser systems
  - » rod systems (Hannover)
    - – uses proven technology but might suffer from thermal management problems
- test power and frequency stabilization schemes

Advanced R&D: High Power Laser
Stanford MOPA Design



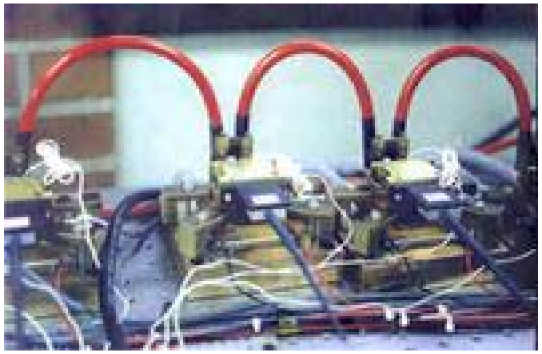


THE *Stanford* GRAVITATIONAL WAVE GROUP

Advanced R&D: High Power Laser Stanford MOPA Results to Date

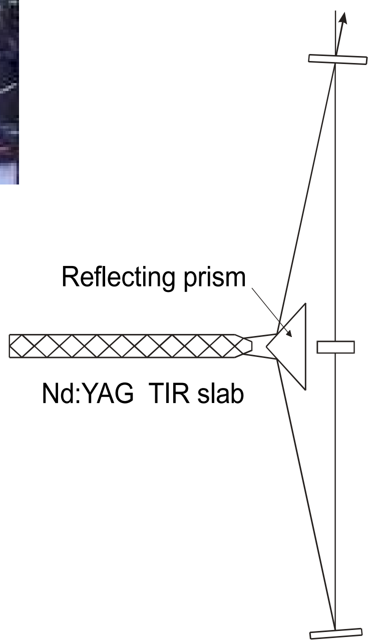
- 12W injection locked laser was shipped to Stanford and showed stable operations
- 27W stable operation of first ampl. stage
- some fluid (oil?) on the entrance surface of second ampl. slab degraded its performance for powers above 35W
- Expect 100W by, or shortly after, the end of CY01

Advanced R&D: High Power Laser Adelaide Configuration



Two in a series of linked pump diode-laser heads.

100W Laser Configuration



- slab is side-pumped by 520W of fibre-coupled diode lasers
- resonator is stable in the zig-zag (horizontal) direction, unstable in the vertical direction

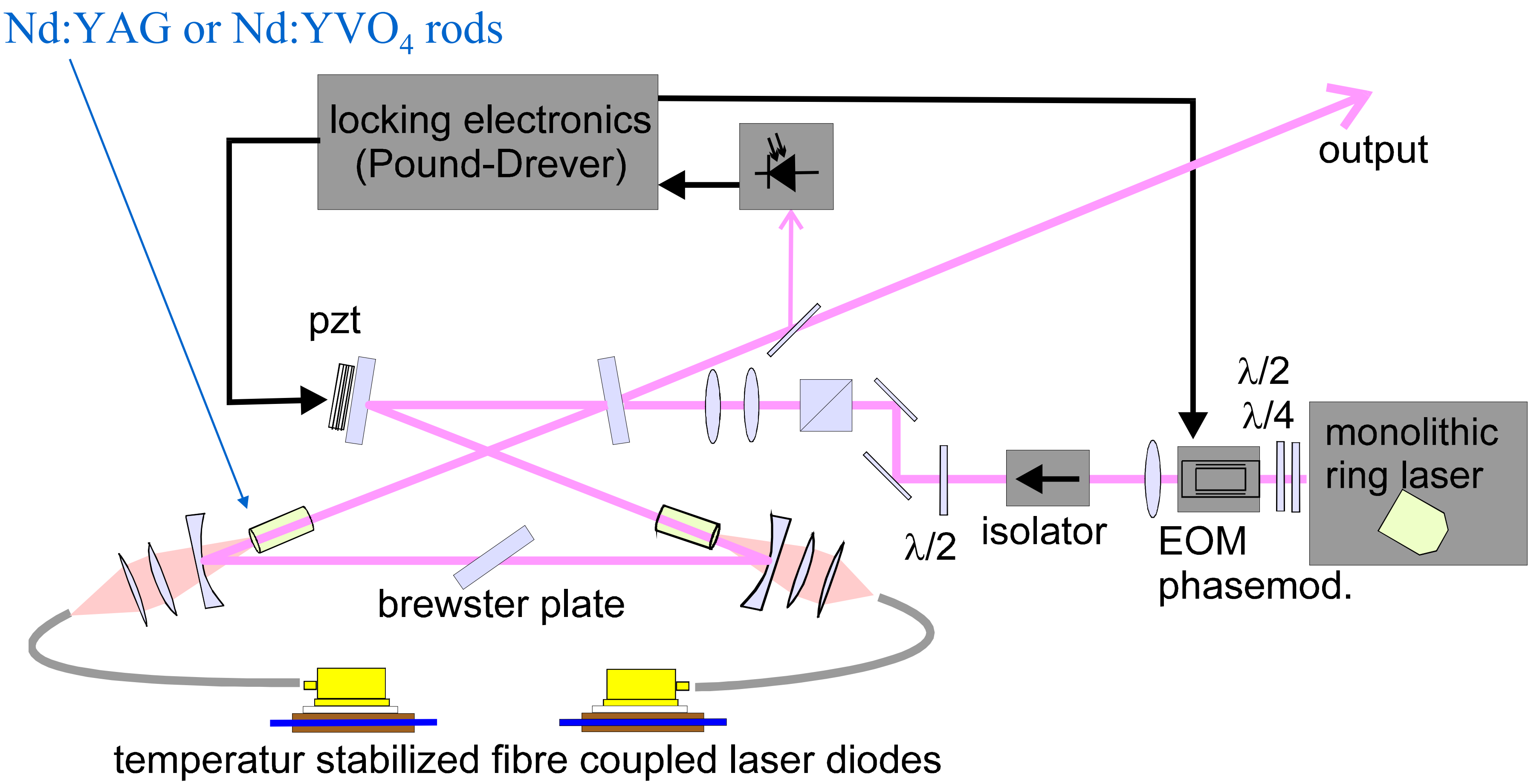
Adelaide University

ACIGA

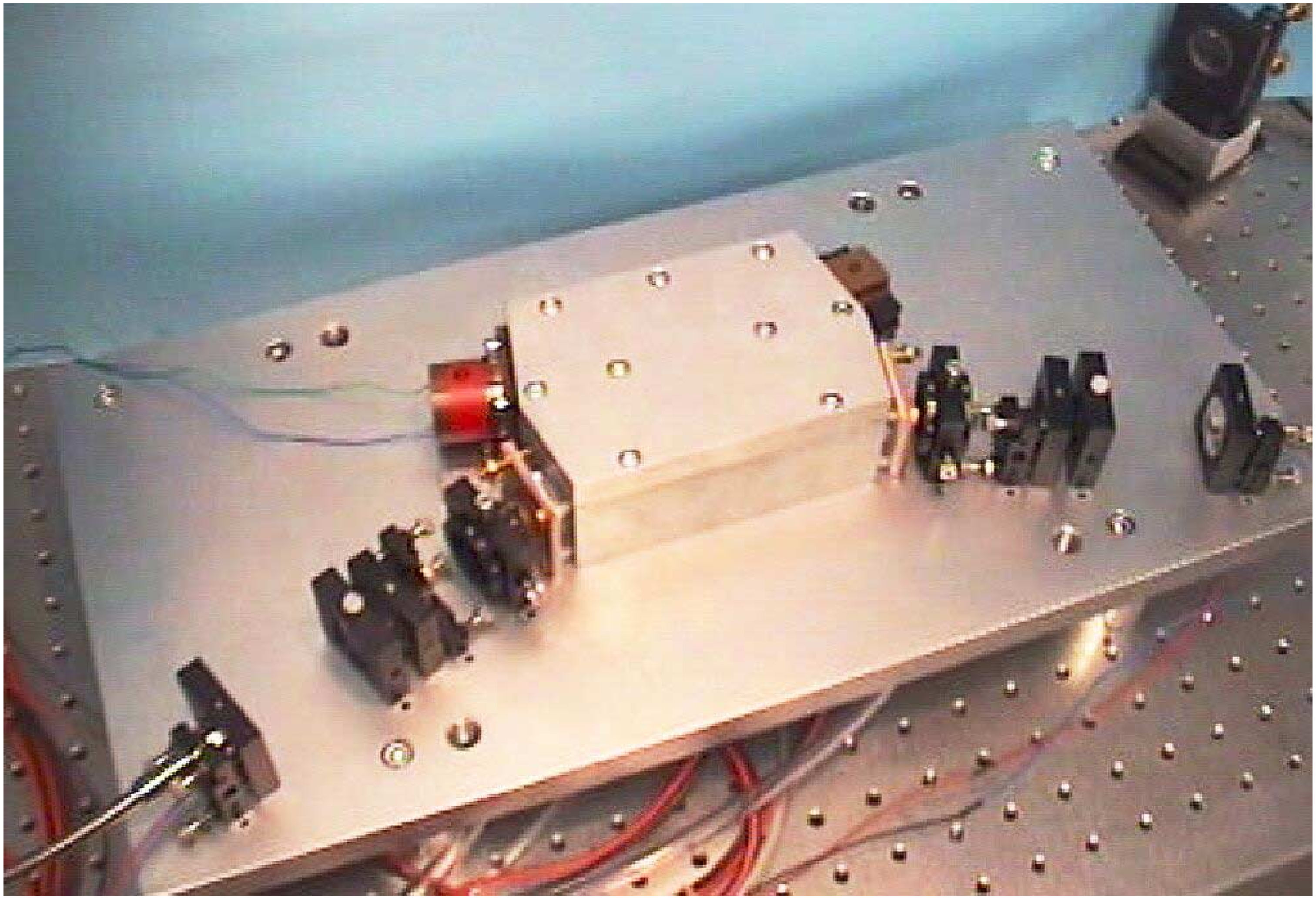
Advanced R&D: High Power Laser
Adelaide Results to Date

- Laser head assembled
  - » initial problems with fibers & birefringence seems to be solved
  - » measurements show the expected slope
  - » Pumping the laser head with ~200W produces a strong vertical thermal lens which makes the oscillator configuration unstable
  - » Reassembling of the laser head with a different side-cooling geometry is planned to solve this problem.
- plan to demonstrate 100 W by 1Q02

Advanced R&D: High Power Laser Hannover Configuration



Advanced R&D: High Power Laser GEO600 Slave Laser



Advanced R&D: High Power Laser Hannover Results to Date

- amplifier design completed
- investigating alternative pump wavelengths (885 nm c.f. 810 nm)
- investigating Nd:$YV0_4$ and Nd:YAG rods
- 100W demonstration by 1Q02

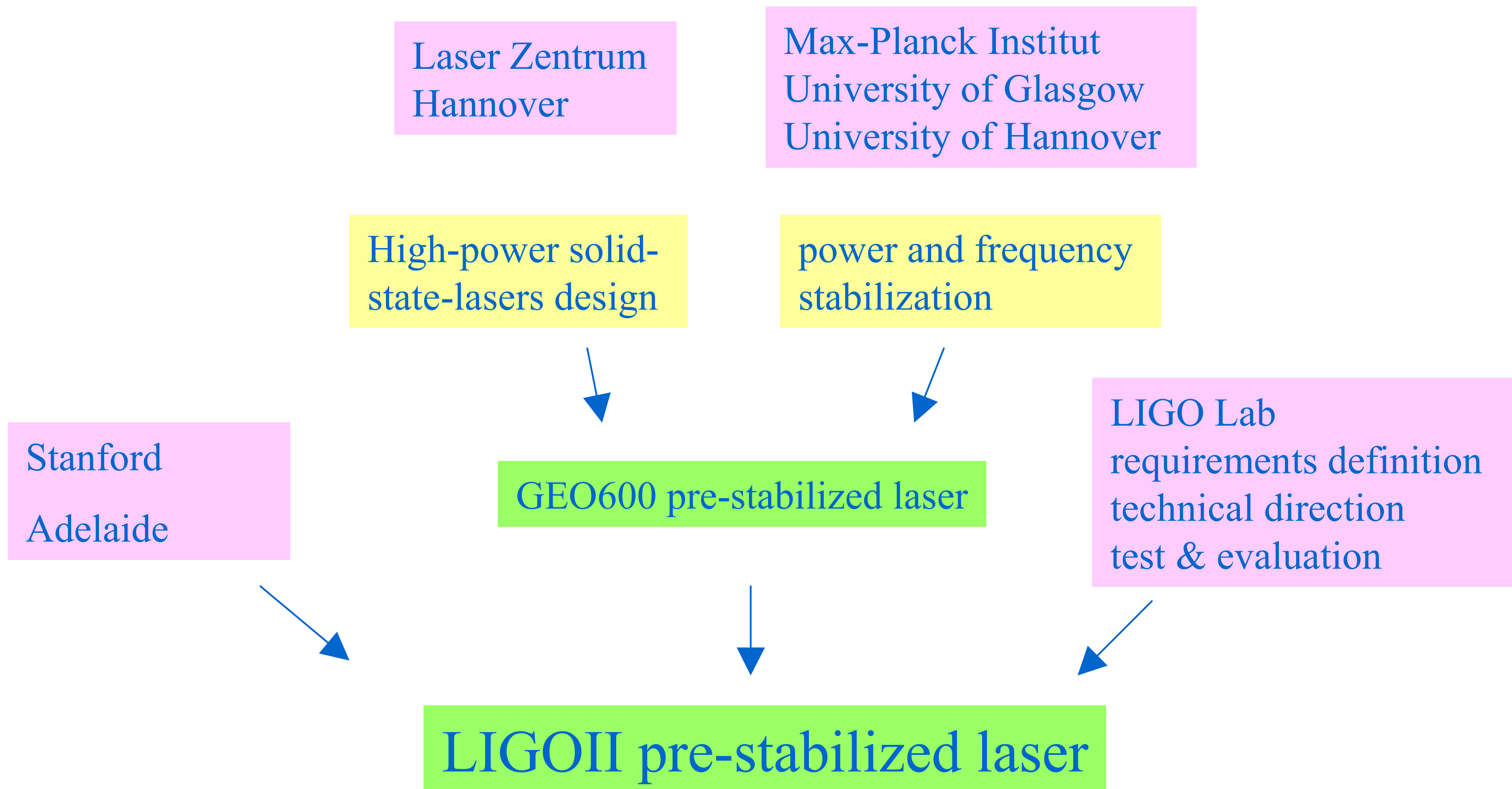
Advanced R&D: High Power Laser Design & Build Laboratory Version

- design reliable laser heads for power stages
- include suitable actuators in laser design
- integrate stabilized front-end, high-power-stages and pre-modecleaner
- design power stabilization (in-loop test)

Advanced R&D: High Power Laser Design & Build Final Version

- optimize design according to lessons learned with lab-version and including system aspects like reliability, safety, robustness, automation and system interfaces (DAQ, power, cooling, ...)
- keep flexibility to react on long-term behavior of lab-version
- Deliver to LASTI (MIT) for integrated mode cleaner testing

Advanced R&D: High Power Laser Team



Advanced R&D: High Power Laser Key Schedule Milestones

• concept phase (100W)	Jan01 - Apr02
• lab-version phase (200W)	Apr02 – Feb04
• longterm test (Hannover/LASTI)	Feb04 – Feb 05
• final version phase	Feb04 – Jul05h

Proposal Request

Includes technical support for R&D

	FY 2002 $M	FY 2003 $M	FY 2004 $M	FY 2005 $M	FY 2006 $M	Total $M
Currently Funded Operations	23.63	24.32	25.05	25.87	26.65	125.52
Increase for Full Operations	5.21	5.20	4.79	4.86	4.95	25.01
Advanced R&D	2.77	2.86	2.95	3.04	3.13	14.76
R&D Equipment in Support of LSC Research	3.30	3.84	3.14			10.28
Total Budgets	**34.91**	**36.21**	**35.93**	**33.77**	**34.74**	**175.57**

Increased Staffing to Support R&D and Modeling

•	Increased staff in the Technical and Engineering Support and Detector Support Groups. The Caltech campus-based support to the observatories declines significantly after the Detector is commissioned. However, the increase for the R&D for an advanced LIGO (planned for installation in 2005-2006) is significant and results in a net increase.	$920,868
•	Increment for engineering and technician labor (4 FTEs) at Livingston to support the LSC science team responsible for Seismic Isolation development. This effort is for two years only and is non-recurring.	$506,300
•	Increased support staff for Modeling and Simulation Group. The increase was suggested by an NSF Review panel.	$282,485

LIGO

R&D Effort

• Stochastic Noise. LASTI integrated system tests of the advanced seismic isolation and suspension prototypes.	$275,222
• Thermal Noise Interferometer. Direct measurement of test mass thermal noise for initial and advanced LIGO designs.	$176,697
• Advanced Core Optics including Sapphire Optics	$283,937
• Advanced Interferometer Sensing and Control including Photodetector Development	$298,779
• Stiff Seismic Isolation System Development	$46,353
• Auxiliary Optics Systems including Active Thermal Control	$366,088
• Advanced Suspensions including Fiber Research.	$208,725
• Improved Low Frequency Strain Sensitivity.	$345,637
• 40-Meter Advanced R&D. Tests of controls and electronics for a signal and power recycled configuration with the read-out scheme and control topology intended for advanced LIGO.	$235,075
• Advanced Controls & System Identification. Research on application of advanced system identification and control concepts to LIGO.	$188,677
• Advanced (highly stabilized) Input Optics Systems.	$347,423

R&D Equipment in Support of LSC Research Program

- Equipment costs for the development of advanced seismic isolation prototypes.
- Equipment costs for the development of multiple pendulum, fused silica fiber suspension prototypes.
- Materials and manufacturing subcontracts to support the development of sapphire test masses and high Q test mass materials and coatings research.
- Investment and non-recurring engineering costs for a large coating chamber and its commissioning
  - » study of coating strategy in progress

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.

Lasers & Optics Research

(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 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 Laboratory 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.

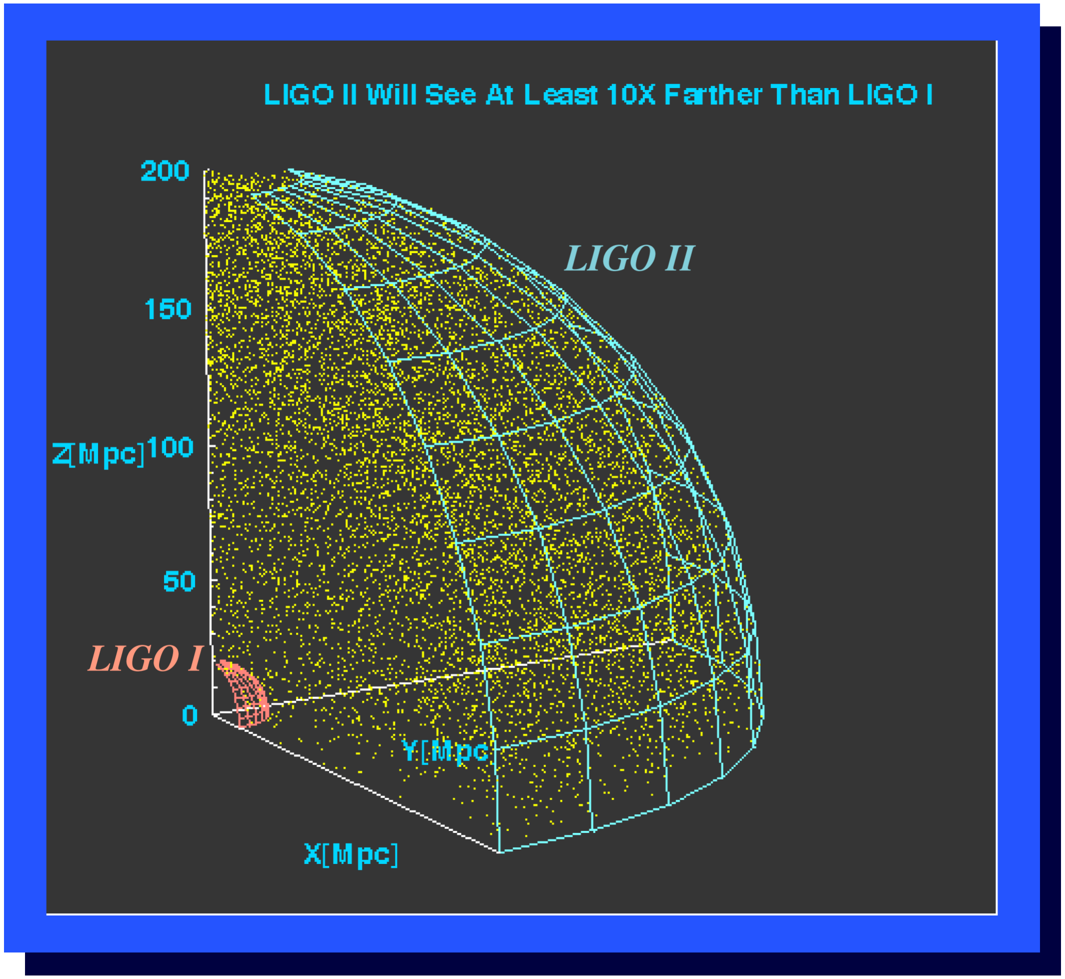
to meet the NSF Counter-proposed Budget

Analysis of Proposal Budget Reductions

NSF_Delta	FY2002 Amount	FY2003 Amount	FY2003 Amount	FY2003 Amount	FY2003 Amount	Total
Baseline	34,910,865	36,214,889	35,930,651	33,770,448	34,739,382	175,566,235
Management Reserve	-232,653					-232,653
Deferred Hiring	-2,375,268		196,000			-2,179,268
Eliminate WAN OC3	-540,500	-542,200	-542,200	-539,500	-539,500	-2,703,900
Defer LSC Suspensions	-300,000		198,117			-101,883
Remove LSC Core Optics	-600,000	-1,971,000	-2,638,000			-5,209,000
Remove Laser Diodes		-450,000				-450,000
Slip Advanced ISC	-190,000	80,750	61,750	47,500		0
Remove Auxiliary Optics	-272,319	-97,381	-51,253			-420,952
Slip Advanced Controls	-188,677	10,982	-44,139	-4,263	-4,391	-230,487
Slip Advanced Input Optics	-347,423	-18,495	57,027	308,891		0
Remove New Outreach	-249,848	-257,343	-265,063	-273,015	-281,206	-1,326,476
Defer LDAS Maintenance	-1,000,000					-1,000,000
Remove LSC Support	-254,678	-262,317	-270,187	-278,293	-286,642	-1,352,117
Miscellaneous Equipment	-359,500					-359,500
Grand Total	**28,000,000**	32,707,885	32,632,703	33,031,768	33,627,643	**160,000,000**

Advanced LIGO Detector Reach

"...2.5 hours of operation will exceed the integrated observations of the 1 year LIGO Science Run..."



Role of LIGO Scientific Collaboration

- The LSC and Lab submitted a White Paper and a Conceptual Project plan in late 1999
  - » this was reviewed by NSF ------------> encouraging current R&D
- This LIGO study sharpened the design and the R&D focus
- **The R&D program has been highly coordinated across the LSC by the Lab and LSC**
  - » **the program is conducted as the early stages of a construction project**
  - » **all R&D tasks are defined in MOU's with the Laboratory**
  - » **systems engineering is carried out**
  - » **the R&D is organized with a detailed cost estimate and schedule**
  - » **monthly coordinating meetings are held to monitor progress**

LSC Participation in Advanced LIGO R&D

Australian Consortium for Interferometric Gravitational Astronomy (ACIGA) *Australian National University (ANU), University of Adelaide (AU), and University of Western Australia (UWA)*	13.5 FTE
Caltech Experimental Gravitational-Physics Group	1.3 FTE
German British Collaboration for the Detection of Gravitational Waves (GEO 600) *University of Hannover, Garching, Albert Einstein Institute in Potsdam, University of Glasgow, and Cardiff University*	17 FTE
Institute of Applied Physics of the Russian Academy of Sciences at Nizhny Novgorod	9.5 FTE
Iowa State University, Eddy-Current Subgroup	0.5 FTE
University of Colorado, JILA Gravity Group	1.5 FTE
Louisiana State University, Experimental Relativity Group	1.5 FTE
Moscow State University	10 FTE
National Astronomical Observatory of Japan TAMA Group	2 FTE
Pennsylvania State University Experimental Relativity Group	4.7 FTE
Department of Physics of Southern University and A&M College	1.5 FTE
Stanford Advanced Gravitational Wave Interferometry Group	12 FTE
Syracuse University Experimental Relativity Group	4 FTE
University of Florida Laser Interferometric Gravitational Wave Group	2.5 FTE

Major International Roles in Advanced LIGO

- GEO (UK, Germany) project has joined the LSC
  - » Initial LIGO involvement is in data algorithms and analysis
  - » advanced LIGO involvement includes leading roles in suspensions, configurations, prestabilized laser.
  - » GEO is proposing a capital contribution/partnership in construction of adv. LIGO
    - – ~$6M USD from UK
    - – ~$6M USD from Germany
- ACIGA project has joined LSC
  - » Initial LIGO involvement is in data algorithms and analysis
  - » advanced LIGO involvement includes laser development, sapphire development and high power issues
  - » ACIGA is proposing a capital contribution/partnership in construction of adv. LIGO
    - – ~$2.5M USD
- Recent discussions have begun with Virgo on collaboration in coating development and in joint data taking and data analysis

Approach to Interferometer Upgrades

- Gravitational wave interferometers are “point” designs
  - » substantial improvements in performance are difficult to achieve with incremental upgrades
  - » lowering one noise floor encounters another
  - » changing the performance of one subsystem causes system mismatch with other subsystems
- Installing an interferometer into the vacuum system is a major campaign
  - » much of the campaign overhead is encountered even with subsystem upgrades
- Installing an interferometer has a high cost in missed scientific opportunity

Upgrade should be a major increase in sensitivity

R&D Program Approach to Risk Reduction

- All significant risks are planned for measurement or verification during the proposed program
- Faithful prototypes of advanced LIGO subsystems are fully tested in parallel to operating LIGO
- Goal is to fully qualify all designs before installing in LIGO vacuum system
  - » 40 Meter qualifies controls system
  - » LASTI qualifies the isolation/suspension system and the prestabilized laser/input optics systems
  - » GinGin & UFL research addresses risks associated with high power
- Installation into LIGO vacuum system occurs when new systems are fully ready and qualified

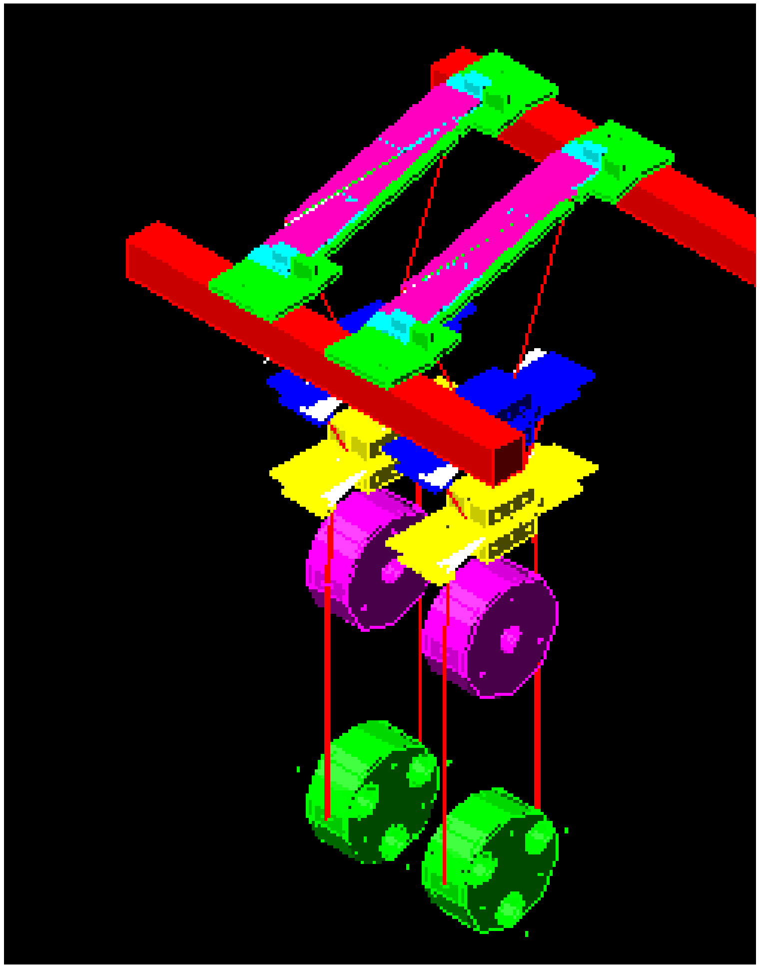
Development Plan

- R&D including Design through Final Design Review
  - » for all long lead or high risk subsystems
  - » LIGO Lab contracts and funds large R&D equipment in 2001-2004
  - » Substantially complete by 2004, tests into 2005
  - » Some long lead purchases occur as early as 2003, esp. COC
    - – NSF budget reduction from request puts this in jeopardy
- Isolation Test Bed (LASTI)
  - » full scale, integrated suspensions & seismic Isolation testing
  - » in-chamber assembly & installation procedure check-out
  - » possible first article test bed
- Integrated Systems Tests
  - » Pre-Stabilized Laser (PSL), Input Mode Cleaner, Suspensions and Seismic Isolation Test at LASTI
  - » Controls & read-out proof-of-concept at GEO 10m in 2002-2003
  - » Integrated Servo Control Electronics Testing at the LIGO 40m Lab
  - » High power system testing at the GinGin facility
  - » Possibly early End Test Mass Suspension & Seismic Isolation replacement at a LIGO Observatory

Development Plan

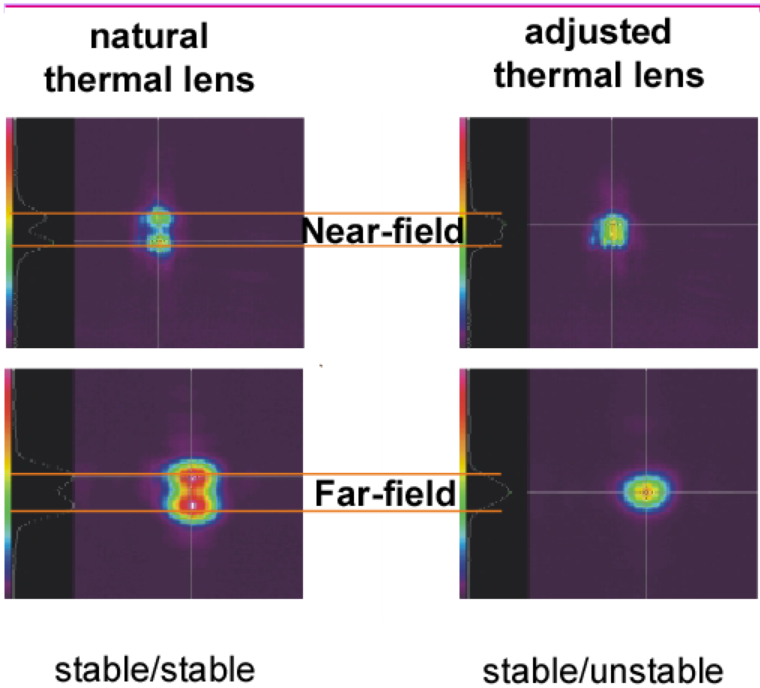
- Construction Phase Proposal
  - » Major Research Equipment (MRE) funding for construction
  - » includes ‘prosaic’ design efforts
  - » Assembly and test outside vacuum system in 2005
  - » Installation:
    - – Minimum of a 1 year of Integrated Science Run Before a Major Upgrade
    - – Schedule to be Coordinated with International GW Observatories to Keep ≥ 2 Detectors Operating
    - – Start Installation Only When Production & Assembly Pipeline Will Not Limit the Installation Schedule
    - – Install One Advanced LIGO Interferometer and Incorporate Lessons Leaned into the Subsequent Advanced Interferometers (time lag of ~ 18 months)

Subsystem Development Plan Highlights



- Core Optics
  - » sapphire material development with Crystal Systems & SIOM
  - » joint mechanical & optical material test matrix in development
  - » spot polishing to compensate for inhomogeneity
  - » coating facility development & low absorption research (MLD & Virgo/Lyon)
- Seismic Isolation
  - » Full scale, HAM-type technology demonstrator @ ETF, Stanford
  - » Full scale prototypes (HAM & BSC types) @ LASTI, MIT
- Suspension
  - » U. of Glasgow/GEO takes the lead to PDR, LIGO Lab leads in Final Design
  - » Triple & quad pendulum 'controls' & 'noise' prototypes tested with the SEI prototypes at

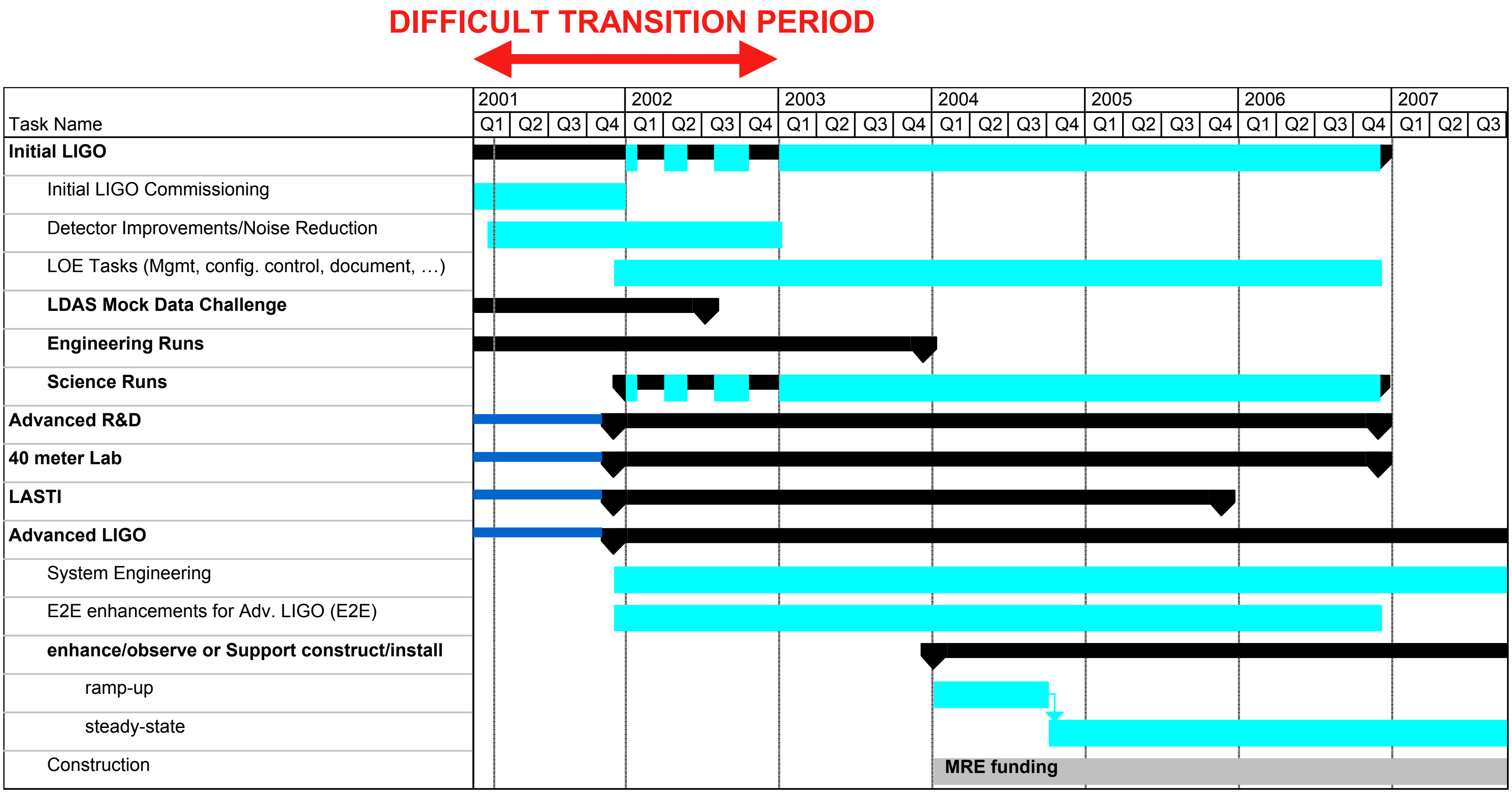
Development Plan Highlights (continued)



- Laser
  - » 3 alternative approaches in trade study
  - » Laser Zentrum Hannover/GEO to take lead; LIGO Lab supplies requirements, interface, and test
  - » Intensity stabilization research at CIT
- Input Optics System (IOS)
  - » University of Florida takes lead, GEO suspensions, LIGO controls
  - » UFL performs enabling high power research on modulators & isolators
- Auxiliary Optics System (AOS)
  - » Substrate thermal focus compensation research @ MIT
  - » Photon actuator for test mass @ CIT
- Interferometer Sensing & Control (ISC)
  - »Shift to ‘DC readout’ (relaxes laser frequency stabilization requirements)
  - »Requires both proof-of-principle (GEO 10m) and precision testing (40m)
  - »High power system testing at the GinGin facility
  - »LIGO Lab leads, with contributions from LSC, esp. GEO

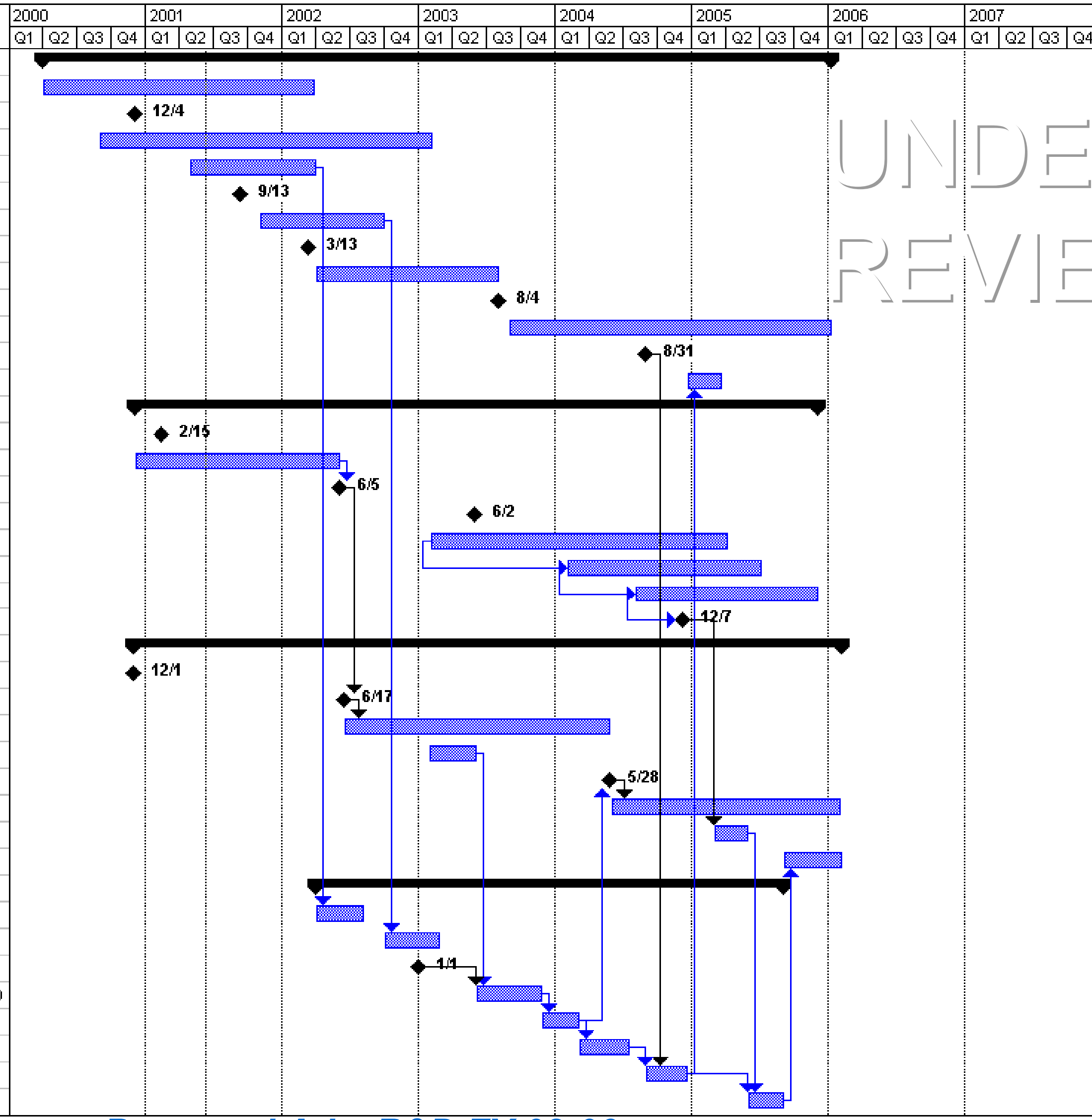
Advanced LIGO Major Research Equipment (MRE):

Overall Proposed Schedule

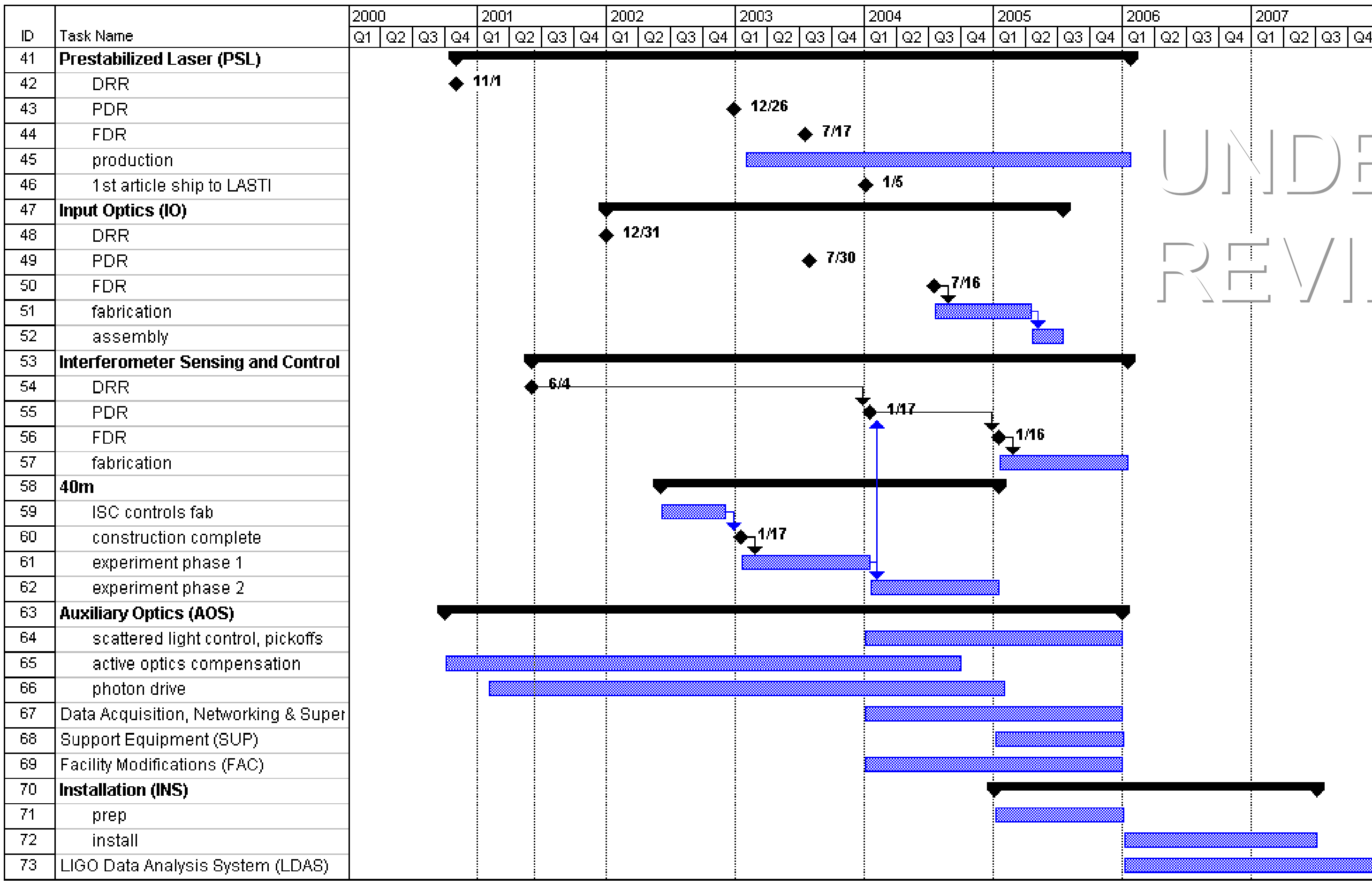


DRAFT Summary Schedule R&D → MRE

ID	Task Name
1	**Seismic Isolation (SEI)**
2	prototype
3	DRR
4	Prelim Design
5	pathfinder fab (HAM)
6	PDR (HAM)
7	pathfinder fab (BSC)
8	PDR (BSC)
9	Final Design
10	FDR
11	production
12	first article avail
13	first article rework
14	**Core Optics Components (COC)**
15	DRR
16	Pathfinder-II
17	PDR/ select Sapphire or FS
18	FDR
19	blanks
20	polish
21	coat
22	IFO1 set avail from QA
23	**Suspension (SUS)**
24	DRR
25	PDR
26	Final Design
27	'noise' prototype fab
28	FDR
29	production
30	first article assy
31	Rework/IFO1 Assy complete
32	**LASTI Experiments/Tests**
33	HAM SEI stand-alone testing
34	BSC SEI stand-alone tests
35	'noise' optics ready
36	assy/instal/test 'noise' SUS proto
37	cavity tests
38	PSL-MC Integ Test
39	SEI 1st Article Test
40	SUS 1st Article Test



DRAFT Summary Schedule R&D → MRE



UNDER REVIEW

Advanced LIGO Major Research Equipment (MRE): MRE Proposal Status

- Technical proposal for advanced LIGO was submitted as part of the Operations and R&D renewal grant proposal
- What remains is basically a costing & schedule estimating exercise
- Initial bottoms-up cost and schedule estimate will be completed in Aug 01
  - » Subsystem by subsystem
  - » Building a data base for the WBS and basis of estimate
  - » Integrating the subsystem schedules
- Major Decisions/Issues to resolve:
  - » 2 or 3 interferometers to upgrade (cost driven decision)
  - » Potentially curtail sapphire development program to reduce cost risk (only if overall costs warrant this action)
  - » Phased implementation for high power (to reduce development risk & cost)

Advanced LIGO Proposal (FY2004 MRE funding start)

- Aug 2001 LIGO Lab MRE Cost Estimate Completed
- Oct 2001 Final MRE Proposal from the LIGO Lab
- Nov 2001 NSF Panel Review
- Nov 2002 NSB approval

The LIGO Lab will continue to work very closely with the larger LSC to prepare and present the MRE proposal to the NSF