Advanced LIGO

David Shoemaker

PAC

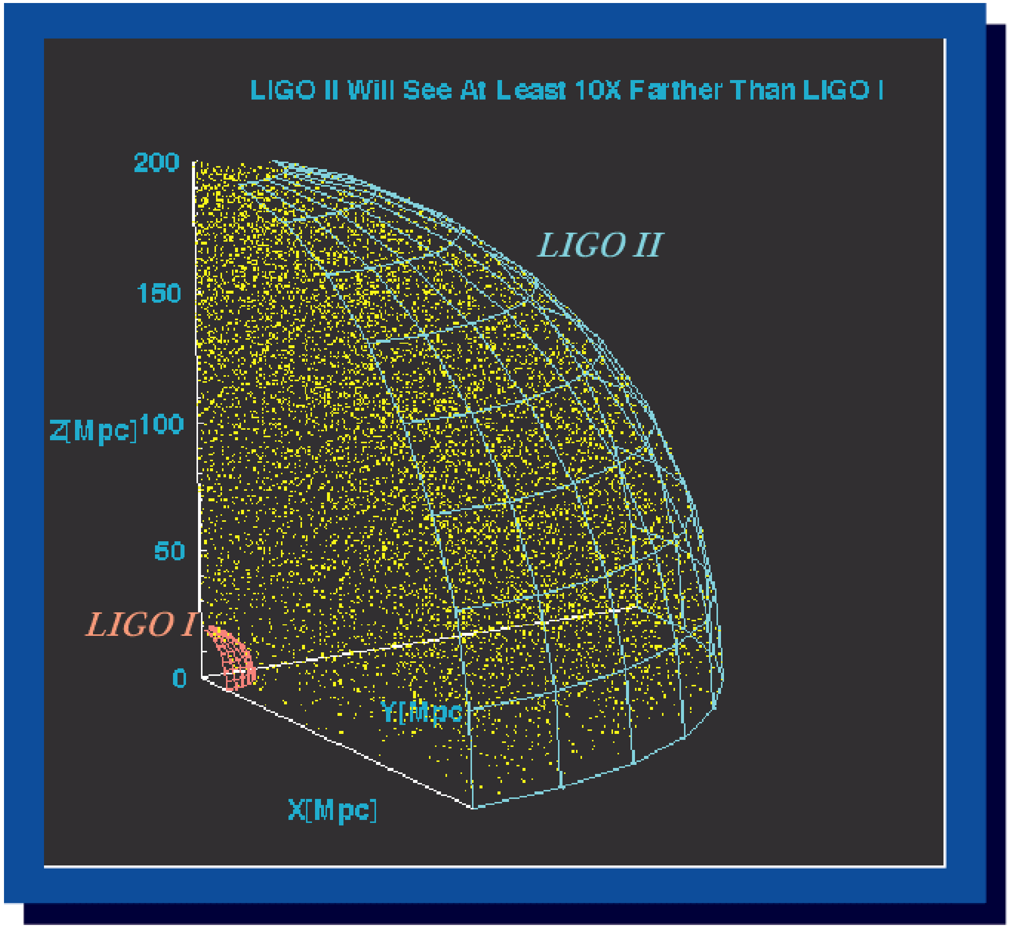
5 December 2002

G020550-00-M

Advanced LIGO

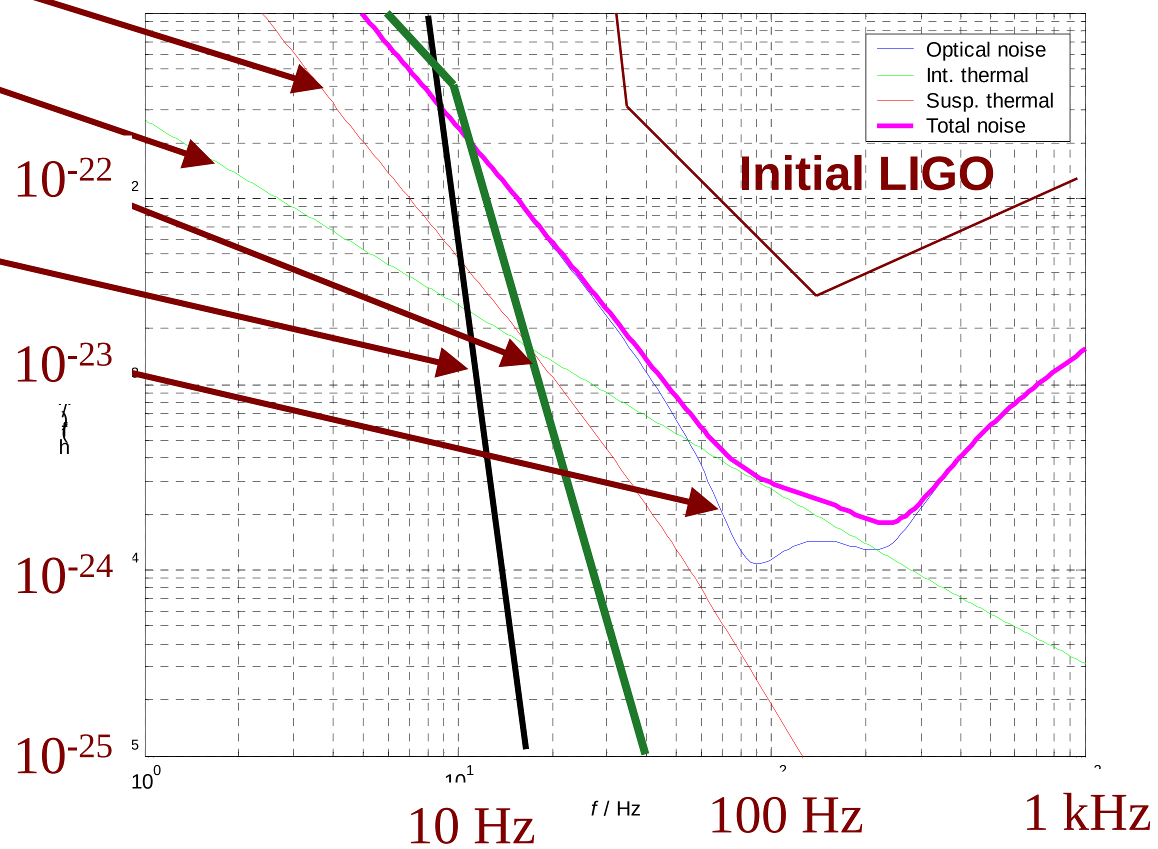
- LIGO mission: detect gravitational waves and

  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



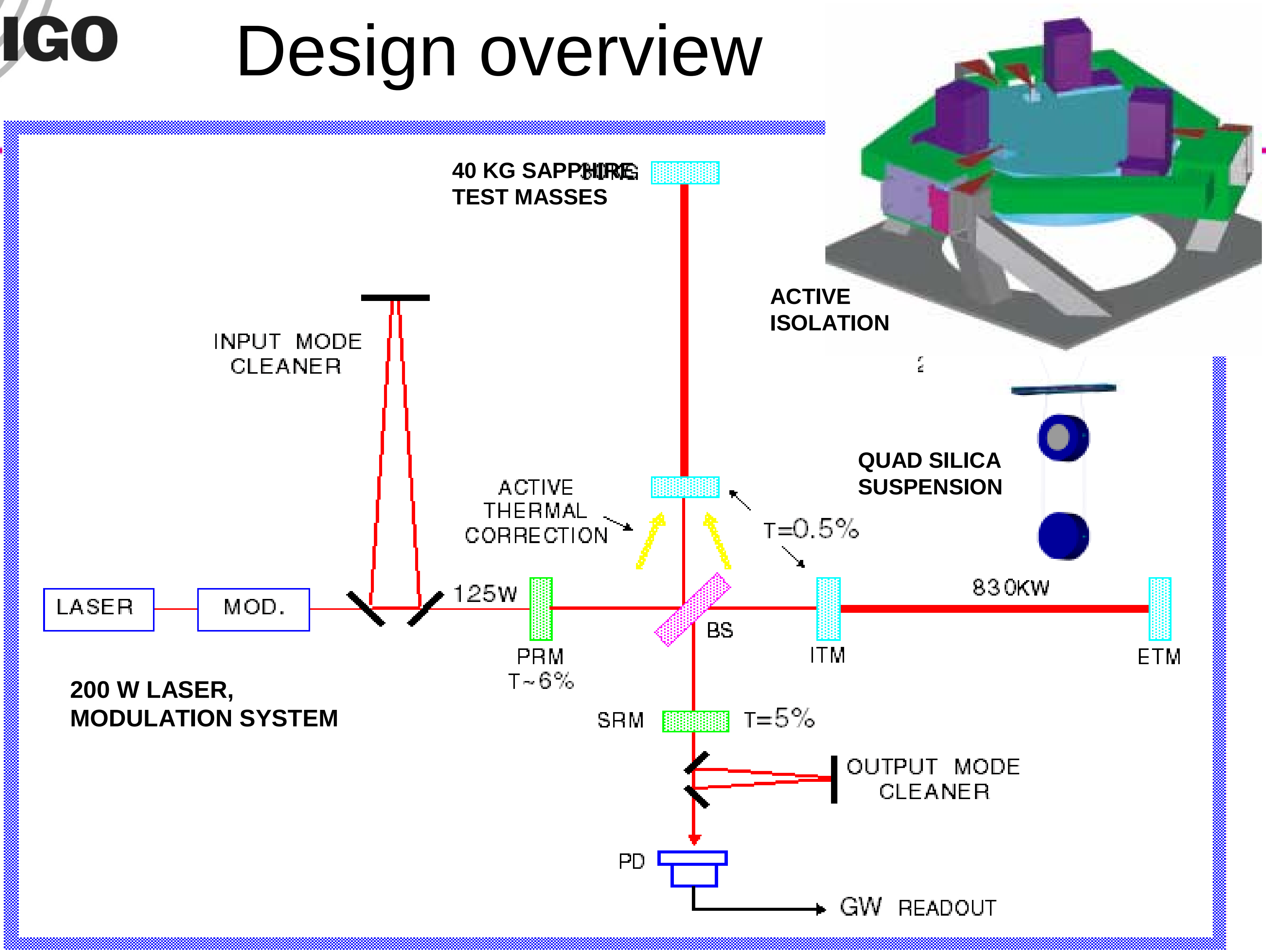
Anatomy of the projected Adv LIGO detector performance

- 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

Design overview



Baseline Plan

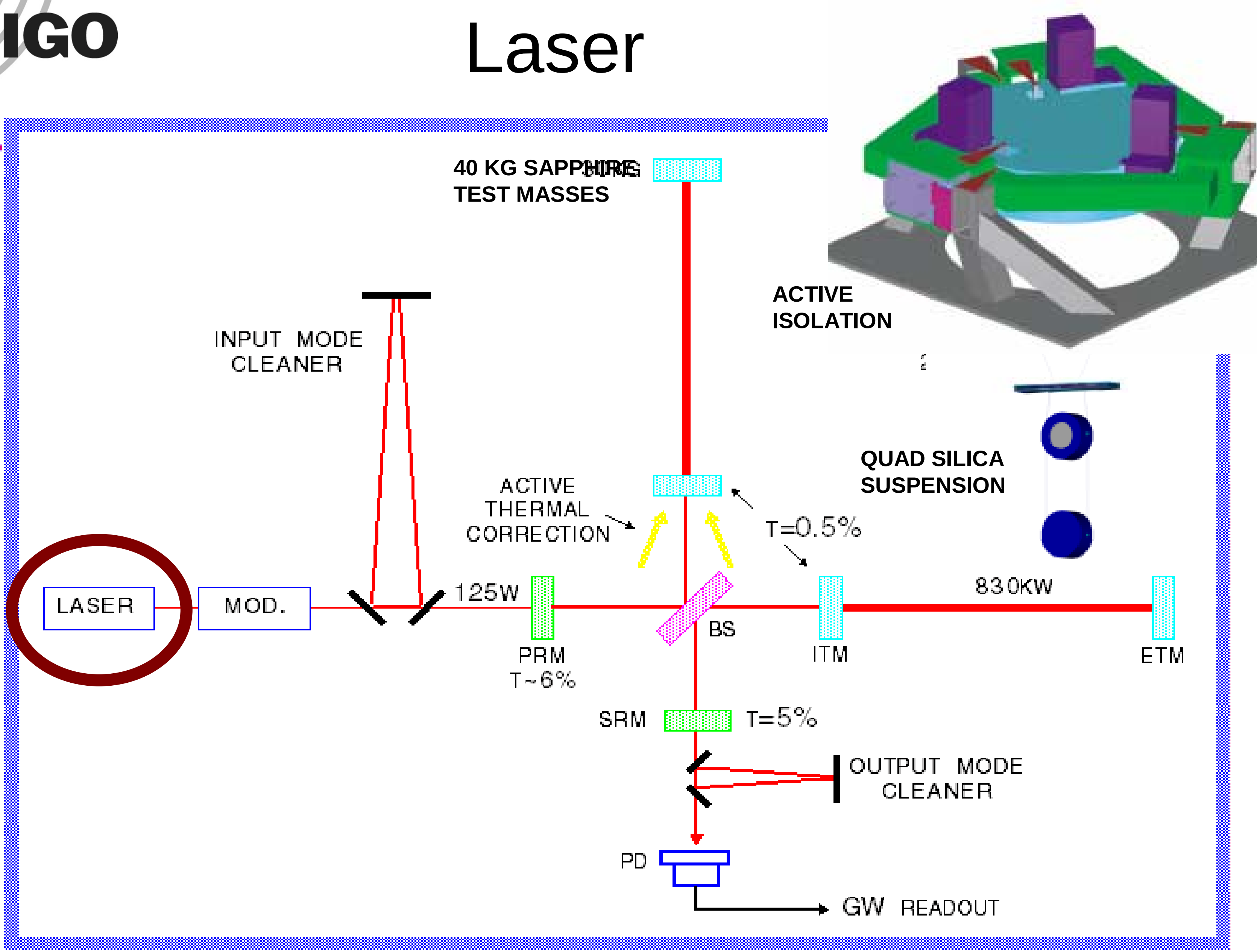
- Initial LIGO Observation 2002 – 2006
  - » 1+ year observation within LIGO Observatory
  - » Significant networked observation with GEO, LIGO, TAMA
- Structured R&D program to develop technologies
  - » Conceptual design developed by LSC in 1998
  - » Cooperative Agreement carries R&D to Final Design, 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

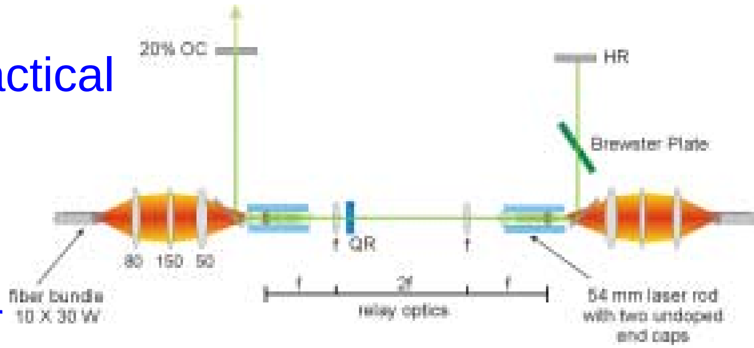
…now, where are we technically in our R&D program?

Laser

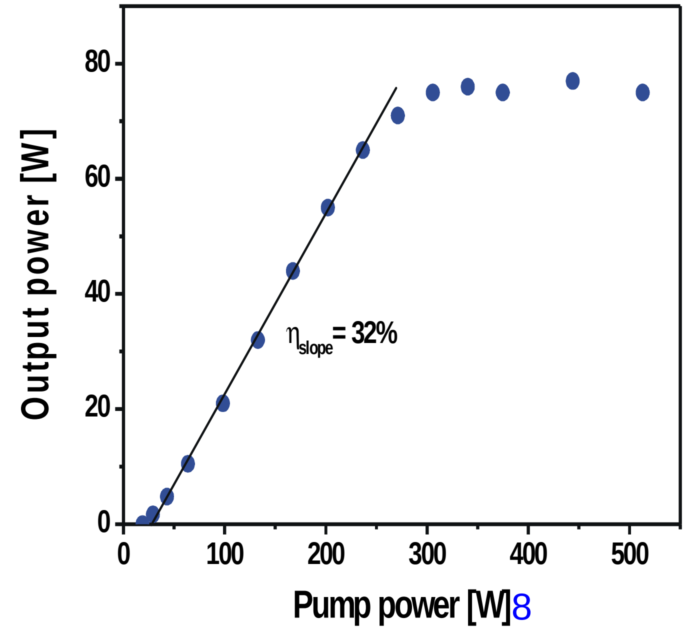

40 KG SAPPHIRE
TEST MASSES
ACTIVE
ISOLATION
QUAD SILICA
SUSPENSION
INPUT MODE
CLEANER
ACTIVE
THERMAL
CORRECTION
T=0.5%
LASER
MOD.
125W
PRM
T~6%
BS
ITM
830KW
ETM
SRM
T=5%
OUTPUT MODE
CLEANER
PD
GW READOUT

LIGO

Pre-stabilized Laser



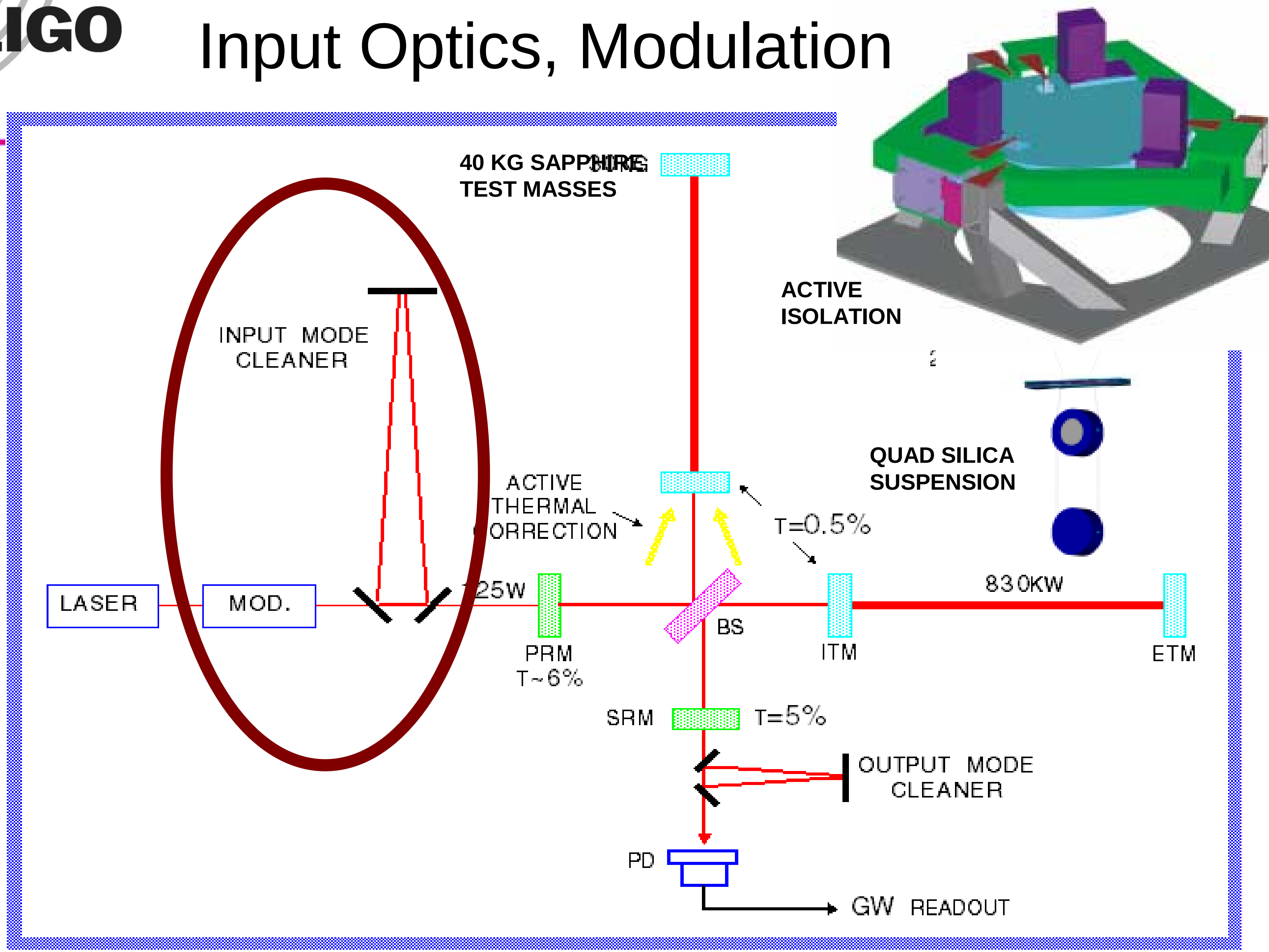
- Require optimal power, given fundamental and practical constraints:
  - » Shot noise: having more stored photons improves sensitivity, but:
  - » Radiation pressure: dominates at low frequencies
  - » Thermal focussing in substrates: limits usable power
- Optimum depends on test mass material, 80 – 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 → March 2003
  - » Proceeding with stabilization, subsystem design



LIGO Laboratory

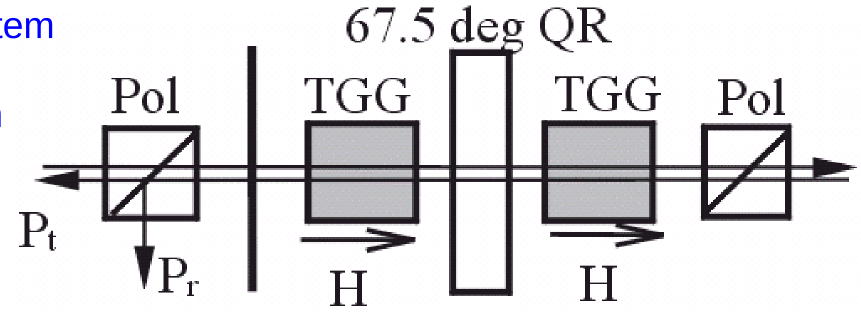
LIGO

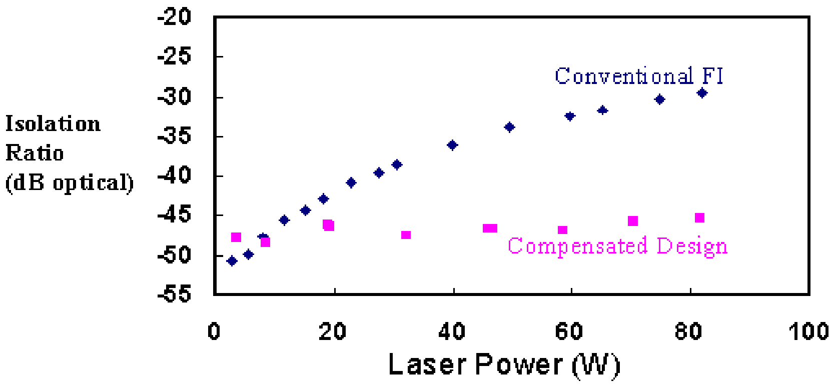
Input Optics, Modulation



Input Optics

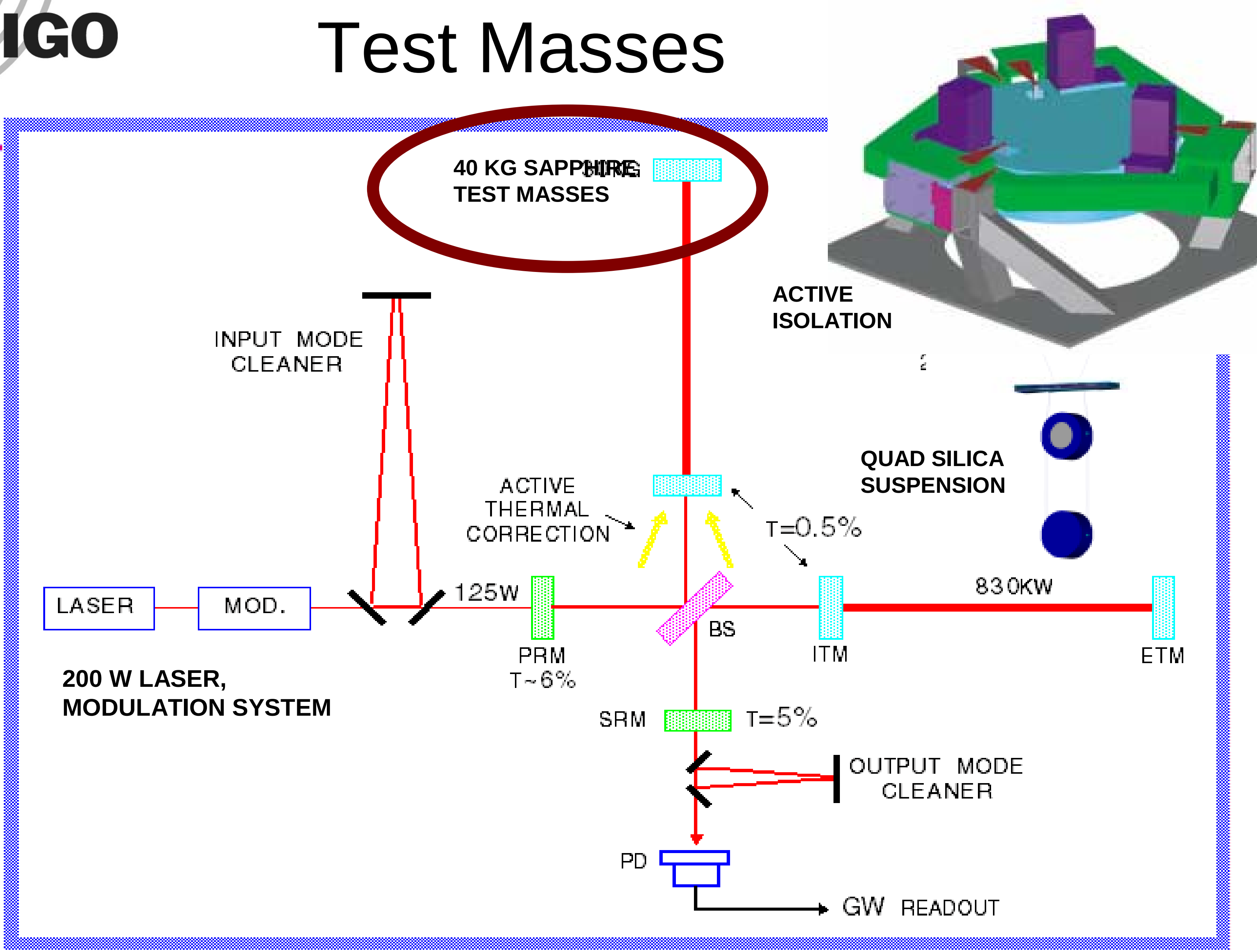
- Subsystem interfaces laser light to main interferometer
  - » Modulation sidebands applied for sensing system
  - » Cavity for mode cleaning, stabilization
  - » Mode matching from ~0.5 cm to ~10 cm beam
- Challenges in handling high power
  - » isolators, modulators
  - » Mirror mass and intensity 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 (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





G020550-00-M

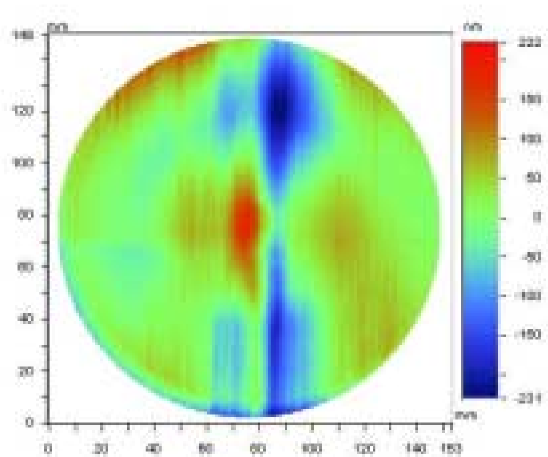
Test Masses

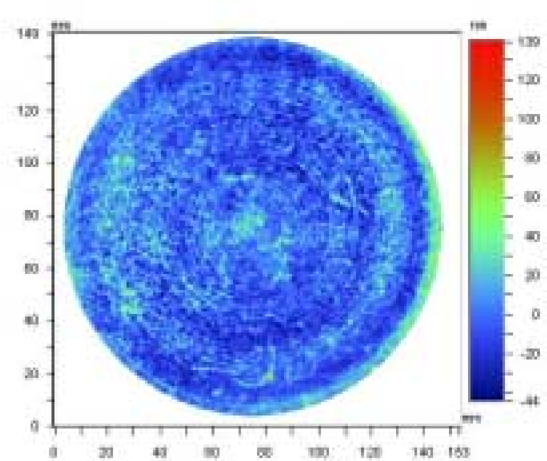


40 KG SAPPHIRE
TEST MASSES
ACTIVE
ISOLATION
INPUT MODE
CLEANER
QUAD SILICA
SUSPENSION
ACTIVE
THERMAL
CORRECTION
T=0.5%
LASER
MOD.
125W
830KW
BS
PRM
T~6%
ITM
ETM
200 W LASER,
MODULATION SYSTEM
SRM
T=5%
OUTPUT MODE
CLEANER
PD
GW READOUT

Sapphire Core Optics

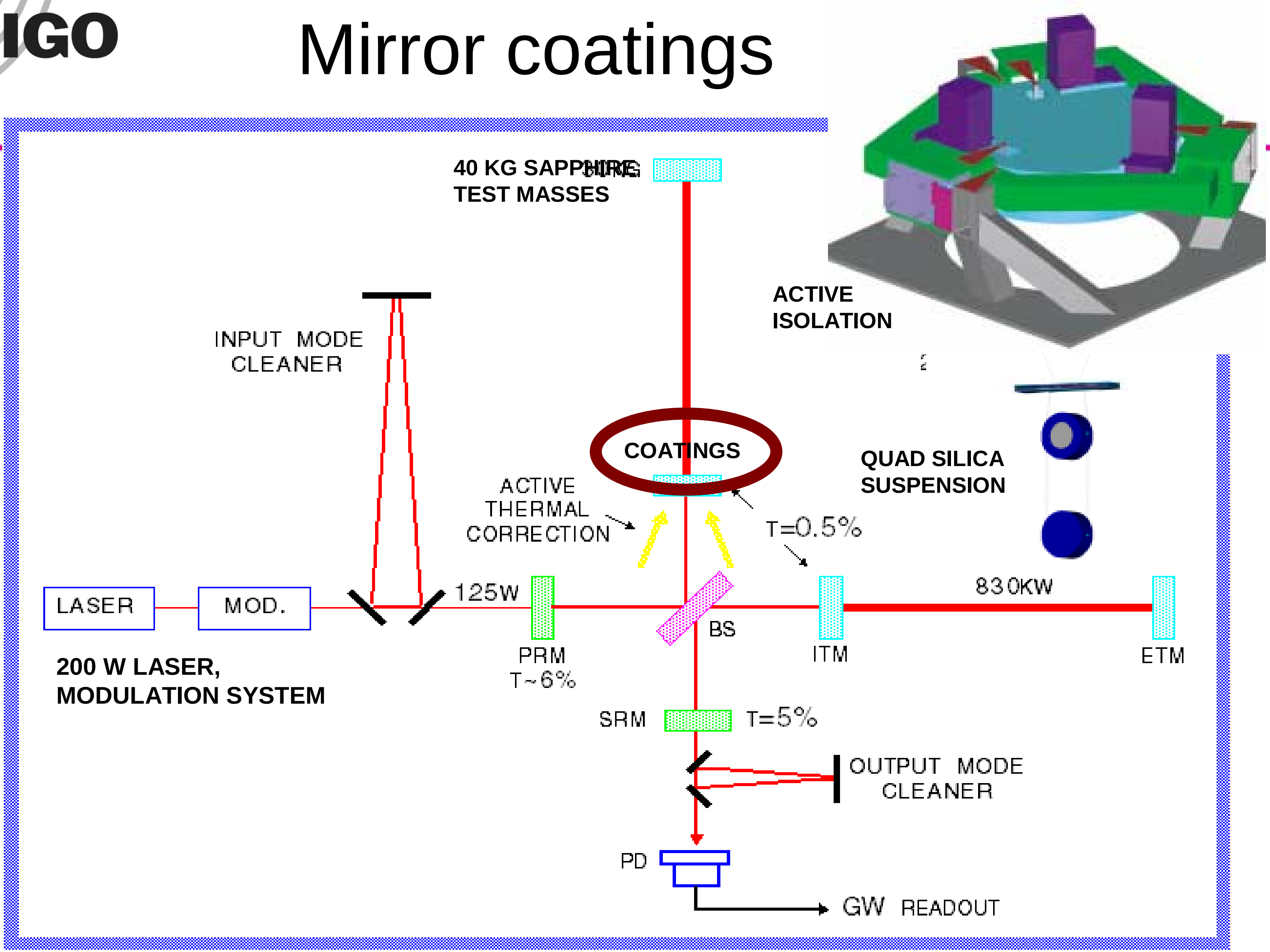
- Focus is on developing data needed for choice between Sapphire and Fused Silica as substrate materials
  - » Sapphire promises better performance, lower cost; feasibility is question
- Progress in fabrication of Sapphire:
  - » 4 full-size Advanced LIGO boules, 31.4 x 13 cm, grown
  - » Delivery in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





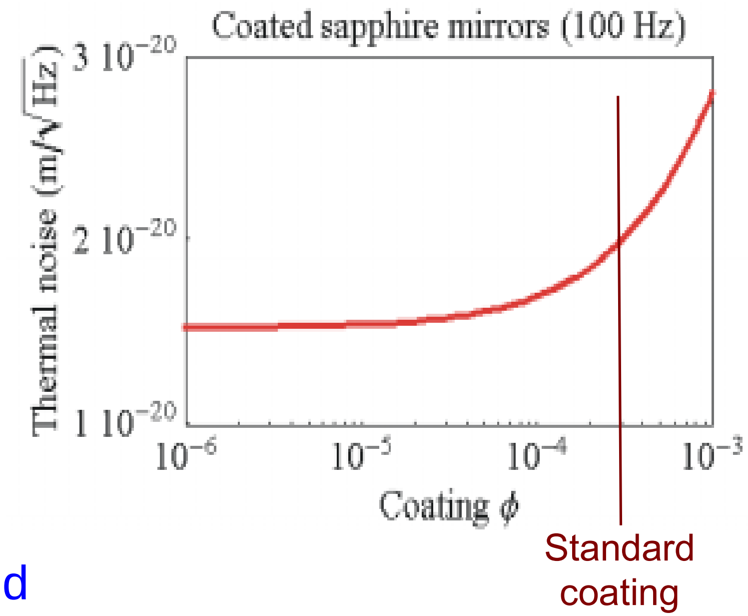
- Progress needed in mechanical loss measurements, optical absorption
- Downselect Sapphire/Silica in March-May 2003

Mirror coatings

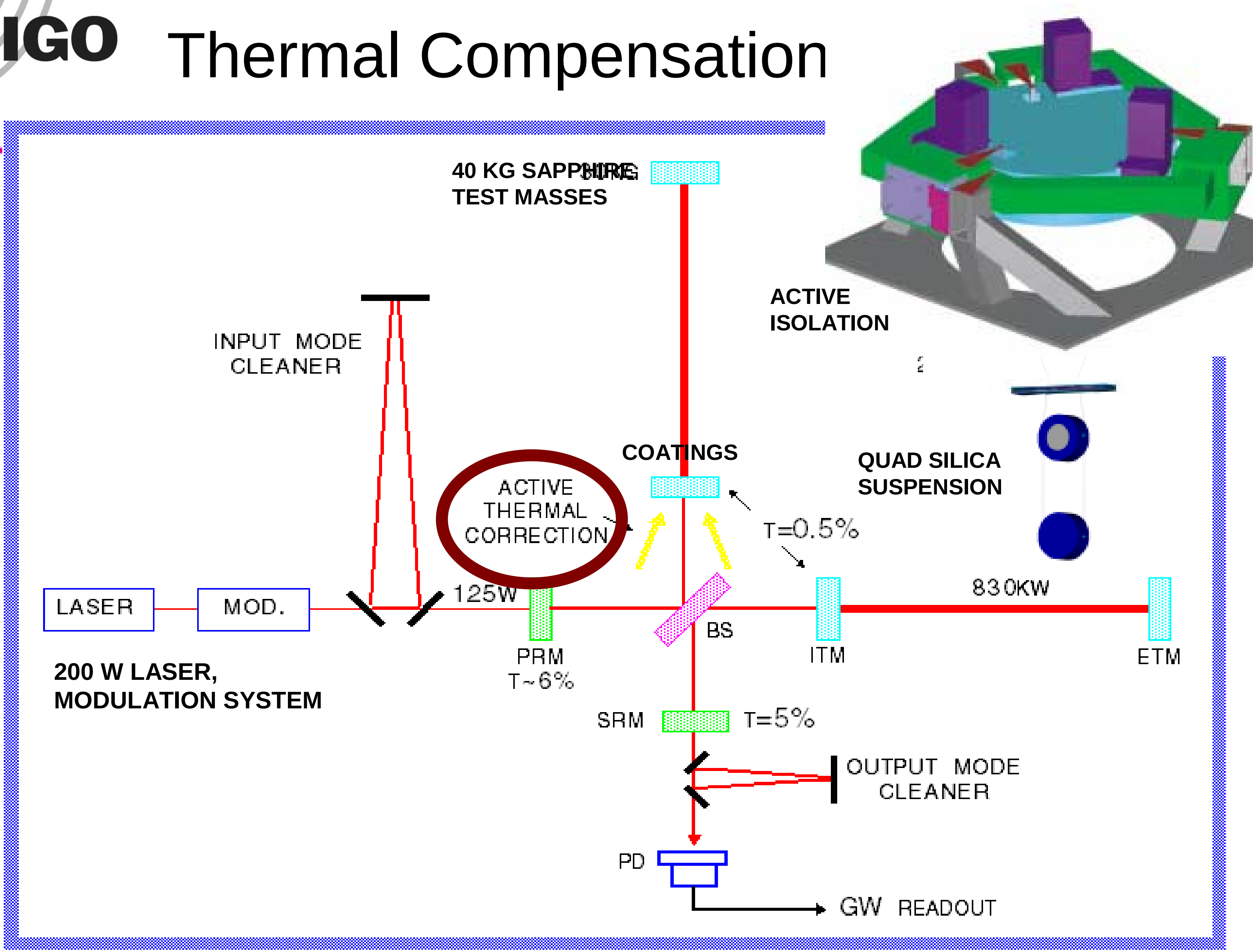


Coatings

- 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 Ta2O5, not SiO2
  - » 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



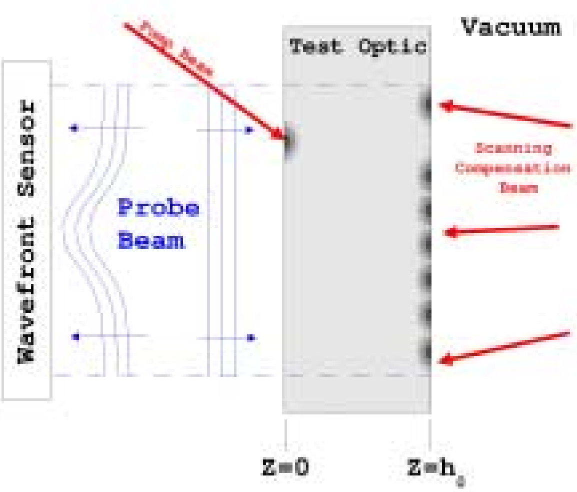
Thermal Compensation

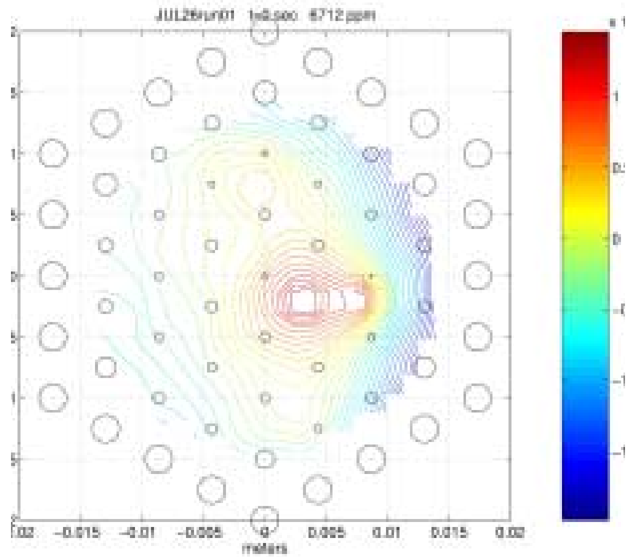


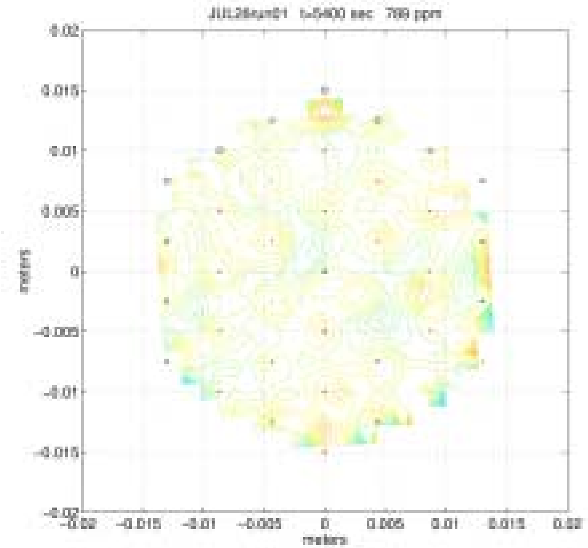
LIGO

Active Thermal Compensation

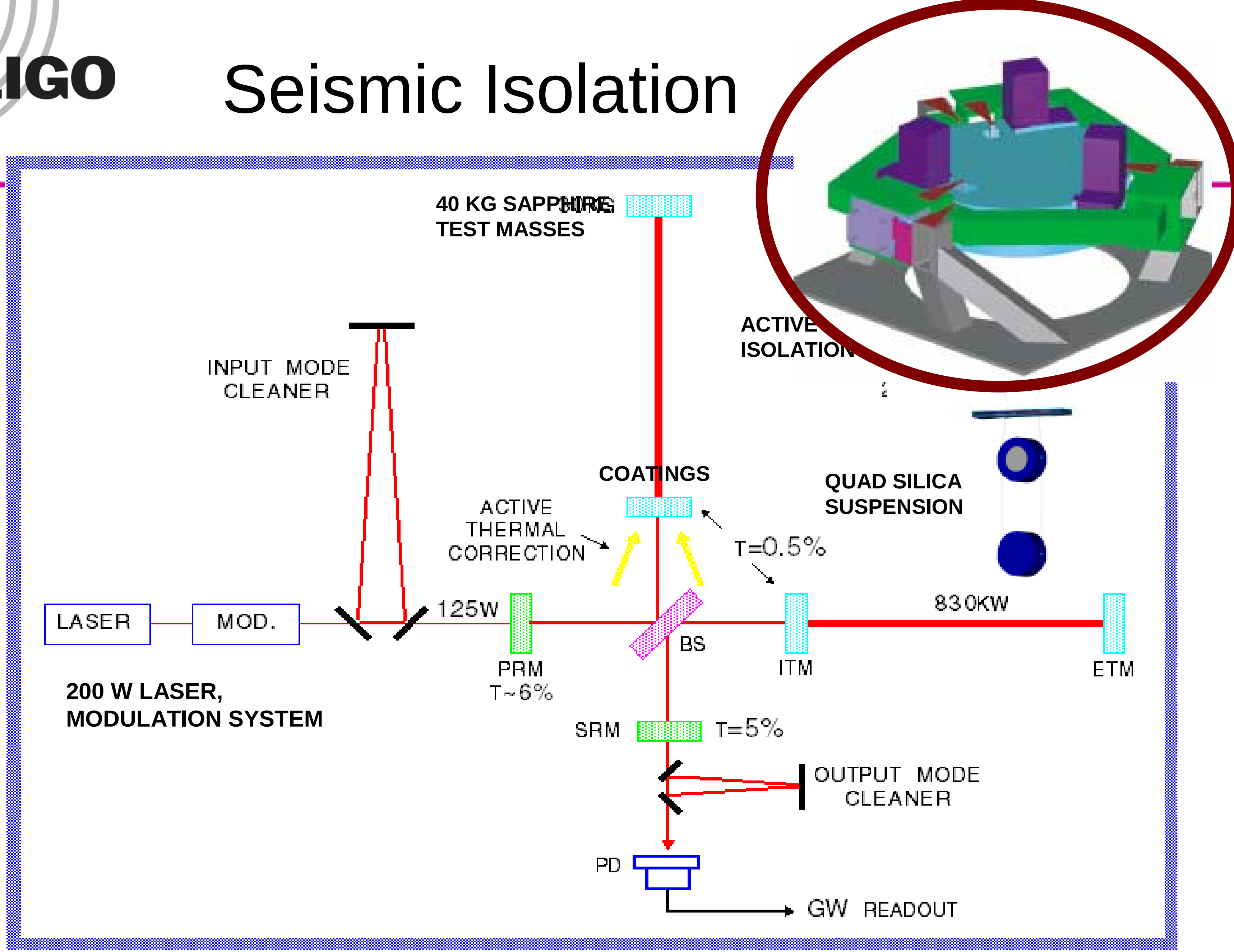
- Removes excess ‘focus’ due to absorption in coating, substrate
- Two approaches possible, alone or together:
  - » quasi-static ring-shaped additional heat (probably on compensation plate, not test mass itself)
  - » Scan (raster or other) to complement irregular absorption
- Models and tabletop experiments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





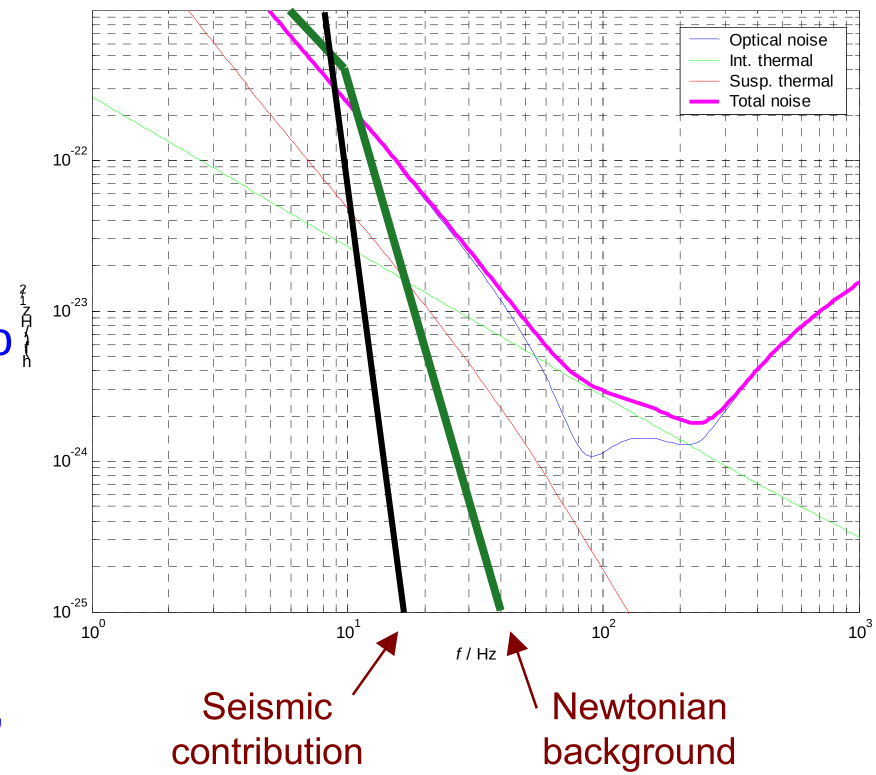


Seismic Isolation



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



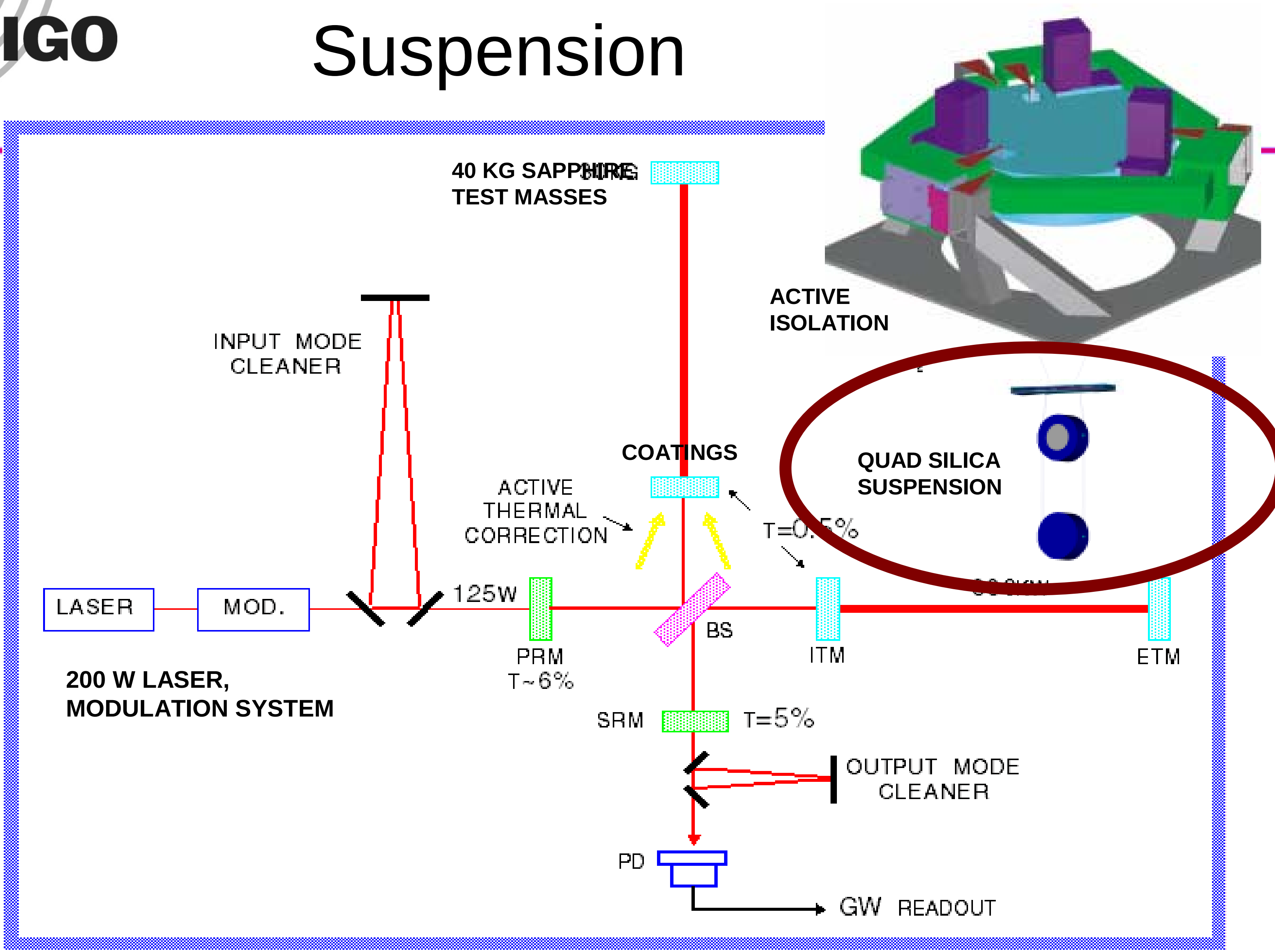
Isolation I: Pre-Isolator

- 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
  - » First servoloops closed on electromagnetic variant
  - » Hydraulic variant in installation
- 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

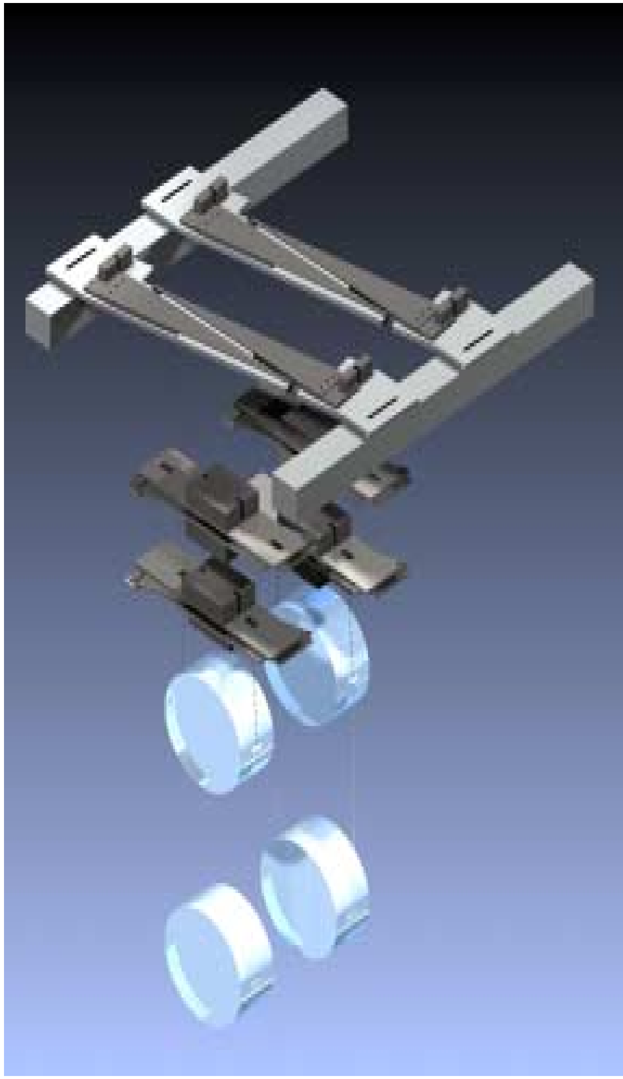
Suspension



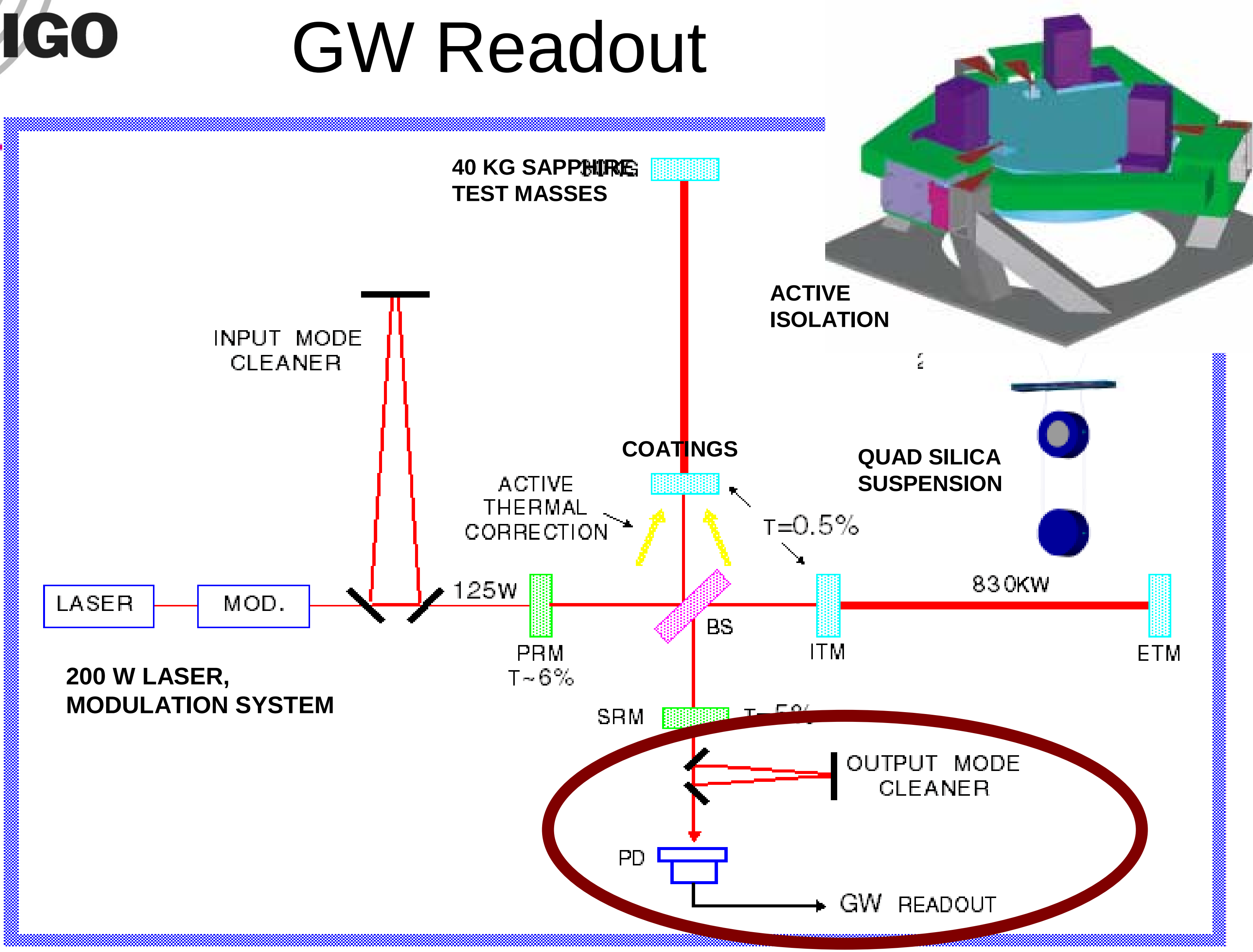
40 KG SAPPHIRE
TEST MASSES
ACTIVE
ISOLATION
INPUT MODE
CLEANER
COATINGS
QUAD SILICA
SUSPENSION
ACTIVE
THERMAL
CORRECTION
LASER
MOD.
125W
PRM
T~6%
BS
ITM
ETM
200 W LASER,
MODULATION SYSTEM
SRM
T=5%
OUTPUT MODE
CLEANER
PD
GW READOUT

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 comfort
- 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


40 KG SAPPHIRE
TEST MASSES
ACTIVE
ISOLATION
INPUT MODE
CLEANER
COATINGS
ACTIVE
THERMAL
CORRECTION
T=0.5%
QUAD SILICA
SUSPENSION
LASER
MOD.
125W
830KW
PRM
T~6%
BS
ITM
ETM
200 W LASER,
MODULATION SYSTEM
SRM
OUTPUT MODE
CLEANER
PD
GW READOUT

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
- Chance that some more insight into quantum/squeezing can be incorporated in the baseline (or in an early upgrade)

Technical challenges (dhs view)

- In order of concern:

- PSL: selection of power technology
- IO: handling high power (thermal focussing issues, aperture)
- Readout/Control: optimization of quantum noise
- Thermal Compensation: prototype test on cavities
- Seismic Isolation: performance of complete system; schedule
- Suspensions: low-noise damping system
- Core Optics/Test Masses: selection of Sapphire/Fused Silica
- Coatings: Development of low-mechanical-loss coatings

Advanced LIGO: History

- Lab & LSC submitted White Paper and Conceptual Project Book in late 1999
- Requested MRE funding in FY2002 to commence support of increased and vigorous R&D
- Planned to install in the vacuum system in 2005
- Cost about $114 million (FY2000) without accounting for contributions from operations budget and international partnerships
- Peoples panel gave favorable review
- **NSF decision to support R&D through design from operating funds (R&RA) in renewal (2002-2006) proposal**

Timing of submission

- Detecting gravitational waves is compelling, and Advanced LIGO “appears” crucial
  - » to detection if none made with initial LIGO
  - » to capitalizing on the science if a detection is made with initial LIGO
- Delaying submission likely to create a significant gap in the field – at least in the US
  - » Encouragement from both instrument and astrophysics communities
- Our LSC-wide R&D program is in concerted motion
  - » Appears possible to meet program goals
- We are reasonably well prepared
  - » Reference design well established, largely confirmed through R&D
  - » Cost estimate and schedule plan coming together with a burst of effort
- Timely for International partners that we move forward now

LIGO

GEO Role in Advanced LIGO

- GEO is in LSC
- UK groups (Glasgow, Birmingham, RAL) have submitted project funding proposal for ~$12 million to fund:
  - Delivery of suspensions
  - Delivery of some sapphire substrates (long lead purchases)
  - Proposal assumes UK funds start 1Q04
- German group will also submit project support proposal
  - Baseline plan is to cover delivery of installed/spare Pre-Stabilized Lasers

The Process

- Initial LIGO must have successful S1 and S2 runs
  - » Produce results
  - » Make good interferometer progress
- Prepare text for proposal
  - » Stability of concept makes this relatively easy
- Prepare cost/schedule for proposal
  - » Most subsystems completed to excruciating detail
  - » MRE proposal must be ≥10% of division budget -- ~$110 M
  - » Within range of (total cost)

    -- (UK+German proposed contribution) – present R&D – operations support
- Work with Tom Lucatorto, Bev Berger, Joe Dehmer
- NSF leadership must be thoroughly briefed and supportive
- FY2003 funding for LIGO operations must be good
- When we submit, we have to be confident of success

LIGO

Upgrade/Proposal Options

- Incremental improvements to initial LIGO
  - » Pre-isolator a bit in this mold – but only helps reach original goal
- Phased Upgrades
  - » High power first (laser, modulation/isolation, thermal compensation)
  - » Separate addition of signal recycling
  - » Low frequency first (most logical phasing choice – hugely invasive)

  -- all waste considerable time and money w.r.t. full Advanced LIGO
- Interferometer count
  - » 3 IFOs
  - » 2 IFOs

  -- a more interesting question: best long-term Astrophysics?
- MRE account vs. program funds
- Proposal coordinated or jointly submitted by LIGO/LSC/GEO/ACIGA

Advanced LIGO

- A great deal of momentum and real technical progress in every subsystem
- No fundamental surprises as we move forward; concept and realization remain intact with adiabatic changes
- Responsible progress in initial LIGO commissioning and observation
- Plan on submission January 2003, targeting observations in 2009