# Advanced LIGO

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NSF LIGO Review

23 October 2002

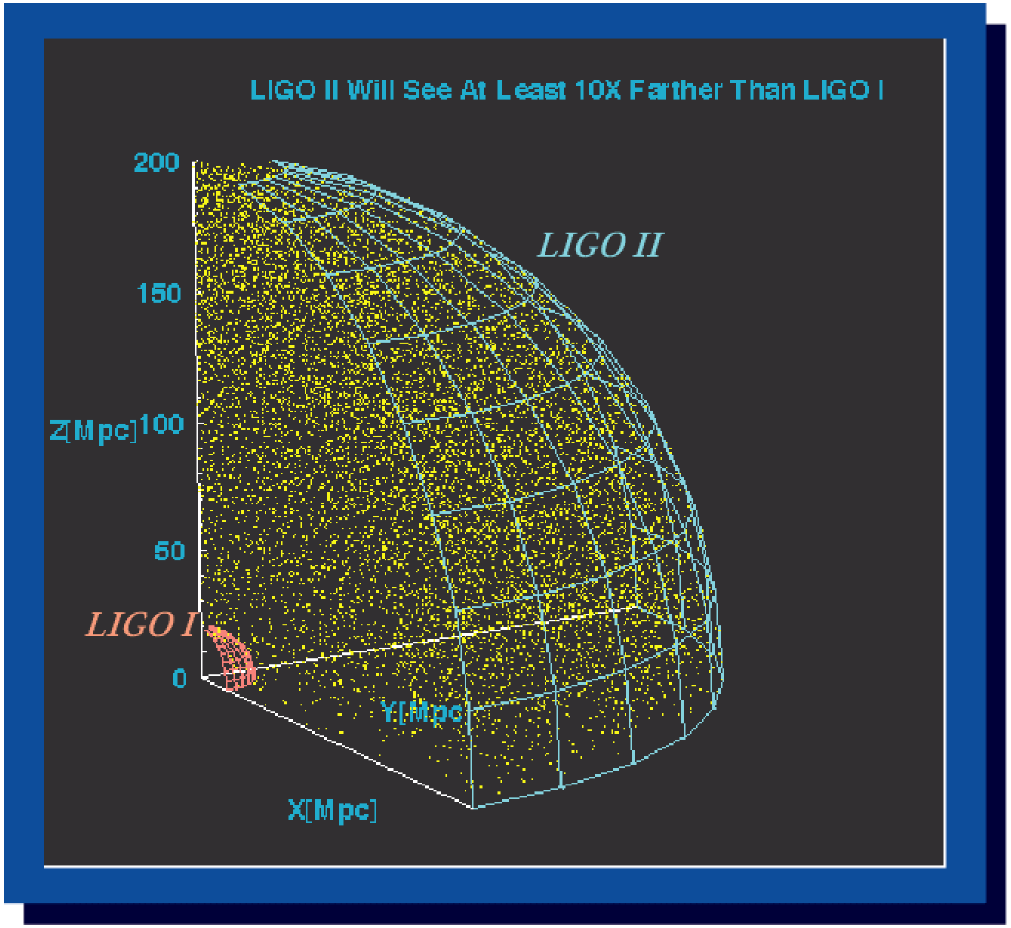


G020477-00-R

# Advanced LIGO

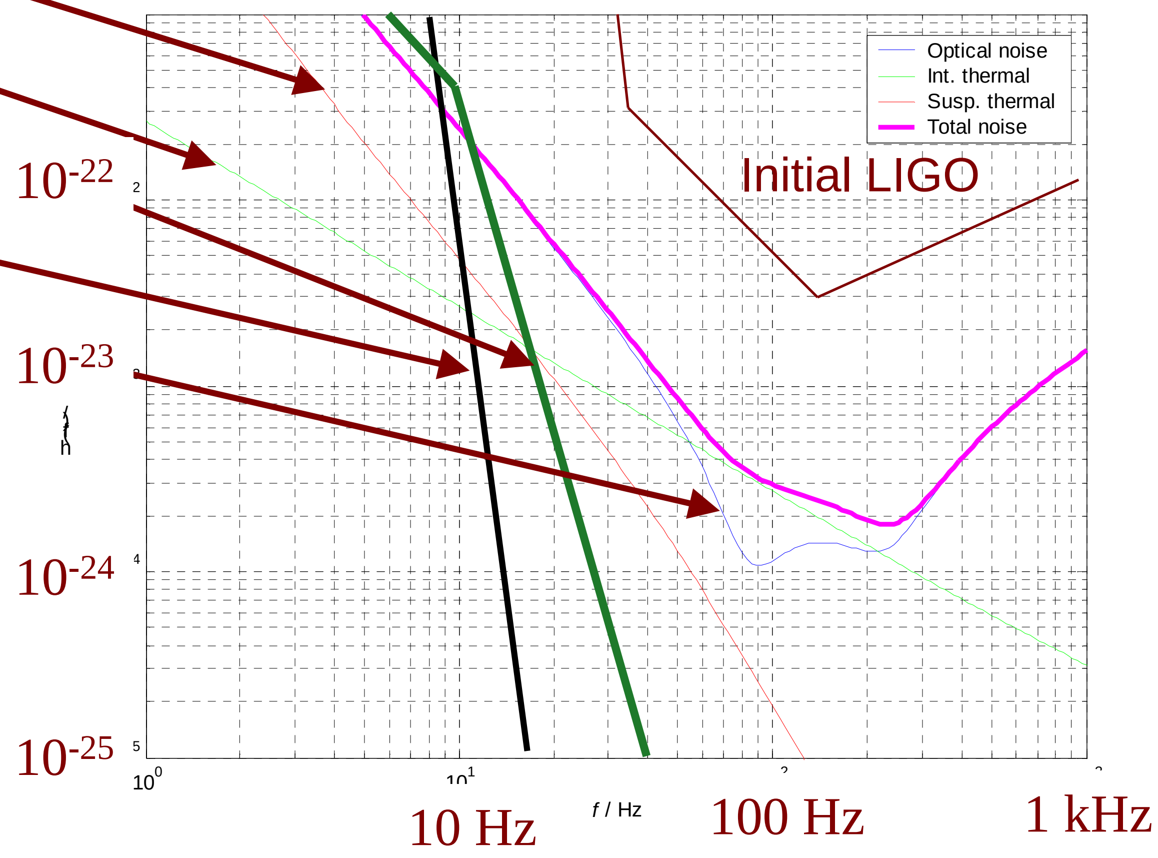
- LIGO mission: detect gravitational waves and

  **initiate GW astronomy**
- Next detector
  - » Must be of significance for astrophysics
  - » Should be at the limits of reasonable extrapolations of detector physics and technologies
  - » Should lead to a realizable, practical, reliable instrument
  - » Should come into existence neither too early nor too late
- Advanced LIGO:
  2.5 hours = 1 year of Initial LIGO
  - » Volume of sources grows with cube of sensitivity
  - » ~15x in sensitivity; ~ 3000 in rate



# Anatomy of the projected Adv LIGO detector performance

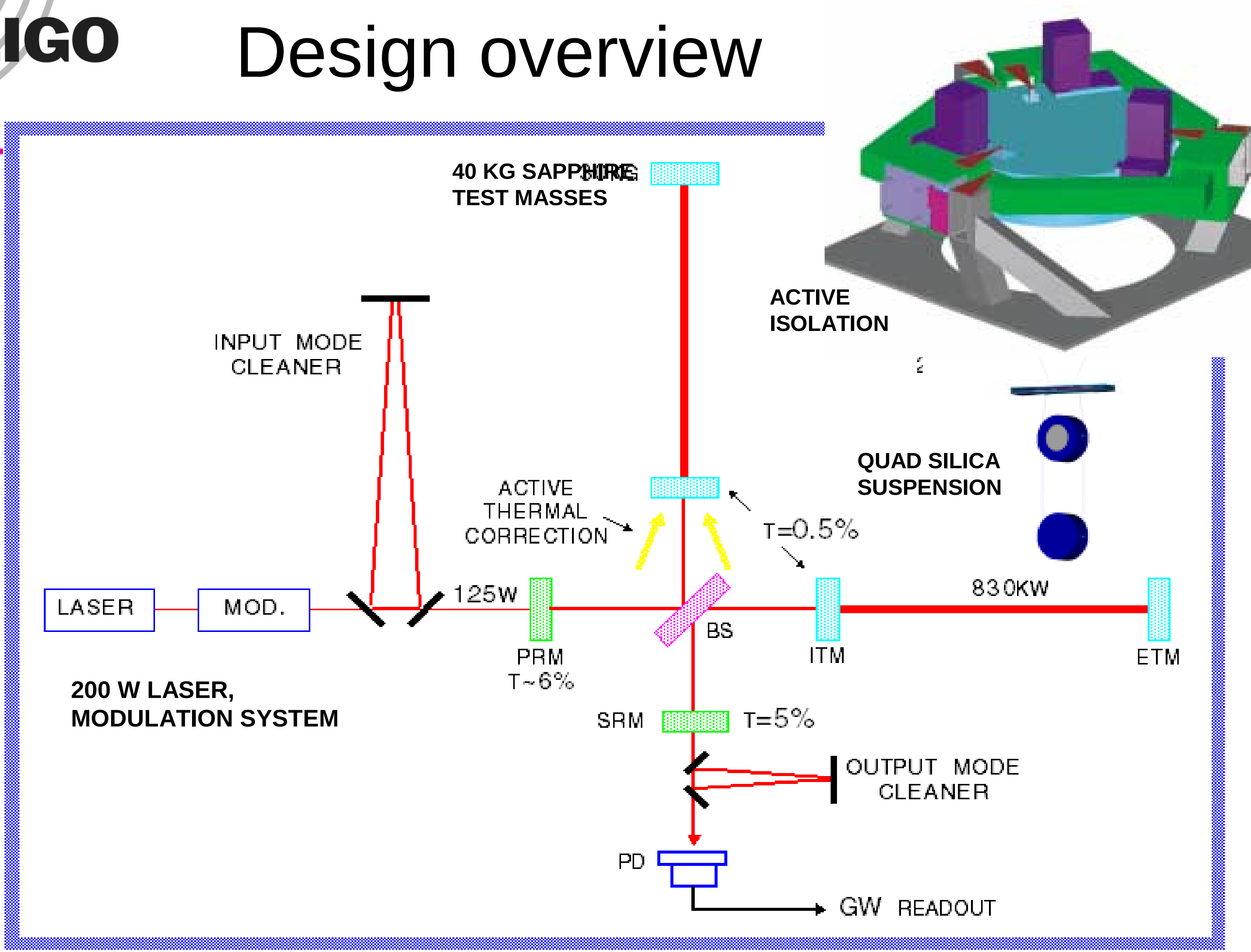
- Suspension thermal noise
- Internal thermal noise
- Newtonian background, estimate for LIGO sites
- Seismic ‘cutoff’ at 10 Hz
- Unified quantum noise dominates at most frequencies for full power, broadband tuning




- NS Binaries: for two LIGO observatories,
  - » Initial LIGO: ~20 Mpc
  - » Adv LIGO: ~300 Mpc
- Stochastic background:
  - » Initial LIGO: ~3e-6
  - » Adv LIGO ~3e-9

LIGO

# Design overview



# 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 |

# Baseline Plan

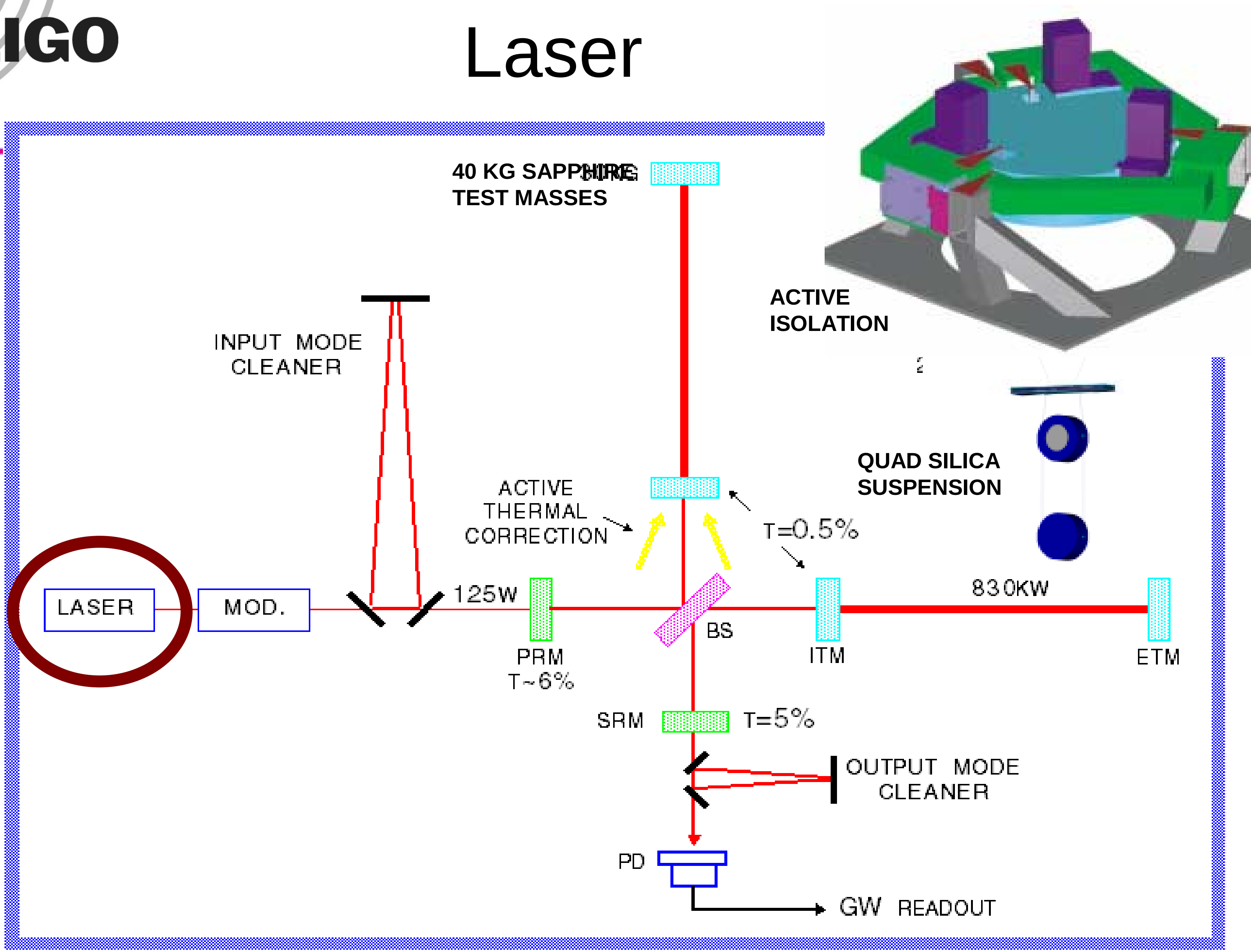
- Initial LIGO Observation 2002 – 2006
  - » 1+ year observation within LIGO Observatory
  - » Significant networked observation with GEO, LIGO, TAMA
- Structured R&D program to develop technologies
  - » Conceptual design developed by LSC in 1998
  - » Cooperative Agreement carries R&D to Final Design, 2005
- Proposal late 2002 for fabrication, installation
- Long-lead purchases planned for 2004
  - » Sapphire Test Mass material, seismic isolation fabrication
  - » Prepare a ‘stock’ of equipment for minimum downtime, rapid installation
- Start installation in 2007
  - » Baseline is a staged installation, Livingston and then Hanford
- Start coincident observations in 2009

# Adv LIGO: Top-level Organization

- Scientific impetus, expertise, and development throughout the LIGO Scientific Collaboration (LSC)
  - » Remarkable synergy
  - » LIGO Lab staff are quite active members!
- Strong collaboration GEO-LIGO at all levels
  - » Genesis and refinement of concept
  - » Teamwork on multi-institution subsystem development
  - » GEO taking scientific responsibility for two subsystems (Test Mass Suspensions, Pre-Stabilized Laser)
  - » UK and Germany planning substantial material participation
- LIGO Lab
  - » Responsibility for Observatories
  - » Establishment of Plan – for scientific observation, for development
  - » Main locus of engineering and research infrastructure

…now, where are we technically in our R&D program?

# Laser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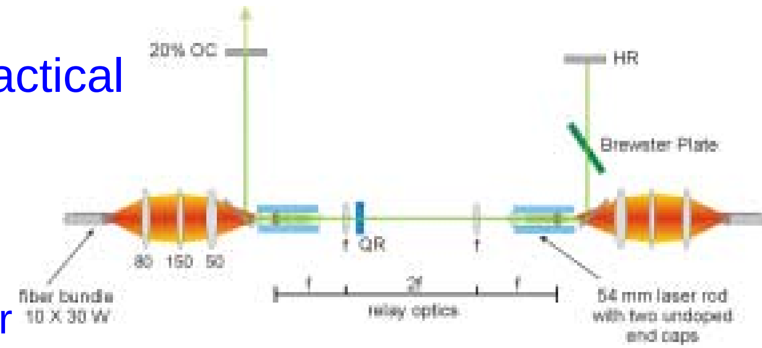
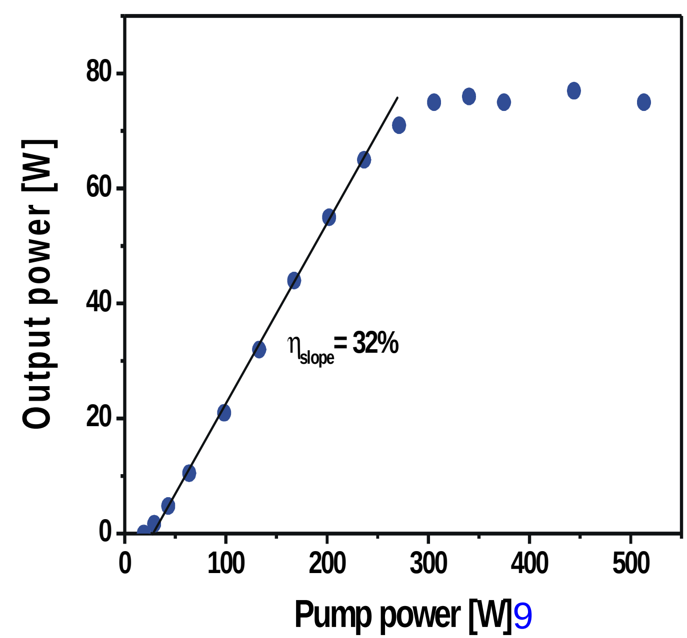
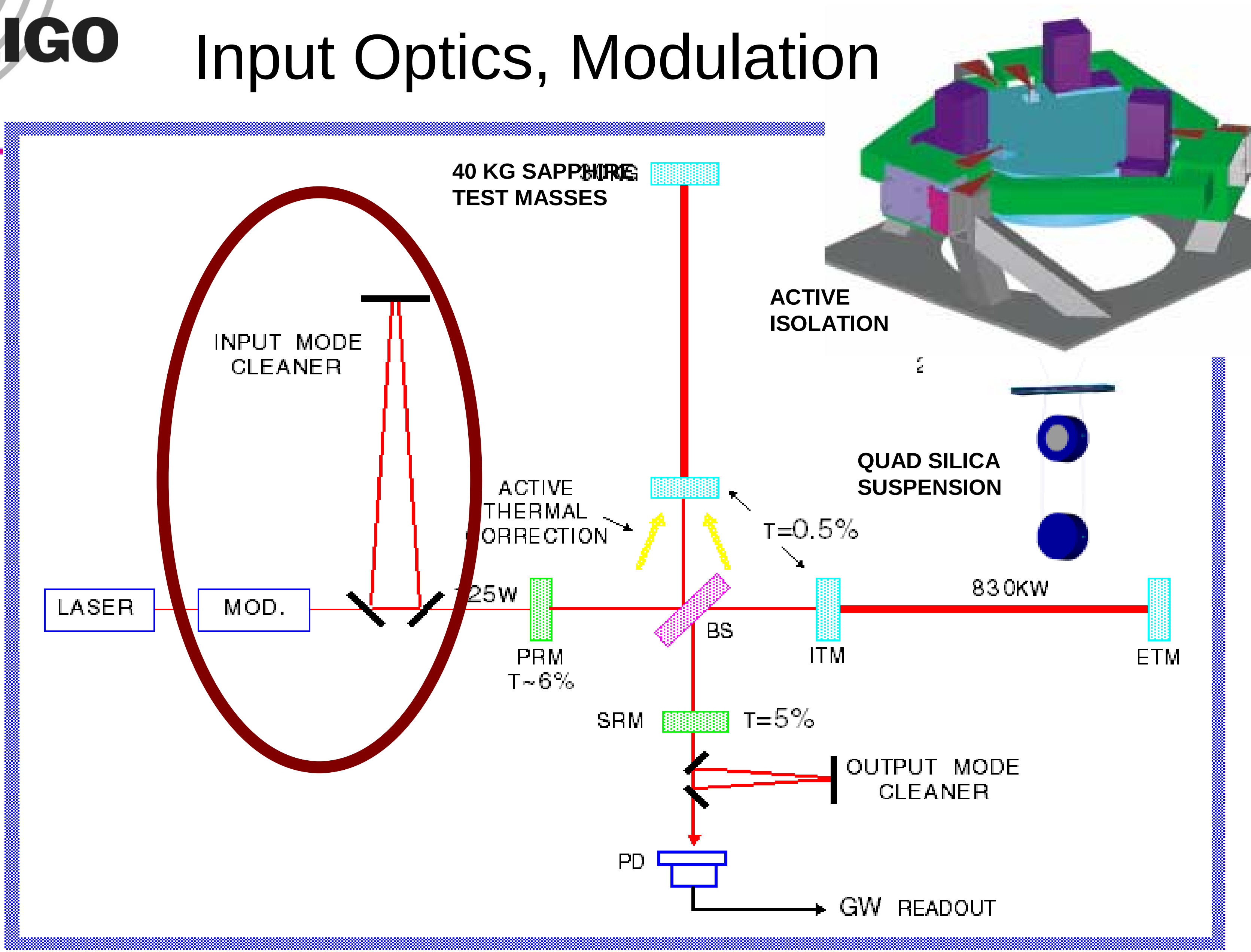
# Pre-stabilized Laser

- 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
  - » Initial LIGO: 10 W
- Challenge is in the high-power ‘head’ (remaining design familiar)
  - » Coordinated by Univ. of Hannover/LZH
    Three groups pursuing alternate design approaches to a 100W demonstration
    - – Master Oscillator Power Amplifier (MOPA) [Stanford]
    - – Stable-unstable slab oscillator [Adelaide]
    - – Rod systems [Hannover]
  - » All have reached ‘about’ 100 W, final configuration and characterized are the next steps
  - » Concept down-select December 2002
  - » Proceeding with stabilization, subsystem design



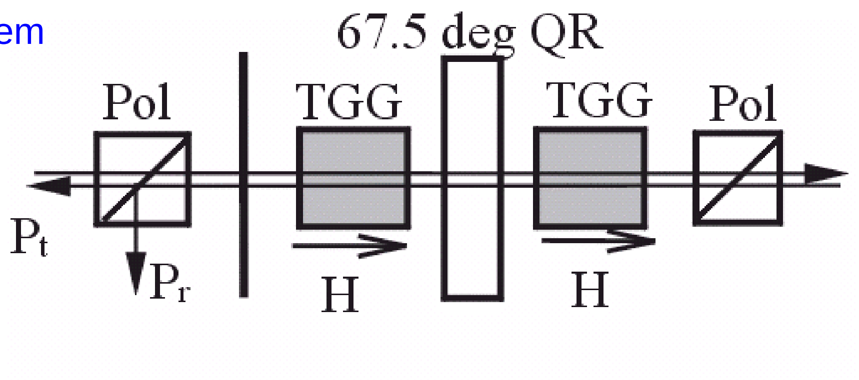



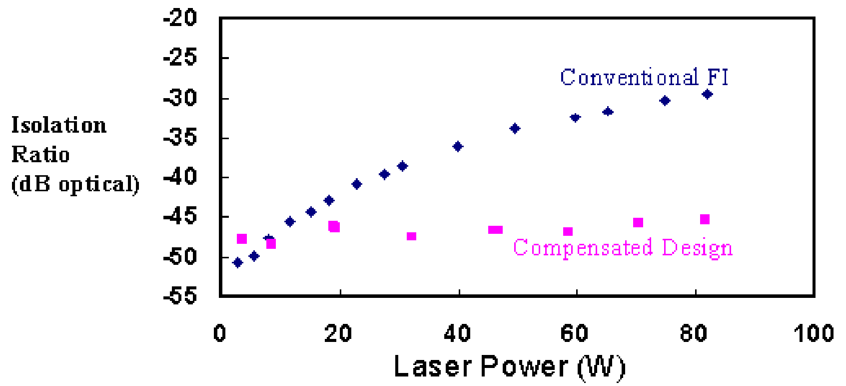
# Input Optics, Modulation



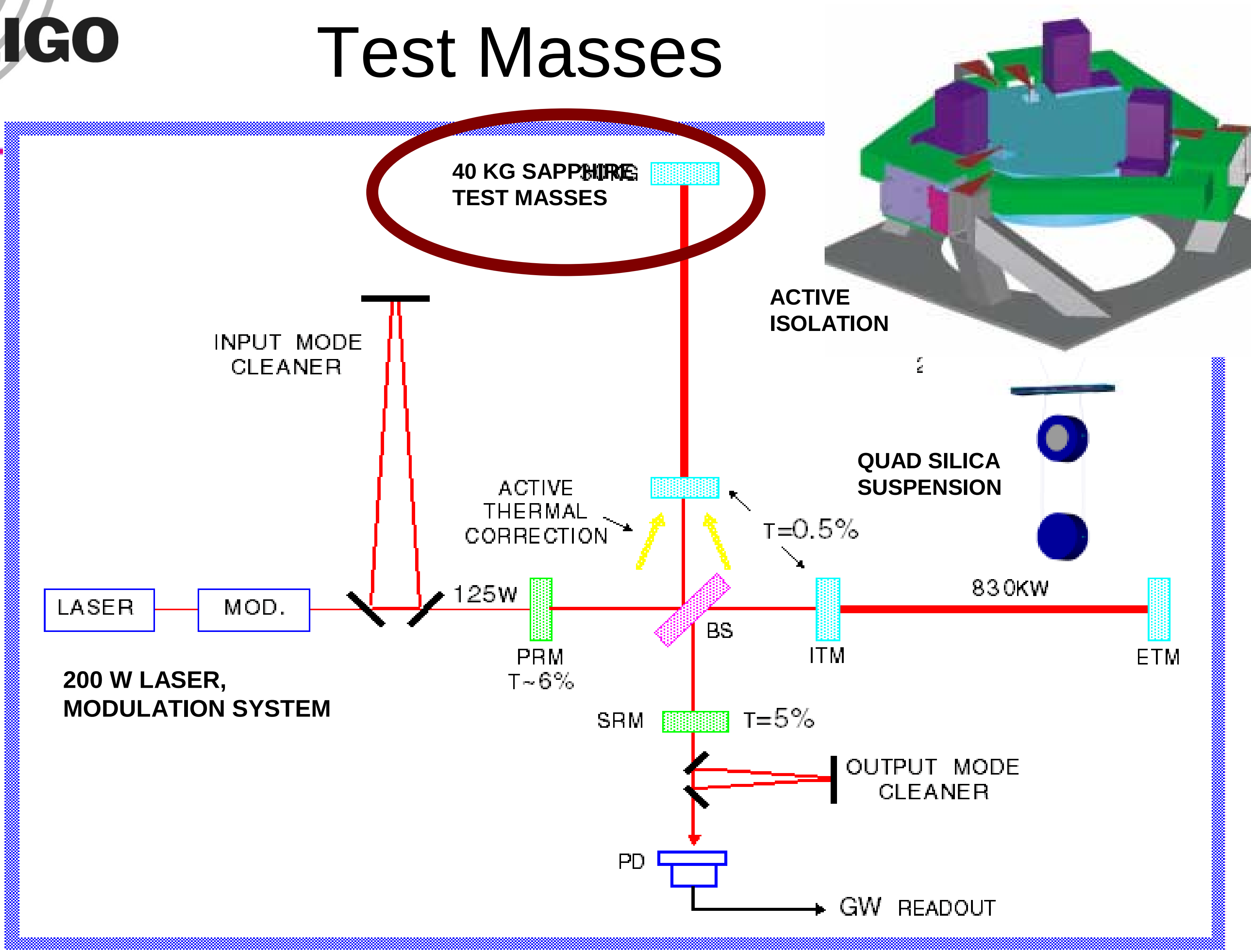
# Input Optics

- Subsystem interfaces laser light to main interferometer
  - » Modulation sidebands applied for sensing system
  - » Cavity for mode cleaning, stabilization
  - » 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
- Design is based on initial LIGO system
- Design Requirements Review held in May 2002: successful
- Many incremental innovations due to
  - » Initial design flaws (mostly unforeseeable)
  - » Changes in requirements LIGO 1 → LIGO II
  - » Just Plain Good Ideas!
- New Faraday isolator materials: 45 dB, 100 W
- Thermal mode matching
- Preliminary design underway



# Test Masses



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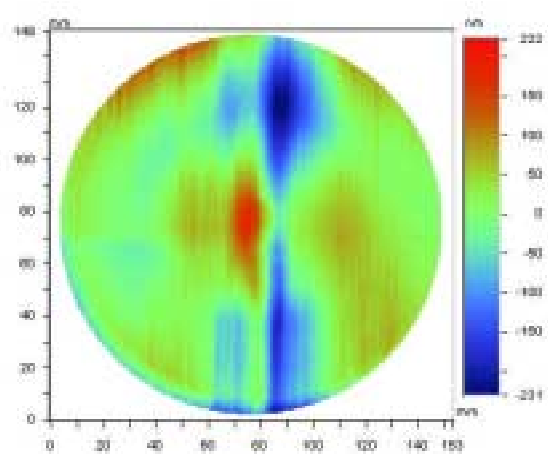
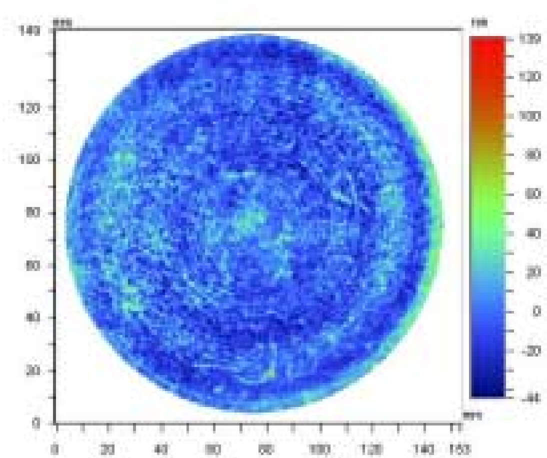
# Sapphire Core Optics

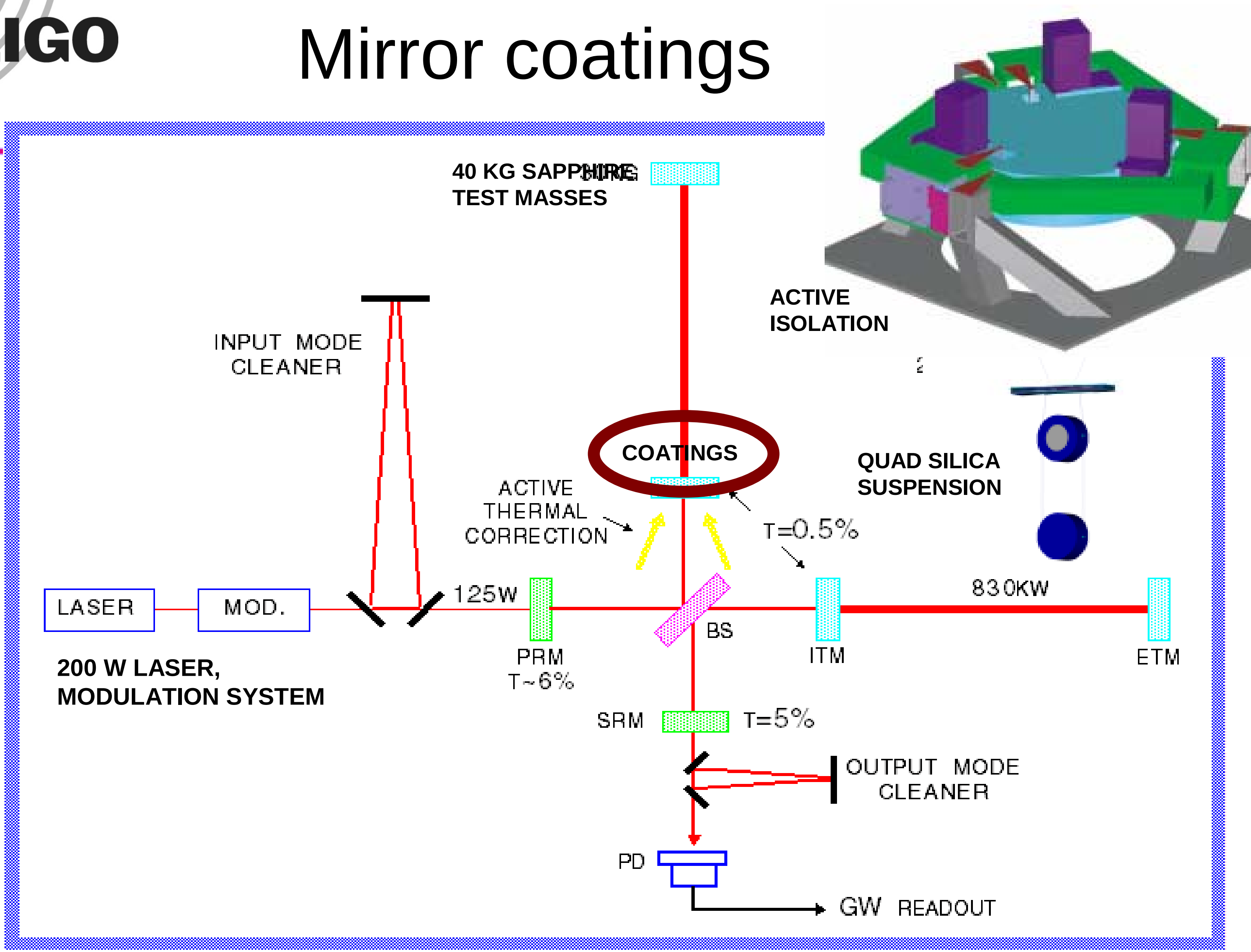
- Focus is on developing data needed for choice between Sapphire and Fused Silica as substrate materials
  - » Sapphire promises better performance, lower cost; feasibility is question
- Progress in fabrication of Sapphire:
  - » 4 full-size Advanced LIGO boules, 31.4 x 13 cm, grown
  - » Delivery in November 2002 – destined for LASTI Full Scale Test optics
- Homogeneity compensation by polishing:  RMS 60 nm → 15 nm (10 nm required)





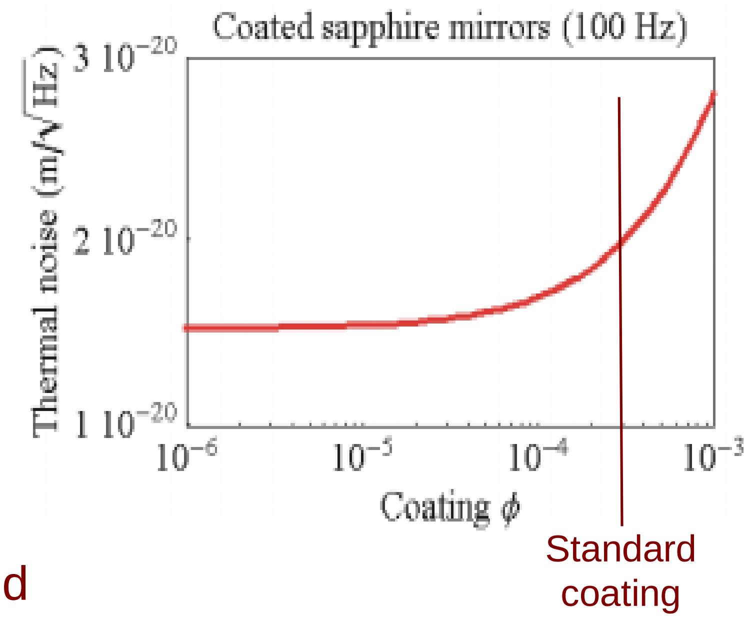
- Progress needed in mechanical loss measurements, optical absorption
- Downselect Sapphire/Silica in May 2003

# Mirror coatings

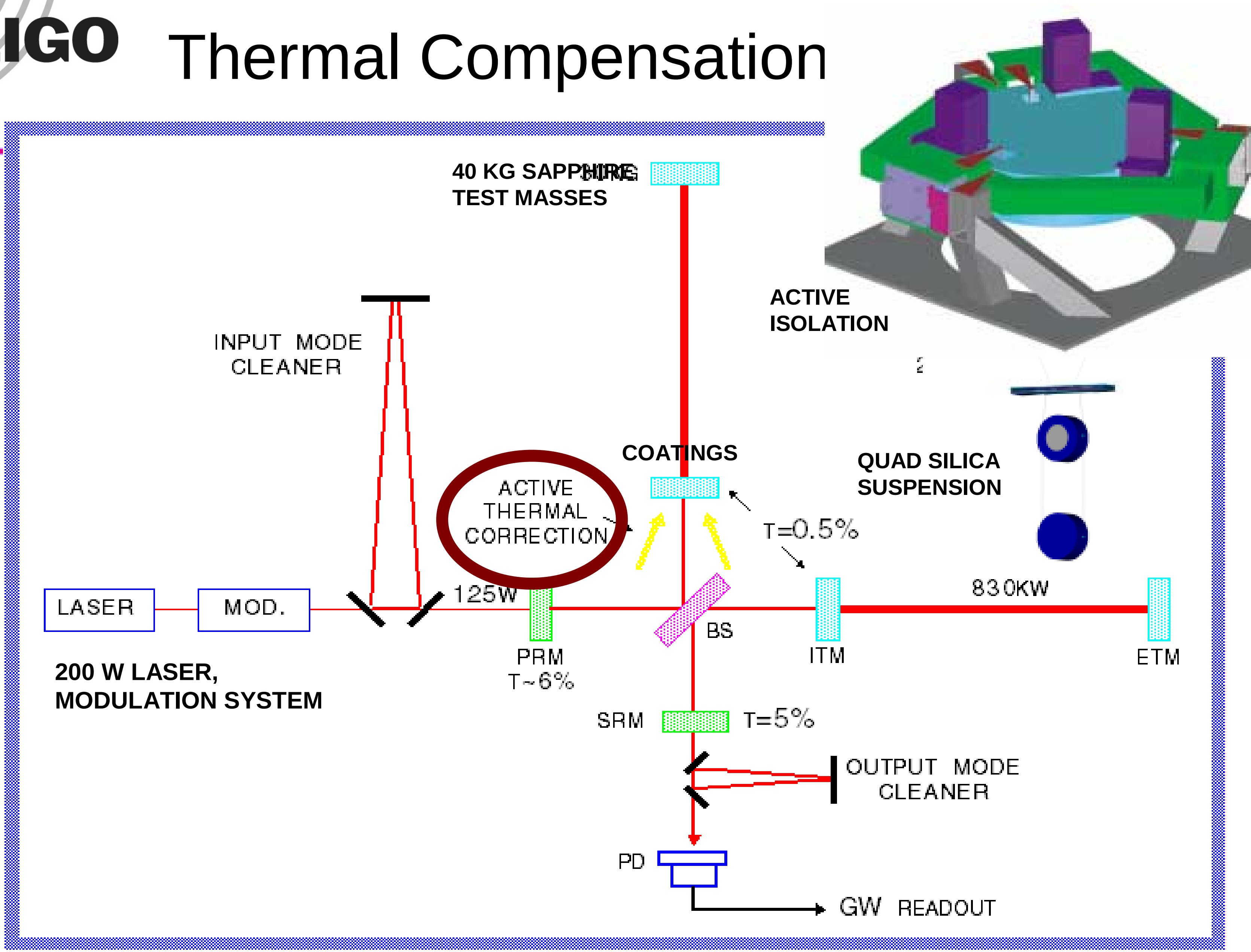


# Coatings

- Evidently, optical performance is critical
  - » ~1 megawatt of incident power
  - » Very low optical absorption (~0.5 ppm) required – and obtained
- Thermal noise due to coating mechanical loss also significant
- Source of loss is associated with $Ta_2O_5$, not $SiO_2$
  - » May be actual material loss, or stress induced
- Looking for alternatives
  - » Niobia coatings optically ok, mechanical losses slightly better
  - » Alumina, doped Tantalum, annealing are avenues being pursued
- Need ~10x reduction in lossy material to have coating make a negligible contribution to noise budget – not obvious

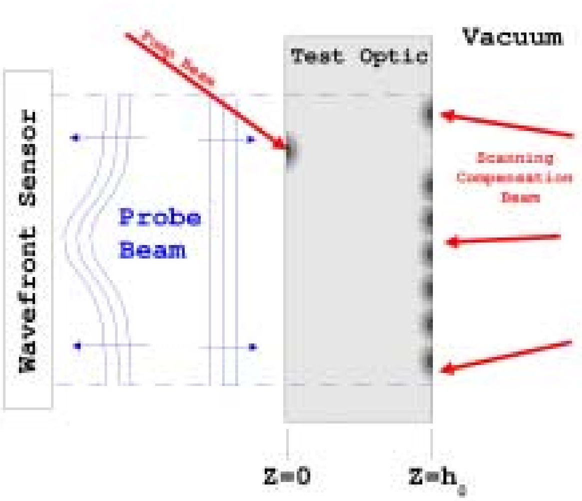


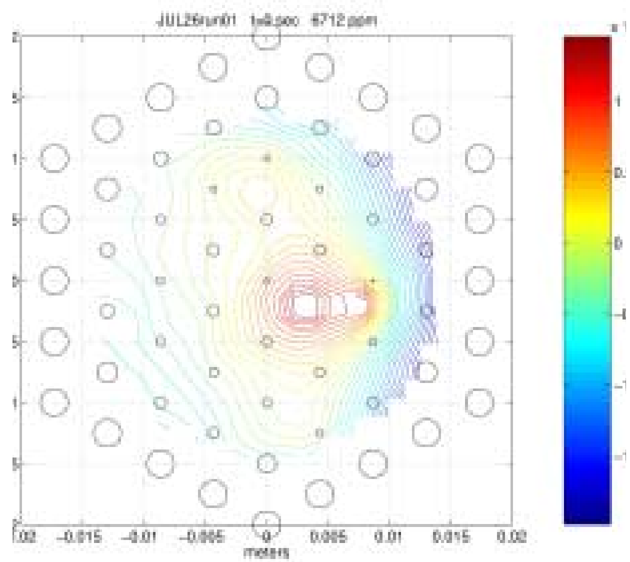
# Thermal Compensation

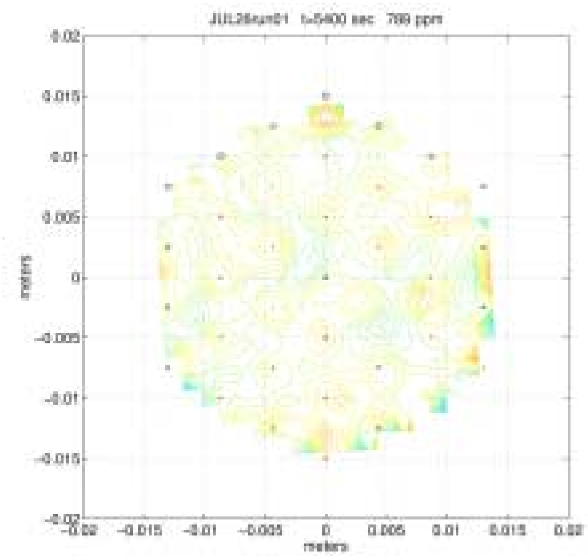


# Active Thermal Compensation

- Removes excess ‘focus’ due to absorption in coating, substrate
- Two approaches possible, alone or together:
  - » quasi-static ring-shaped additional heat (probably on compensation plate, not test mass itself)
  - » Scan (raster or other) to complement irregular absorption
- Models and tabletop experiments agree, show feasibility
- Indicate that ‘trade’ against increased sapphire absorption is possible
- Next: development of prototype for testing on cavity in ACIGA Gingin facility

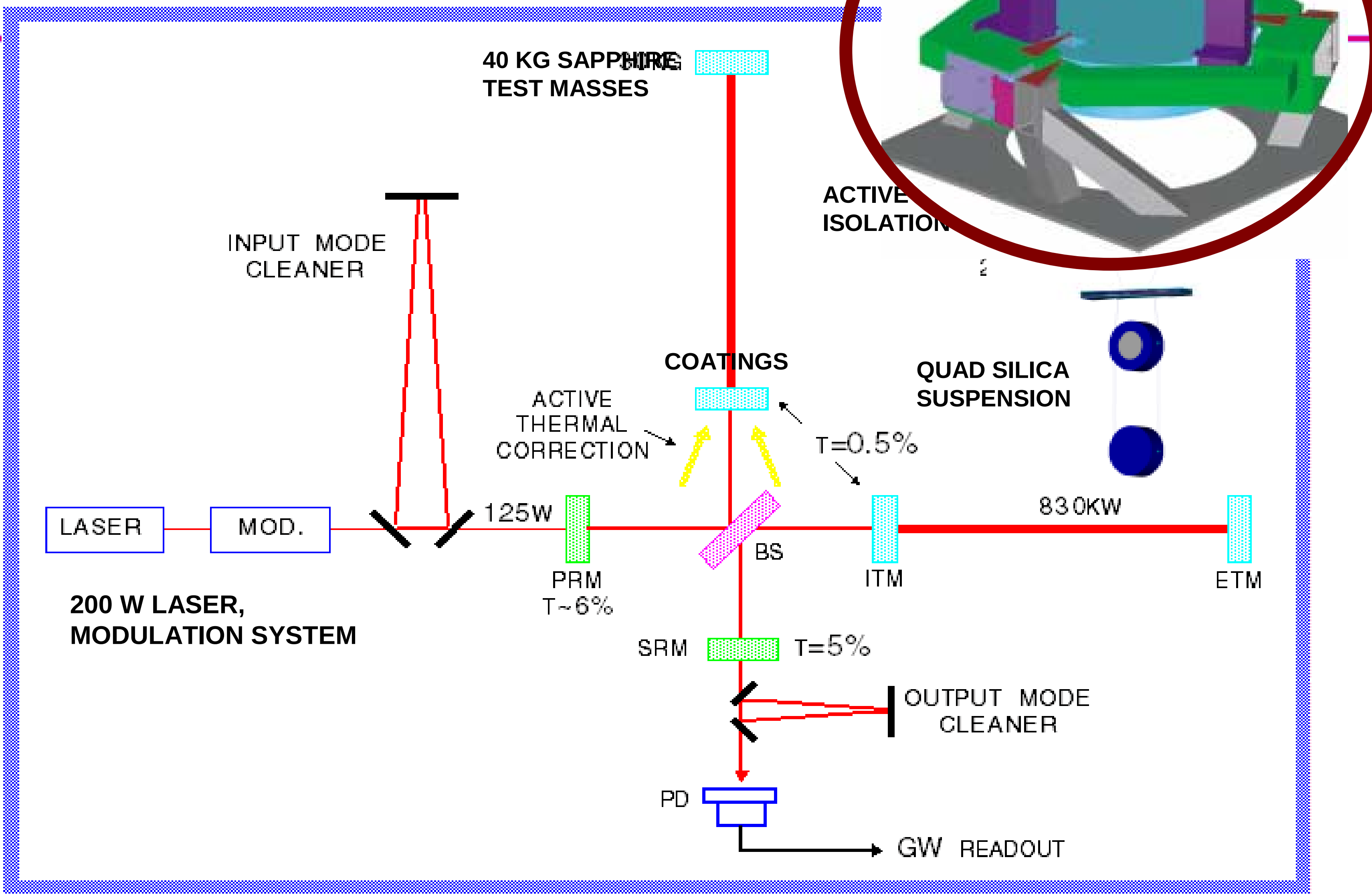


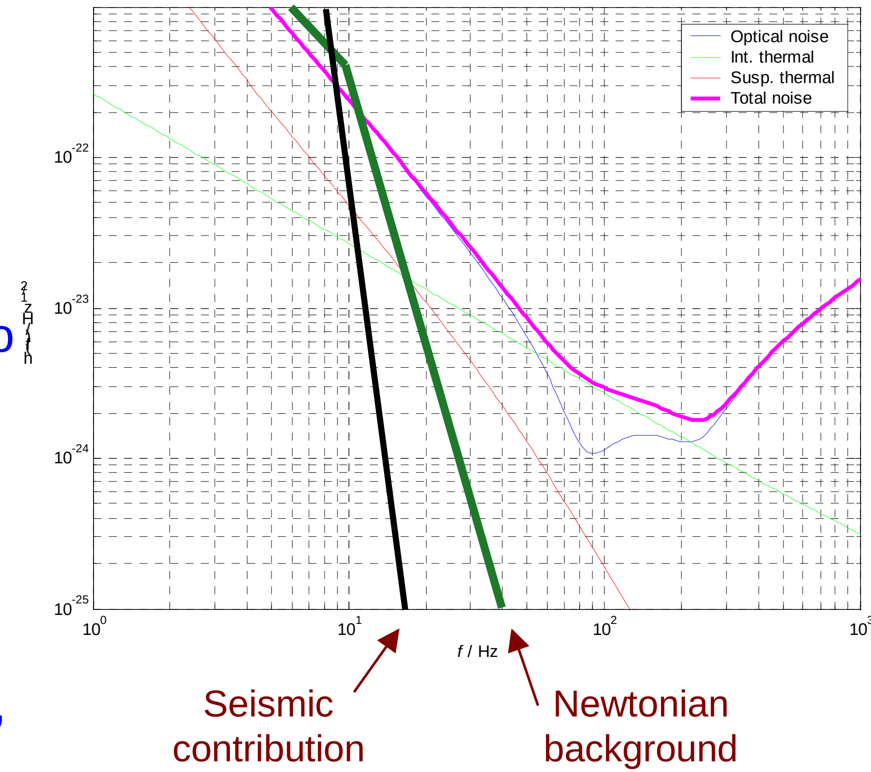
LIGO

# Seismic Isolation



# Isolation: Requirements

- Requirement: render seismic noise a negligible limitation to GW searches
  - » Newtonian background will dominate for >10 Hz
  - » Other ‘irreducible’ noise sources limit sensitivity to uninteresting level for frequencies less than ~20 Hz
  - » Suspension and isolation contribute to attenuation
- Requirement: 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



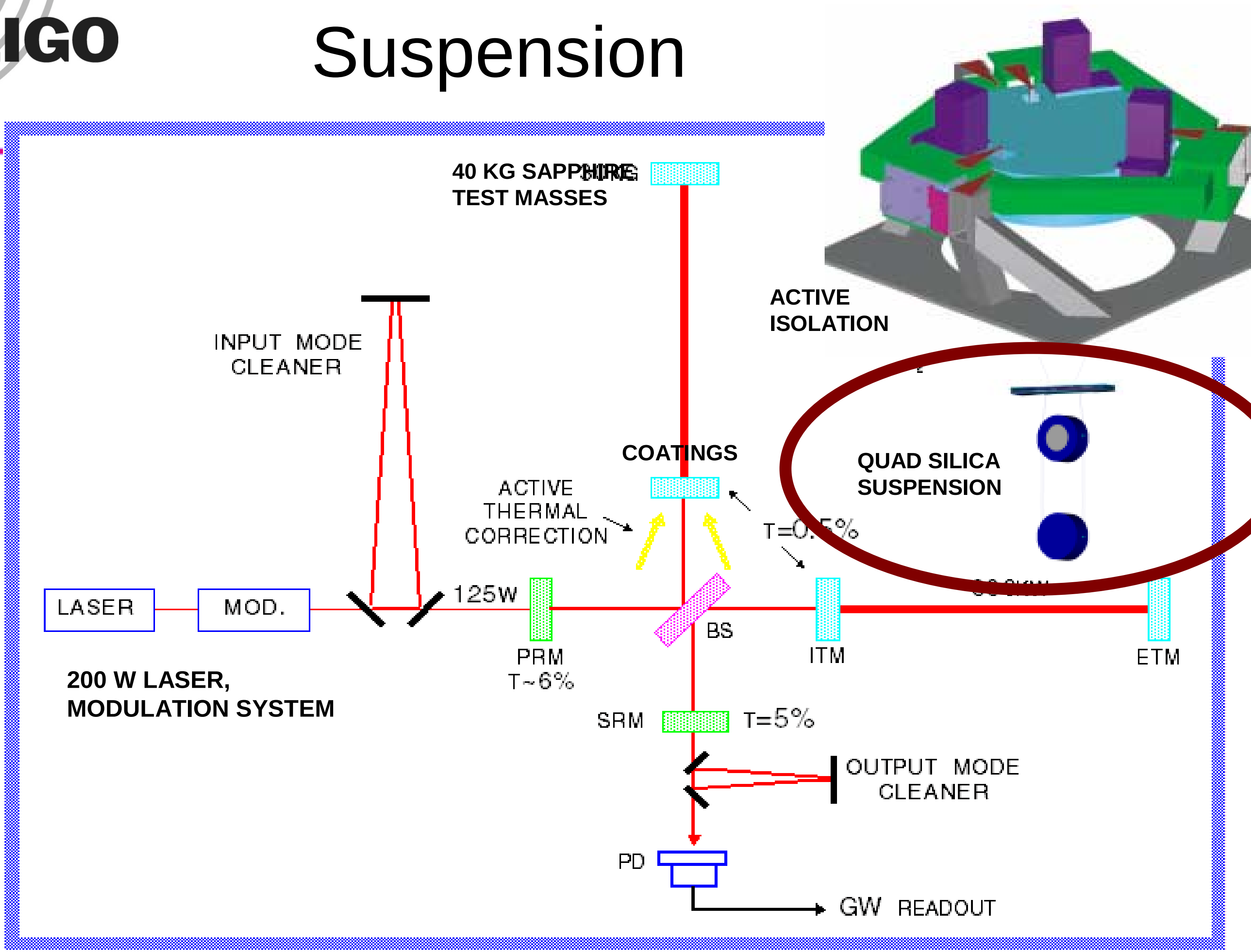
# Isolation I: Pre-Isolator

- Need to attenuate excess noise in 1-3 Hz band at LLO
- Using element of Adv LIGO
- Aggressive development of hardware, controls models
- Prototypes in test
- Dominating Seismic Isolation team effort, until early 2003

# Isolation II: Two-stage platform

- Choose an active approach: high-gain servo systems, two stages of 6 degree-of-freedom each
  - » Allows extensive tuning of system after installation, different modes of operation, flexible placement of main and auxiliary optics on inertially quiet tables
- Stanford Engineering Test Facility Prototype coming on line
  - » Mechanical system complete
  - » Instrumentation being installed for modal characterization
- The original 2-stage platform continues to serve as testbed in interim
  - » Recent demonstration of sensor correction and feedback over broad low-frequency band

# Suspension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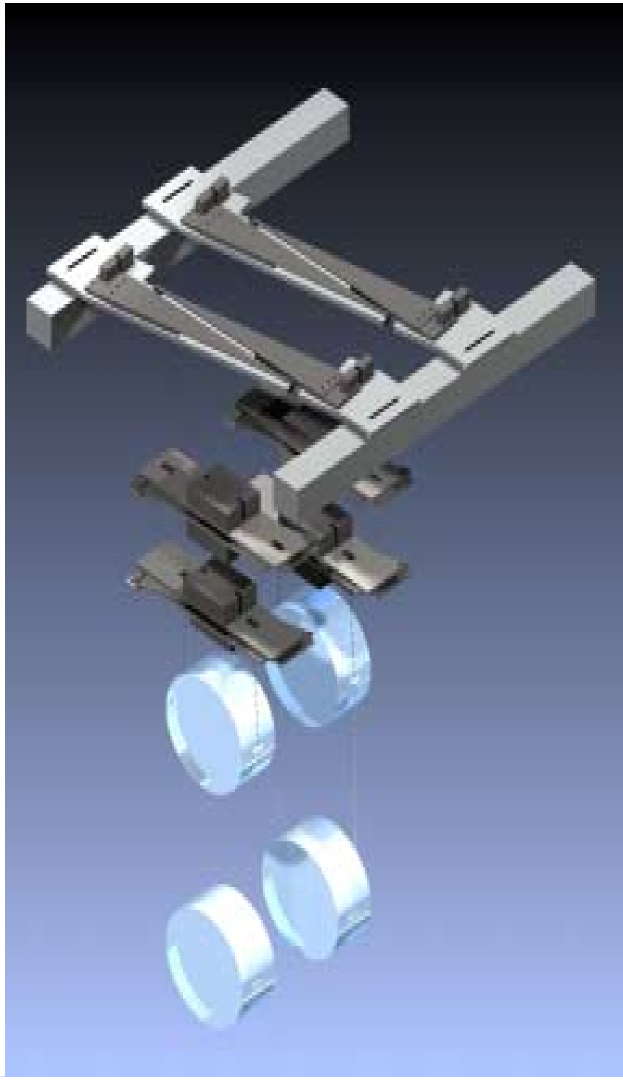
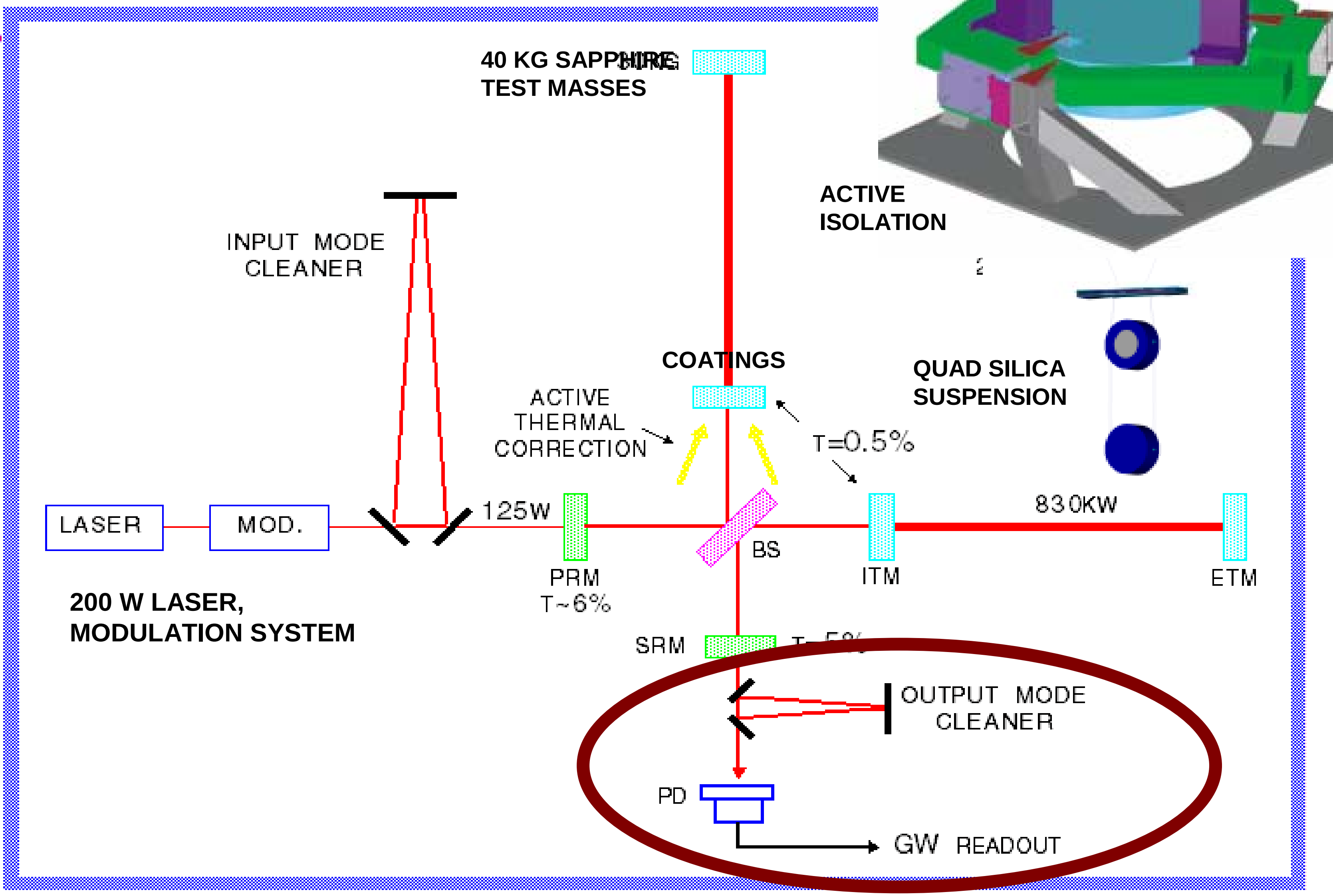
# Suspensions

- Design based on GEO600 system, using silica suspension fibers for low thermal noise, multiple pendulum stages for seismic isolation
- PPARC proposal: significant financial and technical contribution; quad suspensions, electronics, and some sapphire substrates
  - » U Glasgow, Birmingham, Rutherford Appleton
- Success of GEO600 a significant achievement
- A mode cleaner triple suspension prototype now being built for LASTI Full Scale Test
- Both fused silica ribbon and dumbbell fiber prototypes are now being made and tested
- Challenge: developing means to damp solid body modes quietly
  - » Eddy current damping has been tested favorably on a triple suspension
  - » Interferometric local sensor another option



# GW Readout

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# GW readout, Systems

- 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
- Glasgow 10m prototype, Caltech 40m prototype in construction, early testing
  - » Mode cleaner together and in locking tests at 40m
- Calculations continue for best strain sensing approach
  - » DC readout (slight fringe offset from minimum) or ‘traditional’ RF readout
  - » Hard question: which one shows better practical performance in a full quantum-mechanical analysis with realistic parameters?
- Technical noise propagation also being refined

# Advanced LIGO

- A great deal of momentum and real progress in every subsystem
  - » Details available in breakout presentations/Q&A
- No fundamental surprises as we move forward; concept and realization remain intact with adiabatic changes
- Study of costs in progress
- Plan on submission late 2002, targeting observations in 2009