Advanced LIGO 2002-2006

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Aspen 2001

Overview

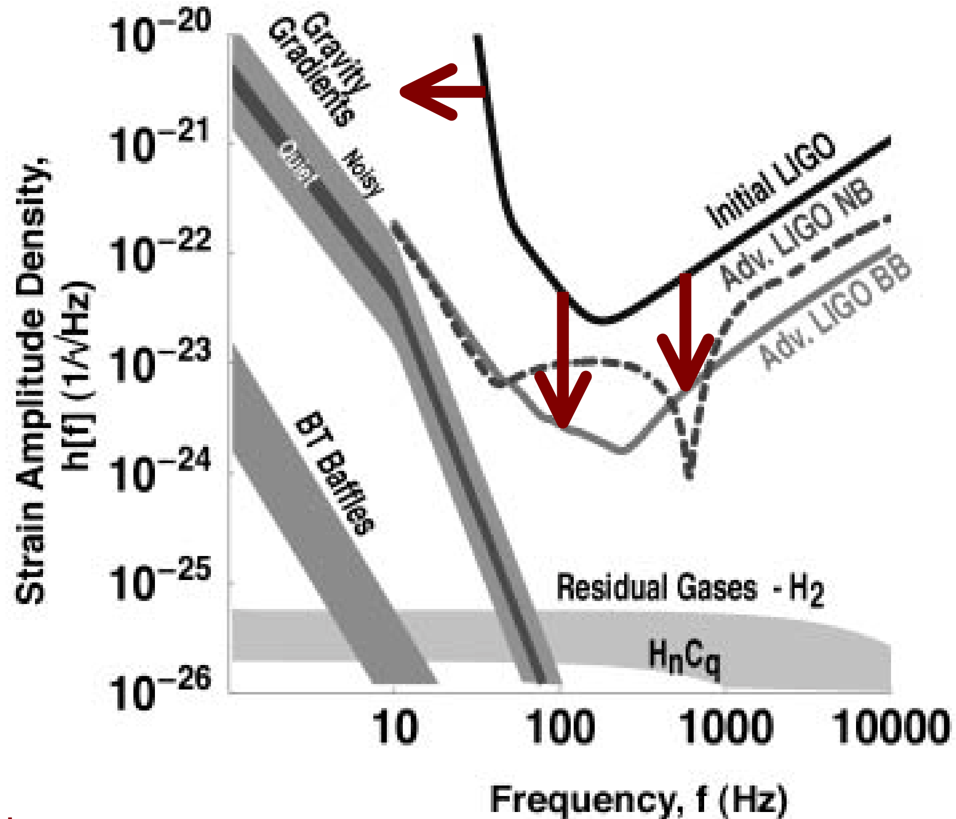
- Evolution intrinsic to LIGO mission
- Next step in detector design:
  - » Should be of astrophysical significance whether it observes gravitational wave signals or if it does not
  - » Should be at the limits of reasonable extrapolations of detector physics and technologies
  - » Should lead to a realizable, 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
  - » LSC working groups determine the direction of the Lab

Choosing an upgrade path

- Wish to maximize astrophysics to be gained
  - » Must fully exploit initial LIGO: no change before 2005-2006
  - » 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 which have taken place since initial LIGO design ‘frozen’ (~1995)
  - » ‘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
  - » Configurations: non-transmissive systems
  - » Not the focus of next LIGO, but exploration must be started now

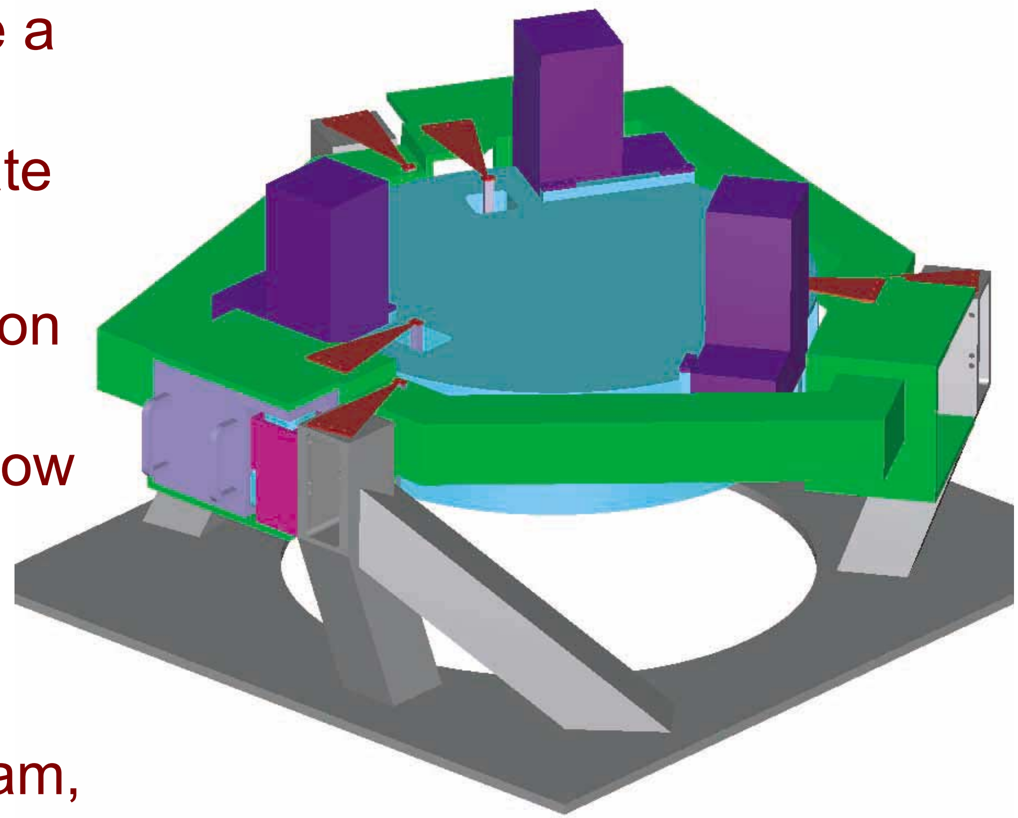


System trades

- Lower frequency cutoff
  - » 'Firm', likely, and possible astrophysics as input, and…
  - » Technology thresholds in isolation and suspension design
- Test mass material
  - » Sapphire: better performance, but development program, anisotropic nature
  - » Fused silica: familiar, but large, expensive, poorer performance
- 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

Seismic Isolation

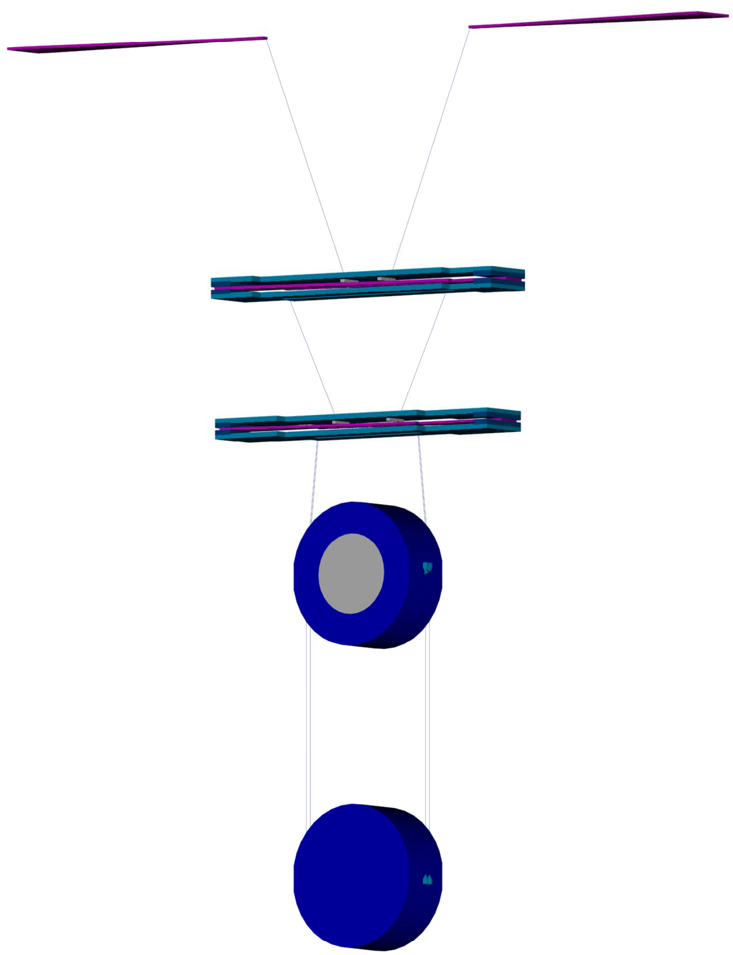
- Goals: render seismic noise a negligible limitation to GW searches; reduce or eliminate actuation on test masses
- High-gain servos bring motion to sensor limit in GW band, reach RMS requirement at low frequencies
- Similar designs for BSC, HAM vacuum chambers
- Later talks by Lantz, Hardham, Hammond



Suspensions

- Adopting a multiple-pendulum approach, based on GEO design
  - » Allows lowest thermal noise from suspension and test mass
  - » replacement of steel suspension wires with fused silica ribbons
  - » 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
- Schedule highlights:
  - » 2Q01: Install first fused silica GEO-600 suspension
  - » 2Q02: Controls prototypes complete, in testing
  - » 2Q03: Noise prototypes complete, in testing

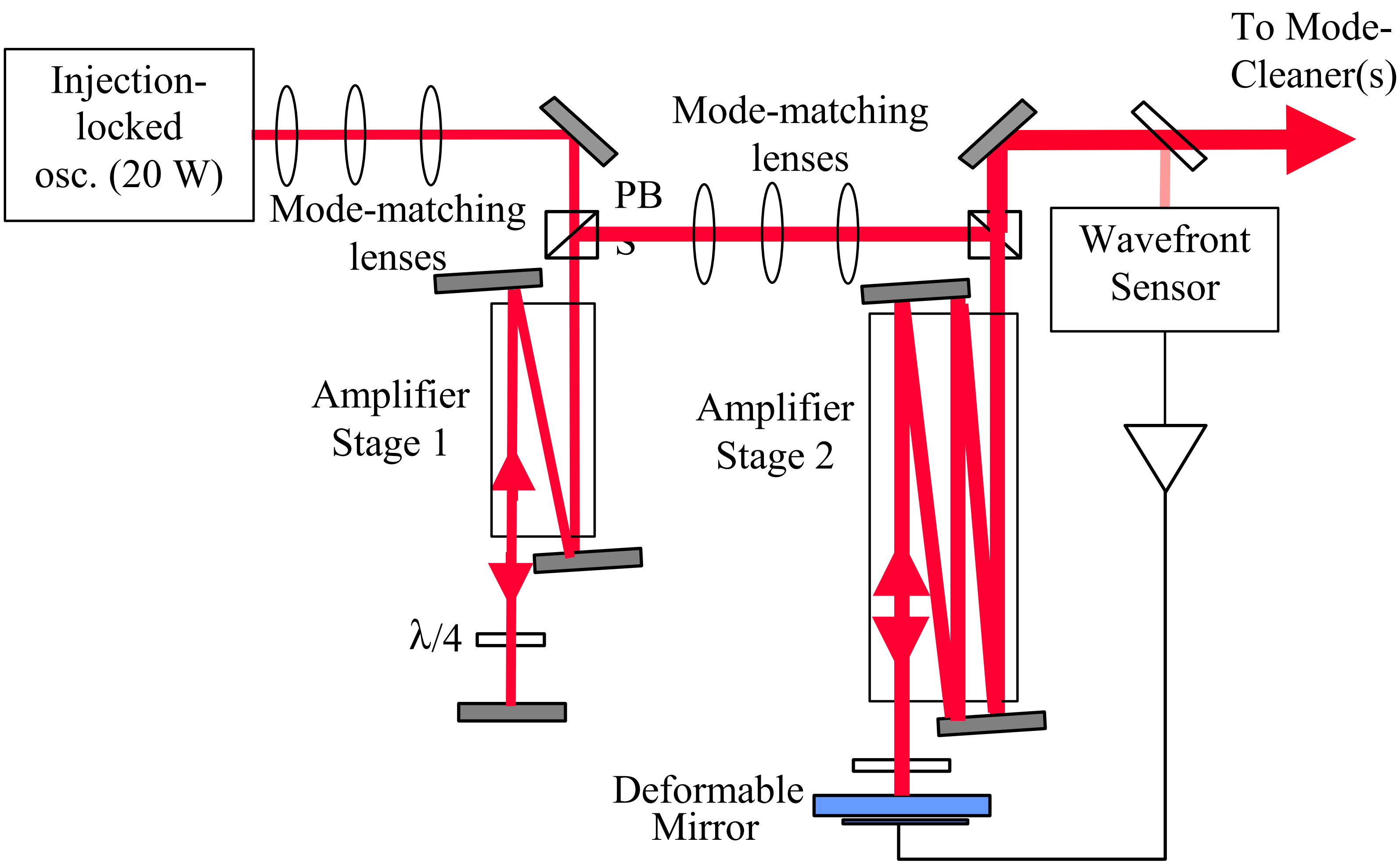
GEO suspension



Laser

- 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 in partnership with LIGO Lab – Benno Willke
- Schedule highlights:
  - » 1Q02: 100 W demonstration
  - » 2Q02: Laser concept downselect
  - » 2Q04: Install advanced LIGO PSL in the LASTI facility

Advanced Laser – One Concept

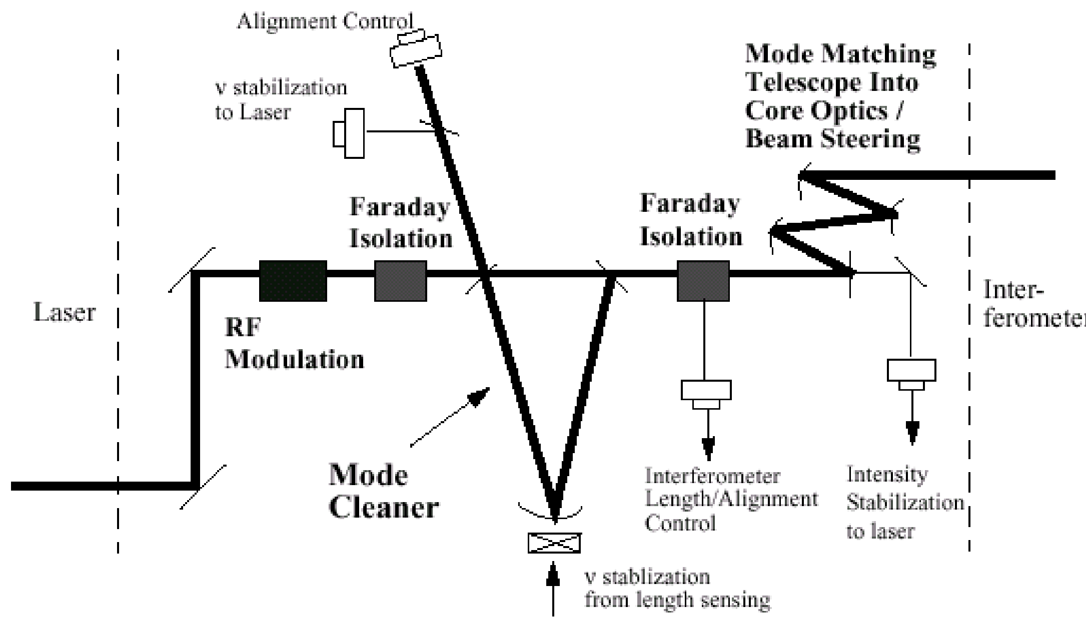


Core Optics

- 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
- Later talk by Jordan Camp, related discussions on coating loss

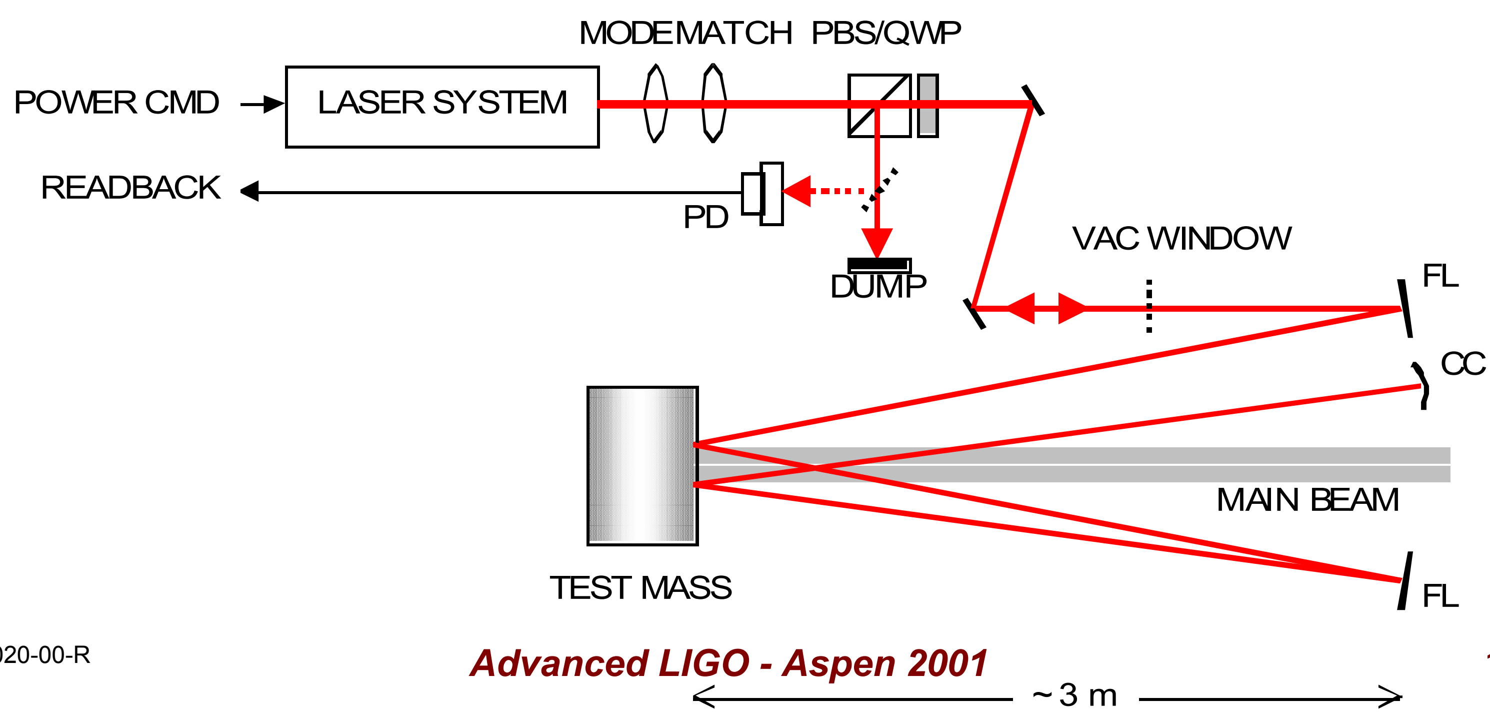
Input Optics

- 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: matching crystals reversed fields to cancel distortion
  - » Modulators: 'side-arm' with full modulation on partial power beam
- University of Florida takes lead



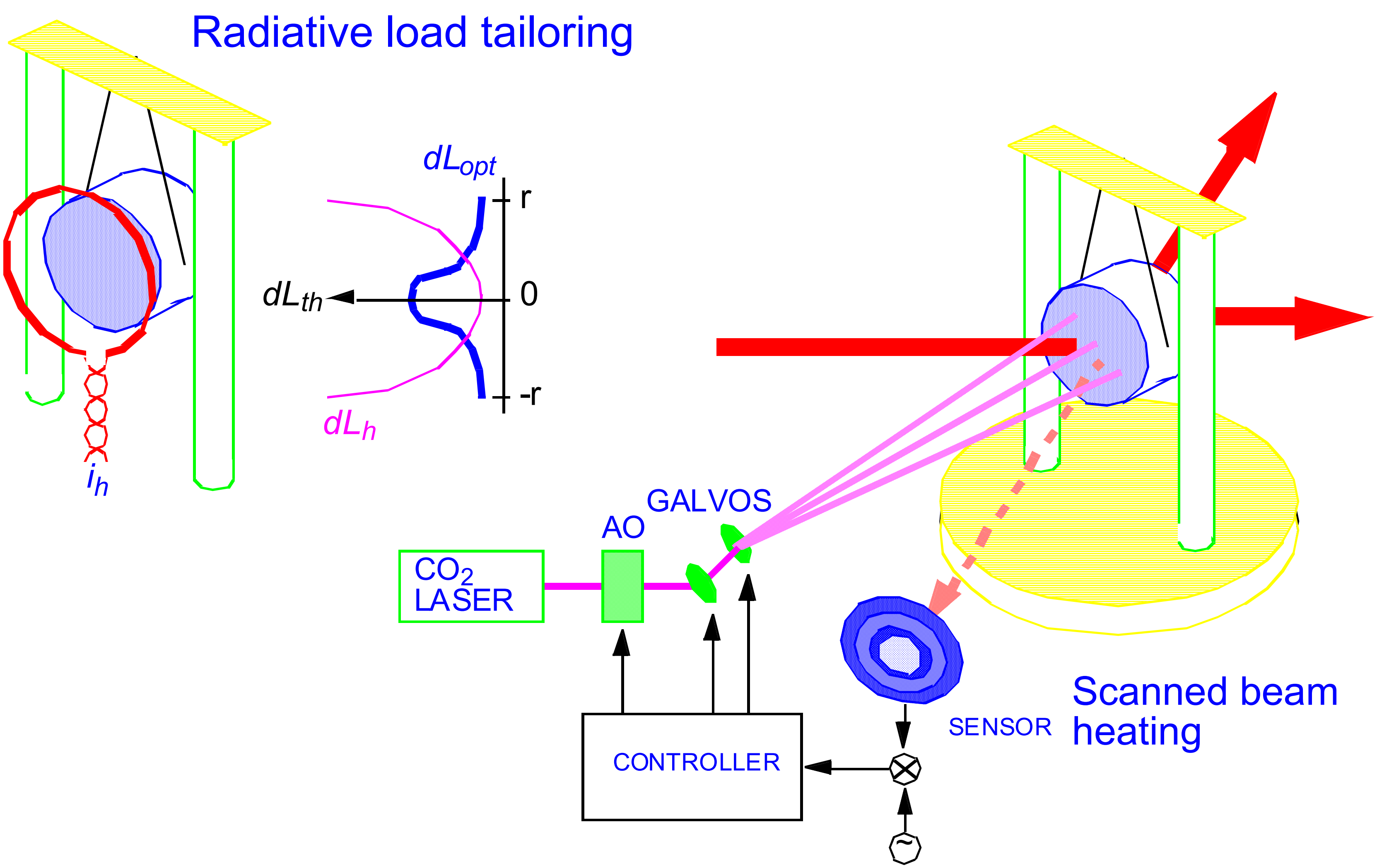
Photon Actuator

- Photon actuator for input test mass
- non-invasive approach to final trim forces (micronewtons)
  - » Avoids thermal noise risks and mechanical complications of electrostatic actuators
  - » …but is a development project in its own right!



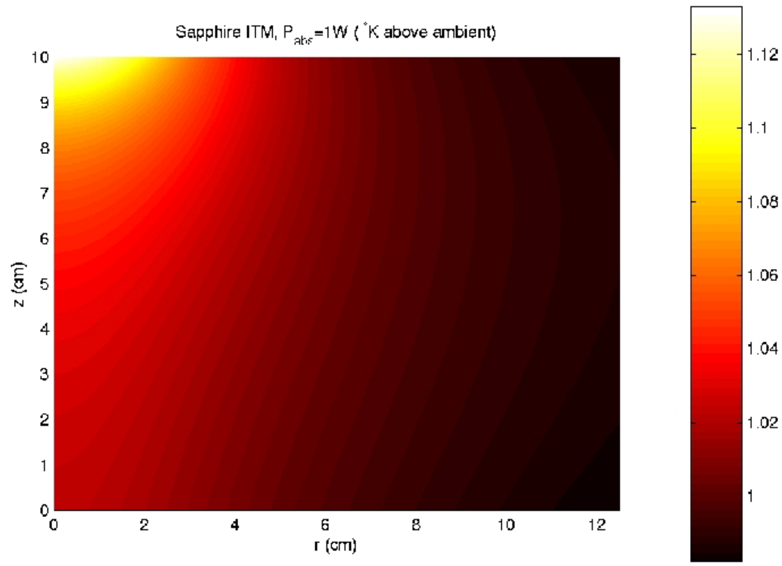
Thermal Compensation

to correct for laser-induced lens in substrate

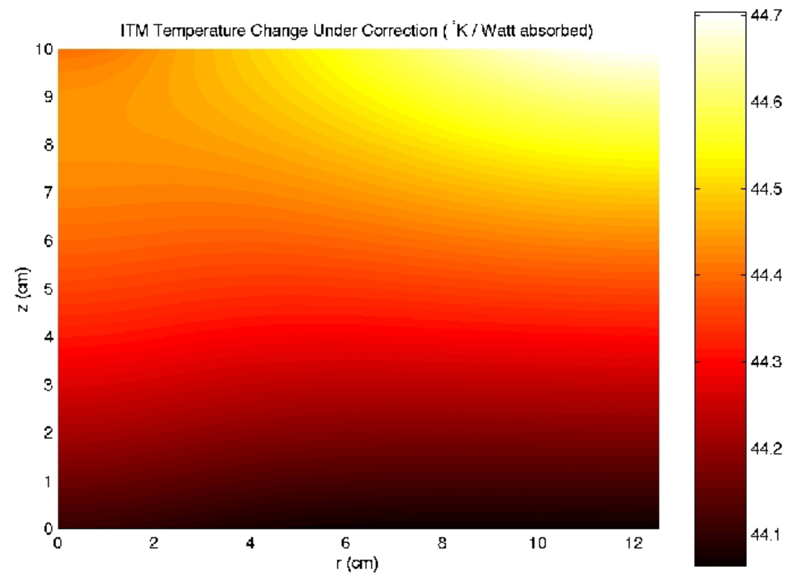


Thermal Compensation

- 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



No compensation

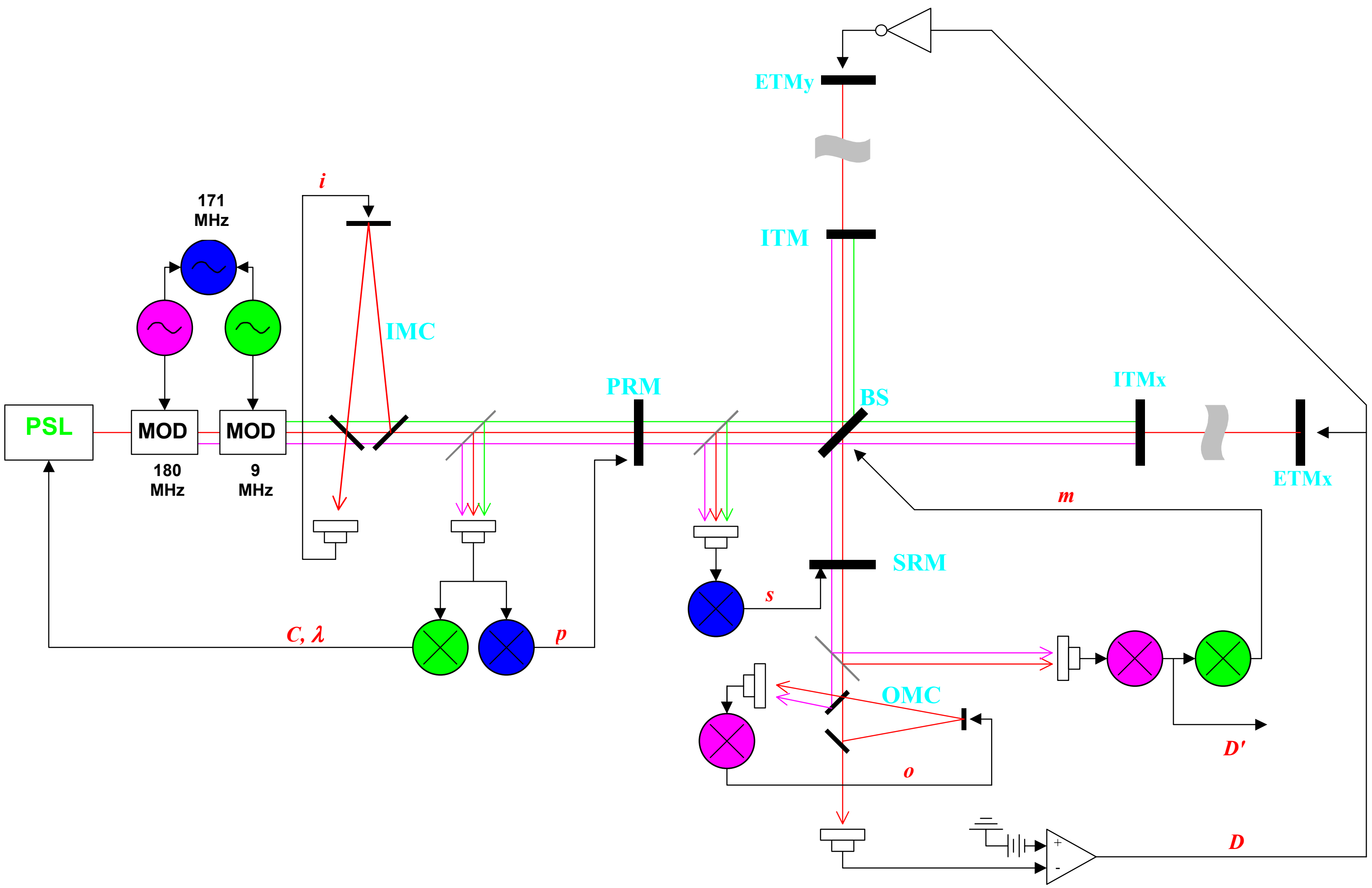


Ring compensation

Advanced Interferometer Sensing & Control (ISC)

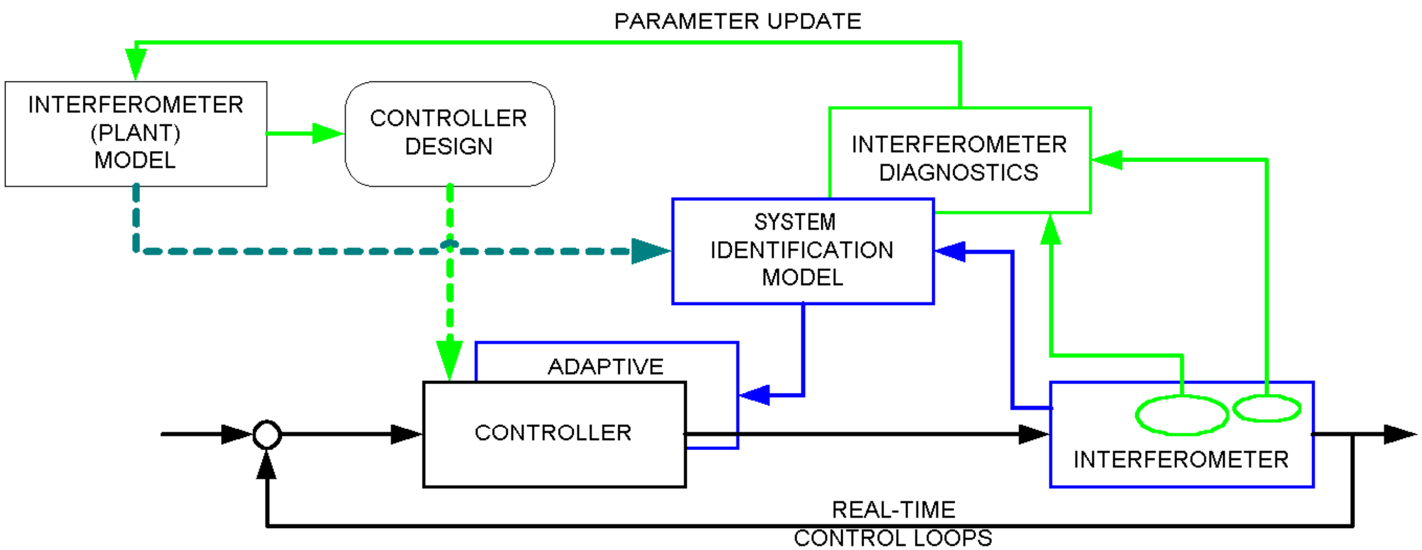
- Responsible for the GW sensing and overall control systems
- Addition of signal recycling mirror increases complexity
  - » Permits ‘tuning’ of response to optimize for noise and astrophysical source characteristics
  - » Requires additional sensing and control for length and alignment
- Possible shift to ‘DC readout’
  - » Rather than RF mod/demod scheme, shift interferometer slightly away from dark fringe; relaxes laser requirements, needs photodiode development;
  - » choice depends on unified quantum noise modeling – later talk by Buonanno and Chen
- Addition of Output Mode Cleaner (reduce power load on photodiode)
- Overall system requires both proof-of-principle (GEO Glasgow 10m) and precision testing (40m)
- LIGO Lab leads, with contributions from LSC, esp. GEO

Interferometer layout



Advanced Controls & System Identification (SID)

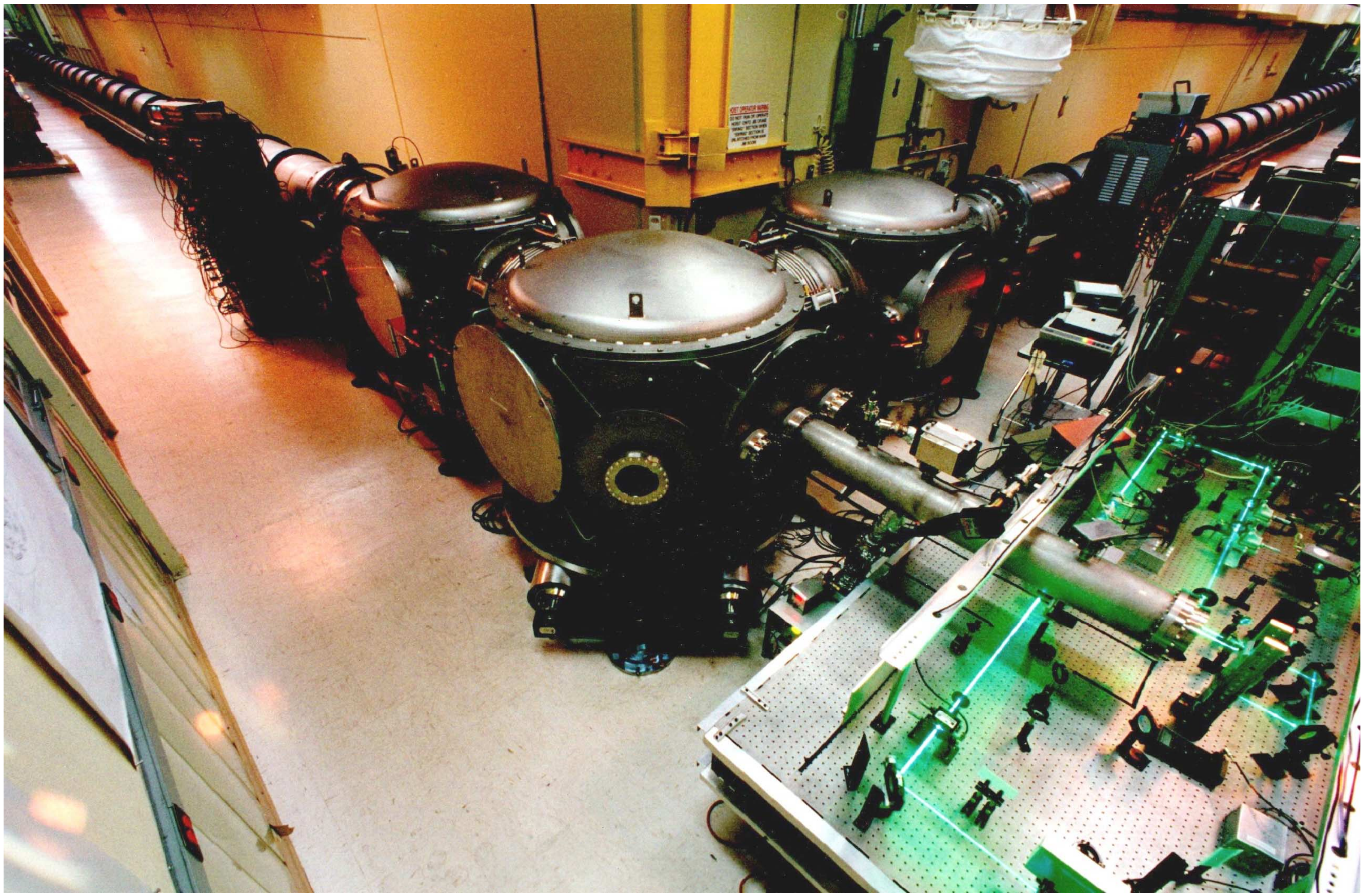
- Modern controls approach to optimization of system
- Interfaces to existing infrastructure
- Allows both noise performance and robustness to be explored
- Leads to Adaptive Control for continuous optimization
- To be applied to LIGO I, 40m RSE experiment, Advanced LIGO



40 m RSE Experiment

- 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
  - » 2Q04: LIGO 40 m configurations research completed; further characterization studies & ISC prototype testing continues

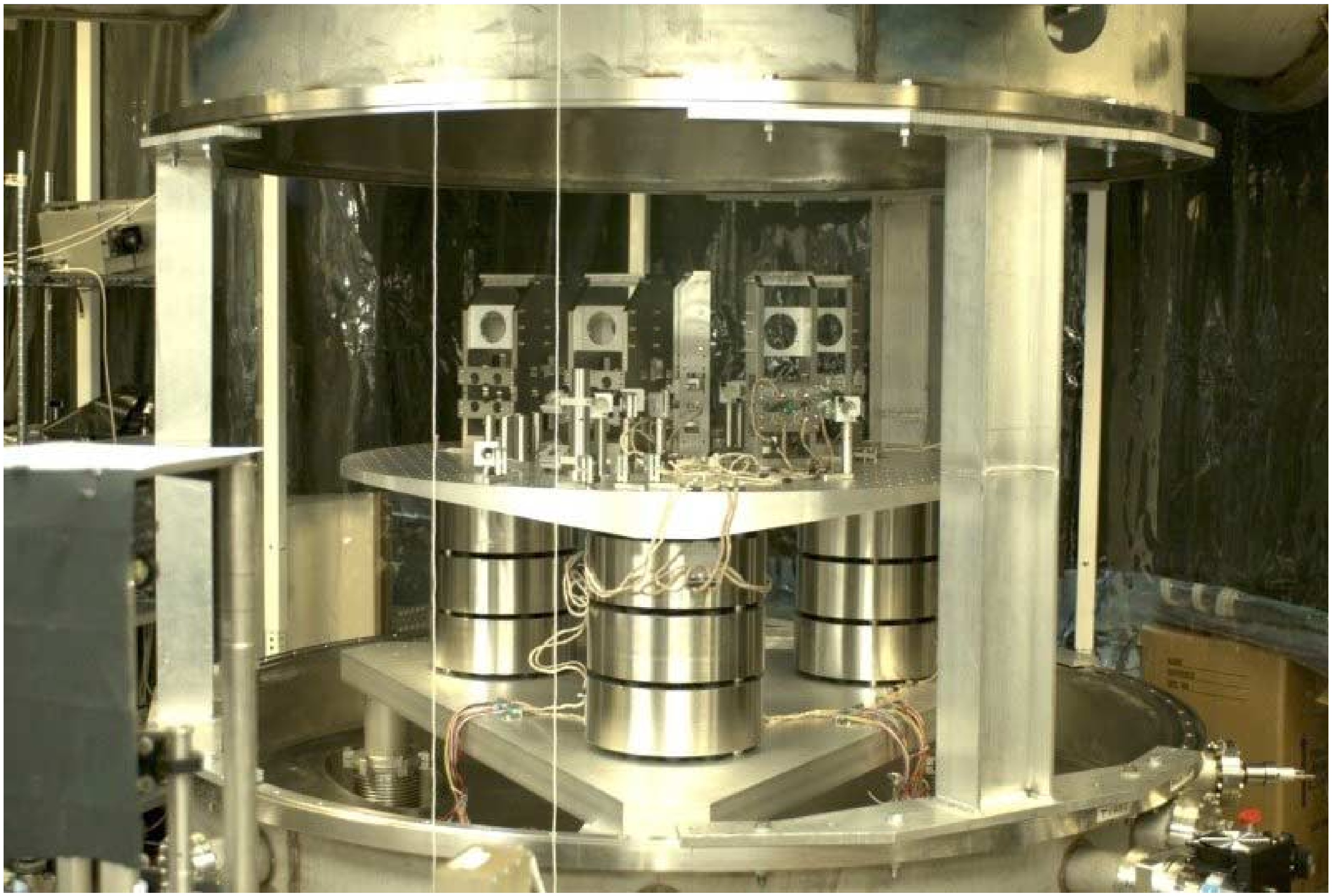
40m Interferometer



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
- Progress and plans:
  - ✓ 4Q00: TNI cavity locks
  - » 2Q01: TNI studies for initial LIGO completed
  - » 2Q02: Sapphire substrates installed
  - » 1Q03: TNI final Sapphire results
- Talk later by Eric Black

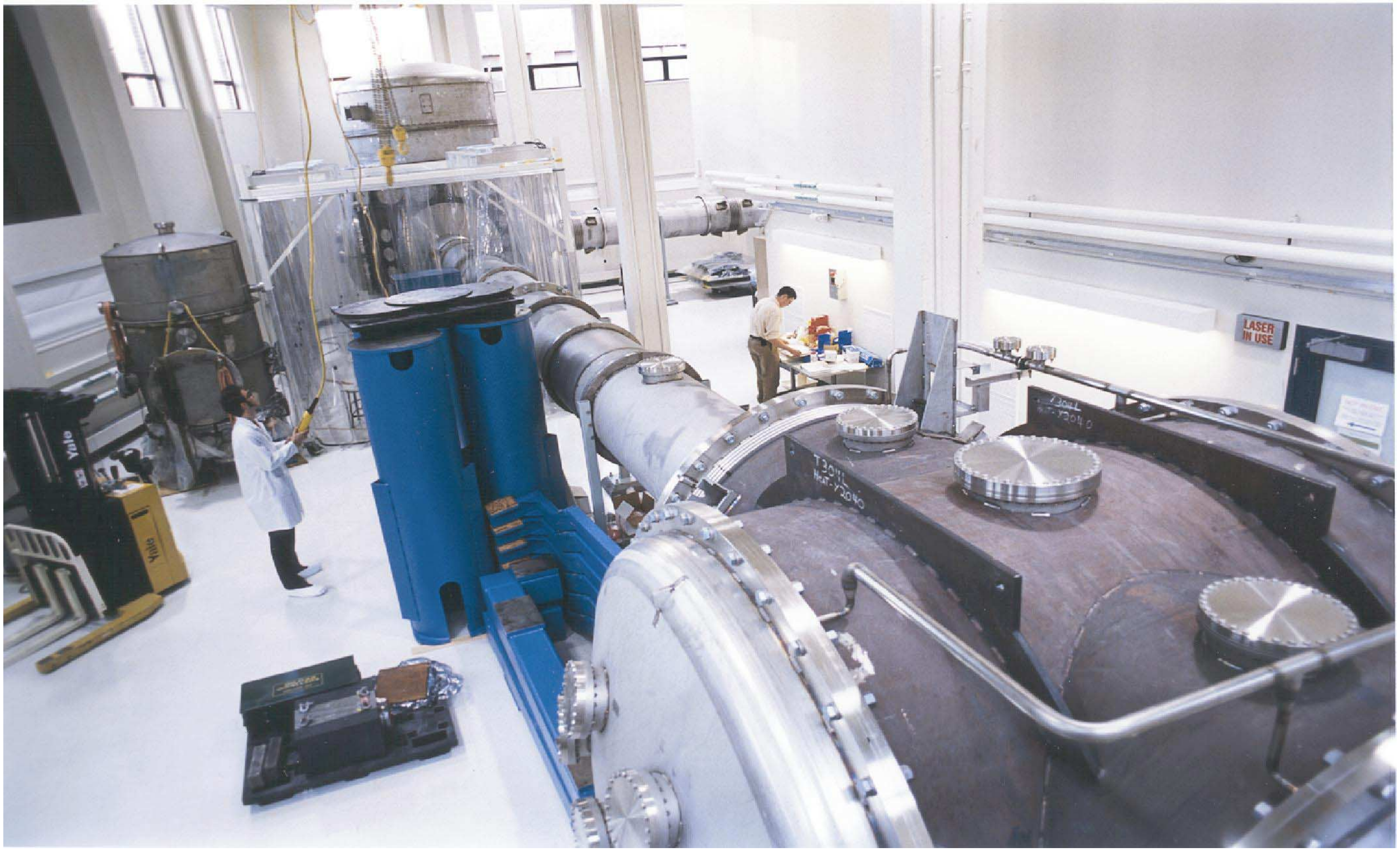
Thermal Noise Interferometer



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, collaborative shakedown and test
- Progress and plans:
  - ✓ 4Q00: Vacuum system qualified, seismic supports in place.
  - » 3Q02: HAM isolation testing completed.
  - » 2Q03: Suspension noise prototypes installed.
  - » 2Q04: Integrated Isolation/suspension testing completed.
  - » 1Q05: PSL-Mode Cleaner integrated performance test

LASTI Laboratory

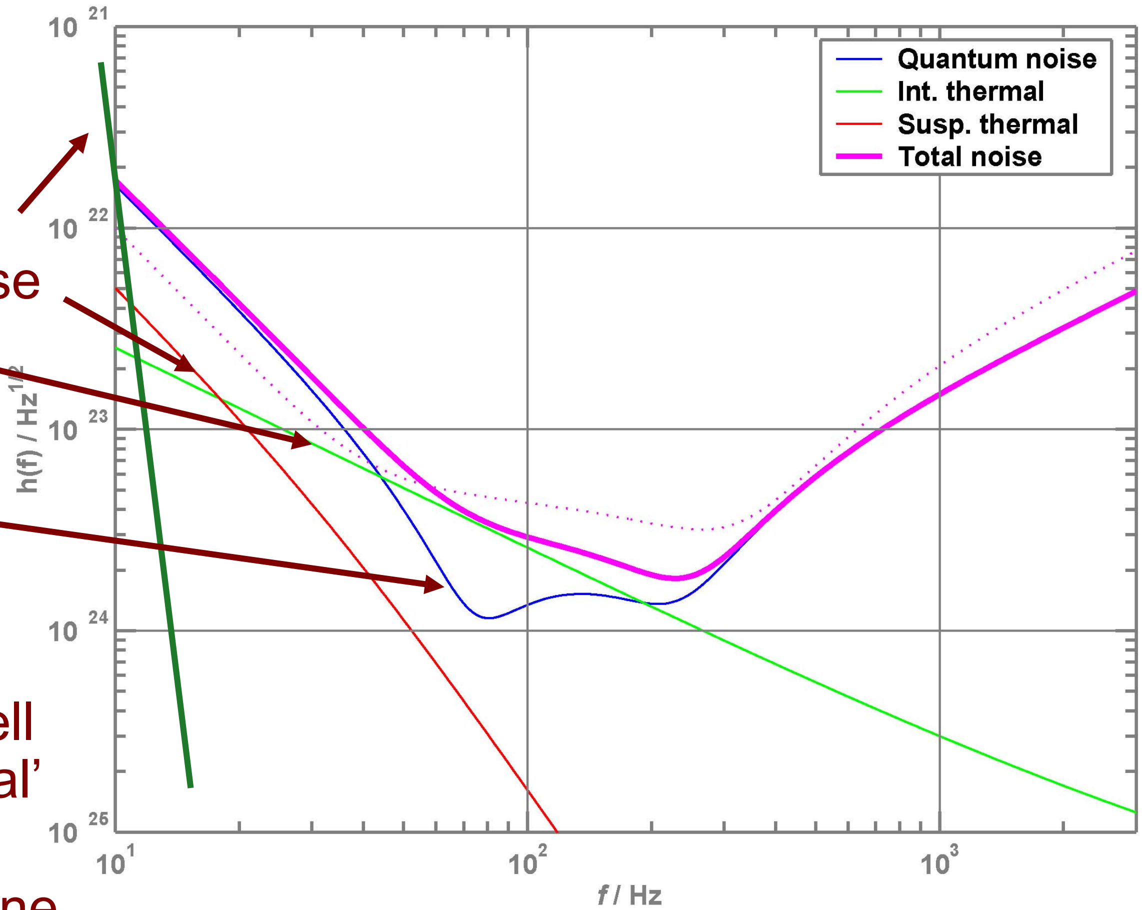


Nominal Advanced LIGO top level parameters

	Advanced LIGO	Initial LIGO
Fabry-Perot arm length	4000 m	
Laser wavelength	1064 nm	
Optical power at interferometer input	125 W	6 W
Power recycling factor	17	50
FP Input mirror transmission	0.5%	3.0%
Arm cavity power	830 kW	42 kW
Power on beamsplitter	2.1 kW	0.5 kW
Signal recycling mirror transmission	6.0%	NA
Signal recycling mirror tuning phase	0.12 rad	NA
Test Mass mass	40 kg	10 kg
Test Mass diameter	32 cm	25 cm
Beam radius on test masses	6 cm	4 cm
Neutron star binary inspiral range (Bench)	300 Mpc	25 Mpc
Stochastic GW sensitivity (Bench units)	8 x 10-9	1 x10-5

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



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 throughout the LSC
  - » 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

Advanced LIGO

- With the initial LIGO commissioning, operation, and observation plan, the Advanced LIGO 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.**