Advanced LIGO Research and Development

David Shoemaker

NSF Annual Review of LIGO

17 November 2003

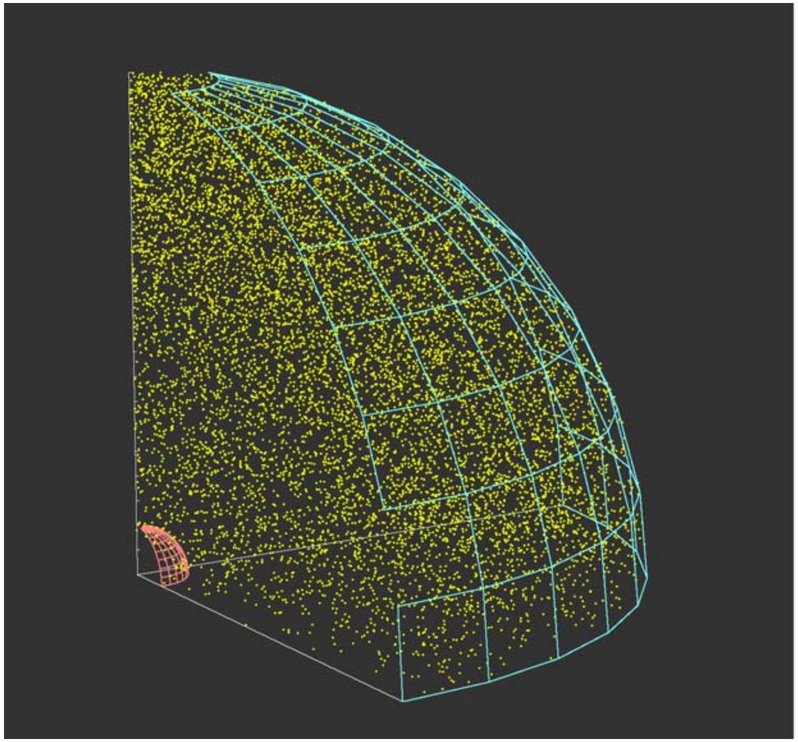
- LIGO mission: detect gravitational waves and

  initiate GW astronomy
- Commissioning talk shows considerable progress toward initial LIGO planned performance and operation
- Direct detection of gravitational waves plausible and eagerly awaited

- How do we move from the sensitivity of initial LIGO to an instrument which regularly makes astrophysical measurements of gravitational waves?

Advanced LIGO

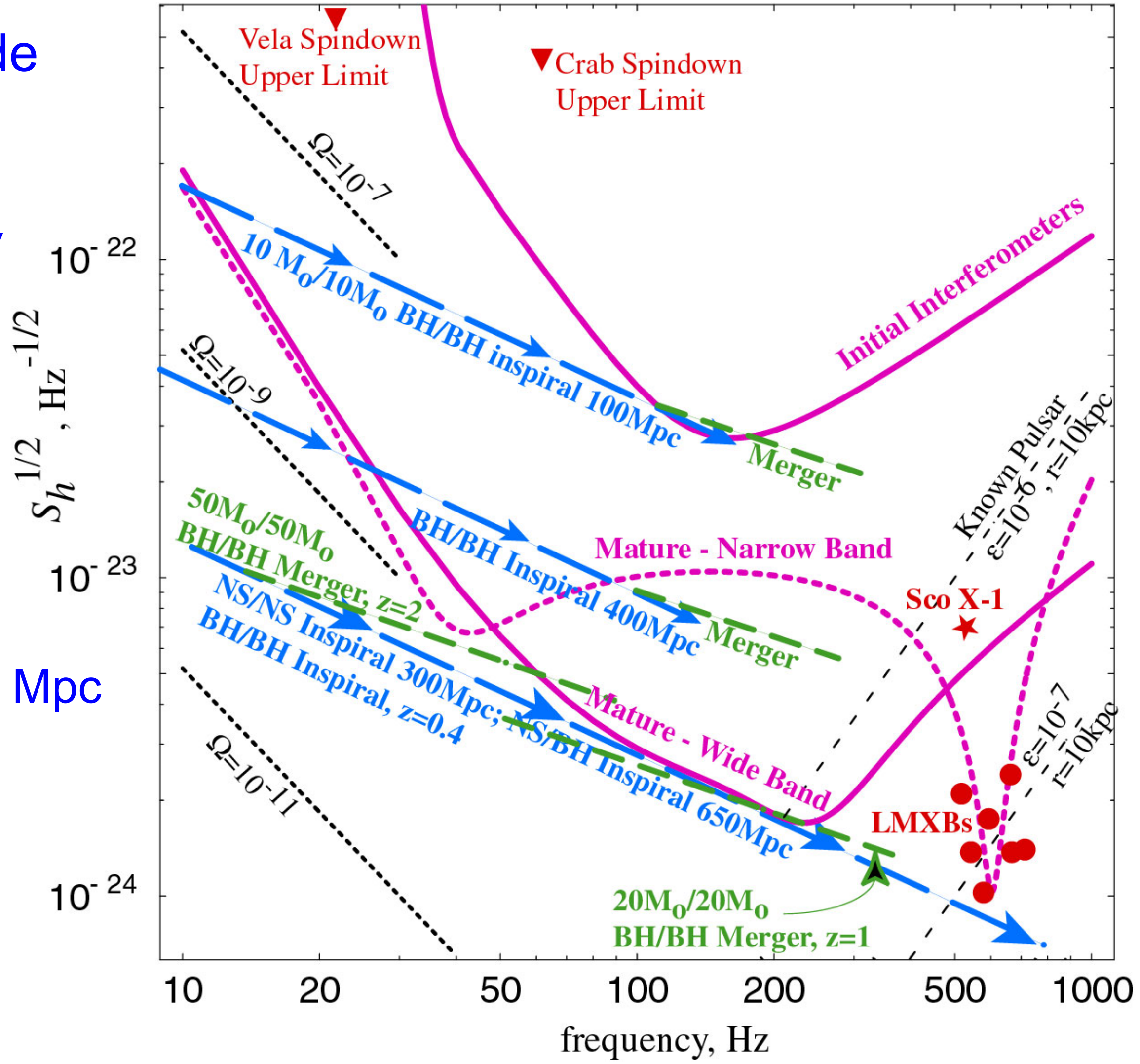
- Requirements for the next detector in the LIGO infrastructure
  - » Should have assured detection of known sources
  - » Should be at the limits of reasonable extrapolations of detector physics and technologies
  - » Must be a realizable, practical, reliable instrument
  - » Should come into existence neither too early nor too late



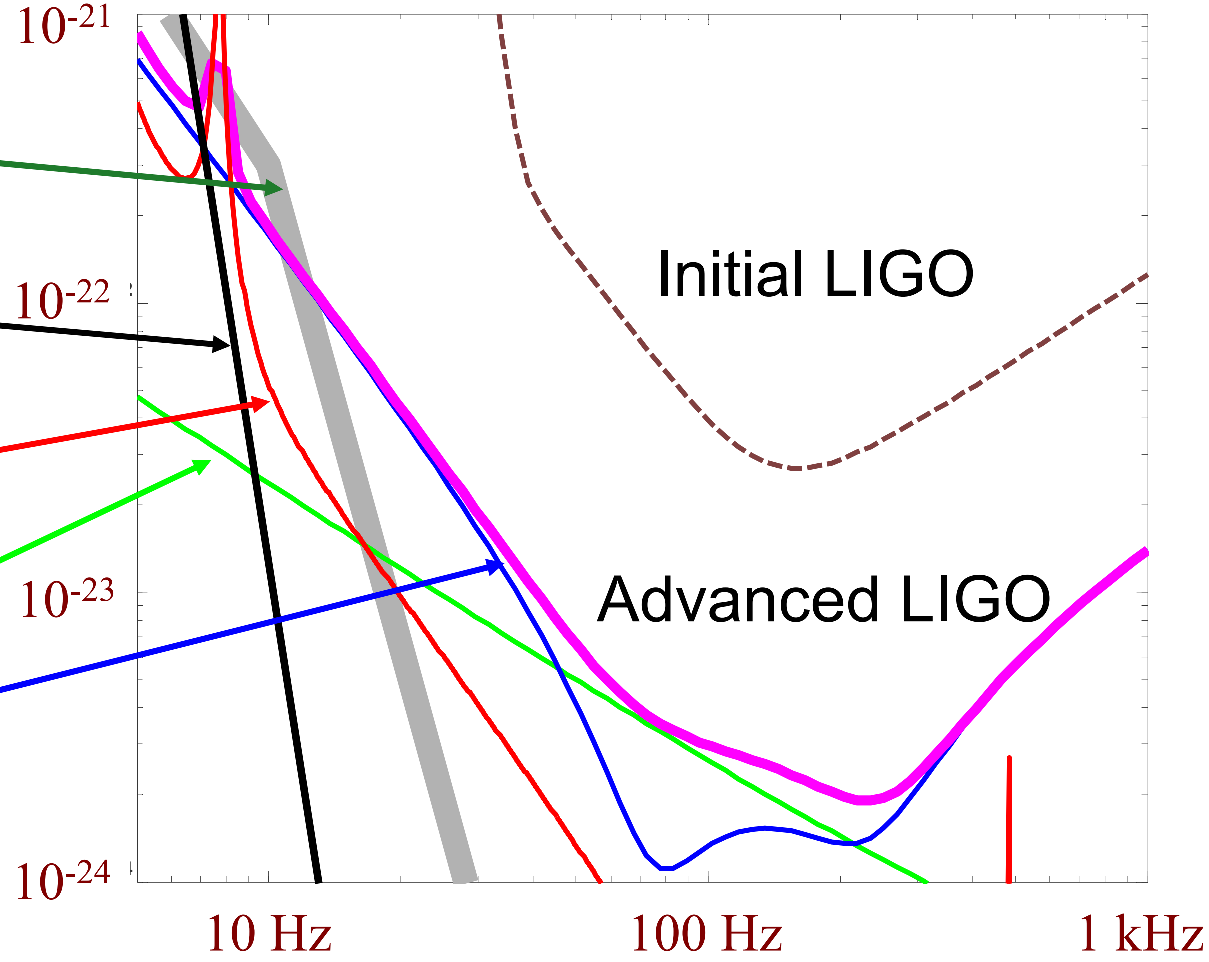
→ **Advanced LIGO**

Initial and Advanced LIGO

- Factor 10 better amplitude sensitivity
  - $(\text{Reach})^3$ = rate
- Factor 4 lower frequency bound
- NS Binaries: for three interferometers,
  - Initial LIGO: ~20 Mpc
  - Adv LIGO: ~350 Mpc
- BH Binaries:
  - Initial LIGO: 10 M_o, 100 Mpc
  - Adv LIGO : 50 M_o, z=2
- Stochastic background:
  - Initial LIGO: ~3e-6
  - Adv LIGO ~3e-9



Anatomy of the projected Adv LIGO detector performance



- Newtonian background, estimate for LIGO sites
- Seismic ‘cutoff’ at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Unified quantum noise dominates at most frequencies for full power, broadband tuning
- Advanced LIGO's Fabry-Perot Michelson Interferometer is flexible – can tailor to what we learn before and after we bring it on line, to the limits of this topology

Limits to the performance

- Two basic challenges:
  - » Sensing the motion of the test masses with the required precision; ideally limited by quantum effects
  - » Reducing undesired motion of the test masses which can mask the gravitational wave; intrinsic thermal motion a fundamental limit, seismic noise an obvious difficulty
- Many ‘merely technical’ challenges
  - » Defects in the sensing system which give an excess above the quantum noise
  - » Control system sensors, dynamic range, actuators, etc.
  - » Work hard on these challenges to make system reliable, ease commissioning, improve statistics of noise, availability

Sensing for initial LIGO

- Shot-noise limited – counting statistics of photons (or photodiode current)
  - Precision improves with (laser power)$^{1/2}$ until….

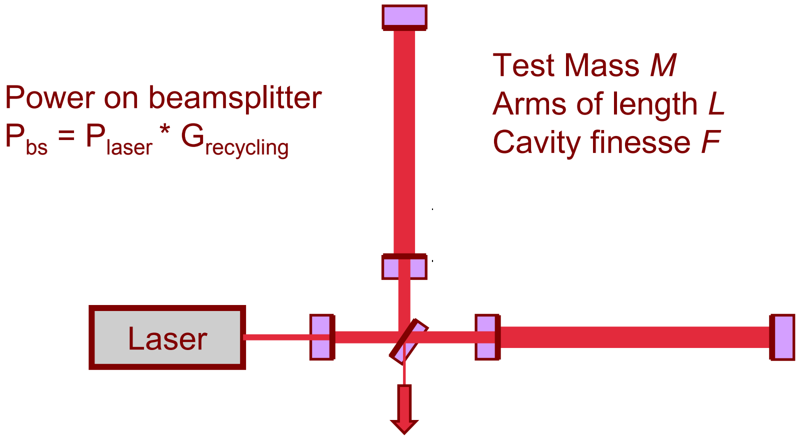
$$h(f) = \frac{1}{F^2 L}\sqrt{\frac{hc\lambda}{8P_{bs}}}\,\frac{1}{T_{ifo}(\tau_s, f)}$$

- Transfer of momentum from photons to test masses starts to dominate
  - $1/f^{\,2}$ spectrum (inertia of test masses)
  - Gives ‘standard quantum limit’

$$h(f) = \frac{2F}{ML}\sqrt{\frac{2\hbar P_{bs}}{\pi^3 c\lambda}}\,\frac{T_{ifo}(\tau_s, f)}{f^2}$$

- Initial LIGO power recycled interferometer layout
  - Michelson for sensing strain
  - Fabry-Perot arms to increase interaction time
  - Power recycling mirror to increase circulating power

….still far from standard quantum limit

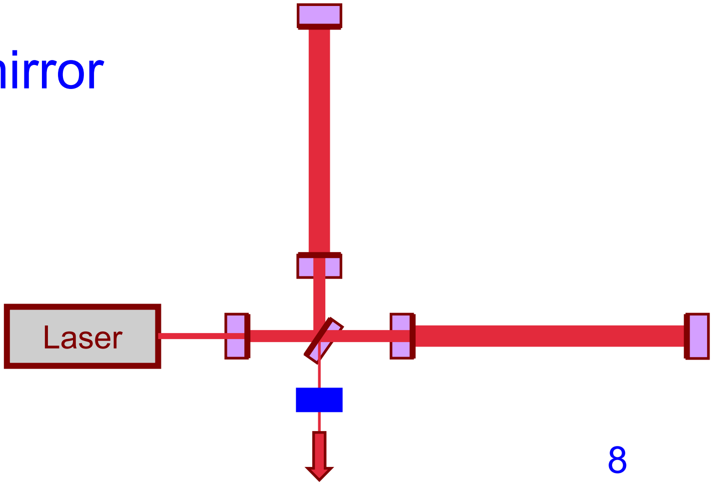


Power on beamsplitter
$P_{bs} = P_{laser} * G_{recycling}$

Test Mass *M*
Arms of length *L*
Cavity finesse *F*

Sensing for Advanced LIGO

- Build on initial LIGO layout –
  - retain Fabry-Perot cavities, power recycling
- Increase the laser power to a practical limit to lower shot noise
  - Laser power – require TEM00, stability in frequency and intensity
  - Absorption in optics – state-of-the-art substrates and coatings, compensation system to correct for focussing
  - ~180 W input power is the practical optimum for Advanced LIGO
  - Leads to ~0.8 MW in cavities (6cm radius beams, though)
  - Significant motion due to photon pressure – quantum limited!
- Modify optical layout: Add signal recycling mirror
  - Gives resonance for signal frequencies – can be used to optimize response
  - Couples photon shot noise and backreaction – some squeezing of light



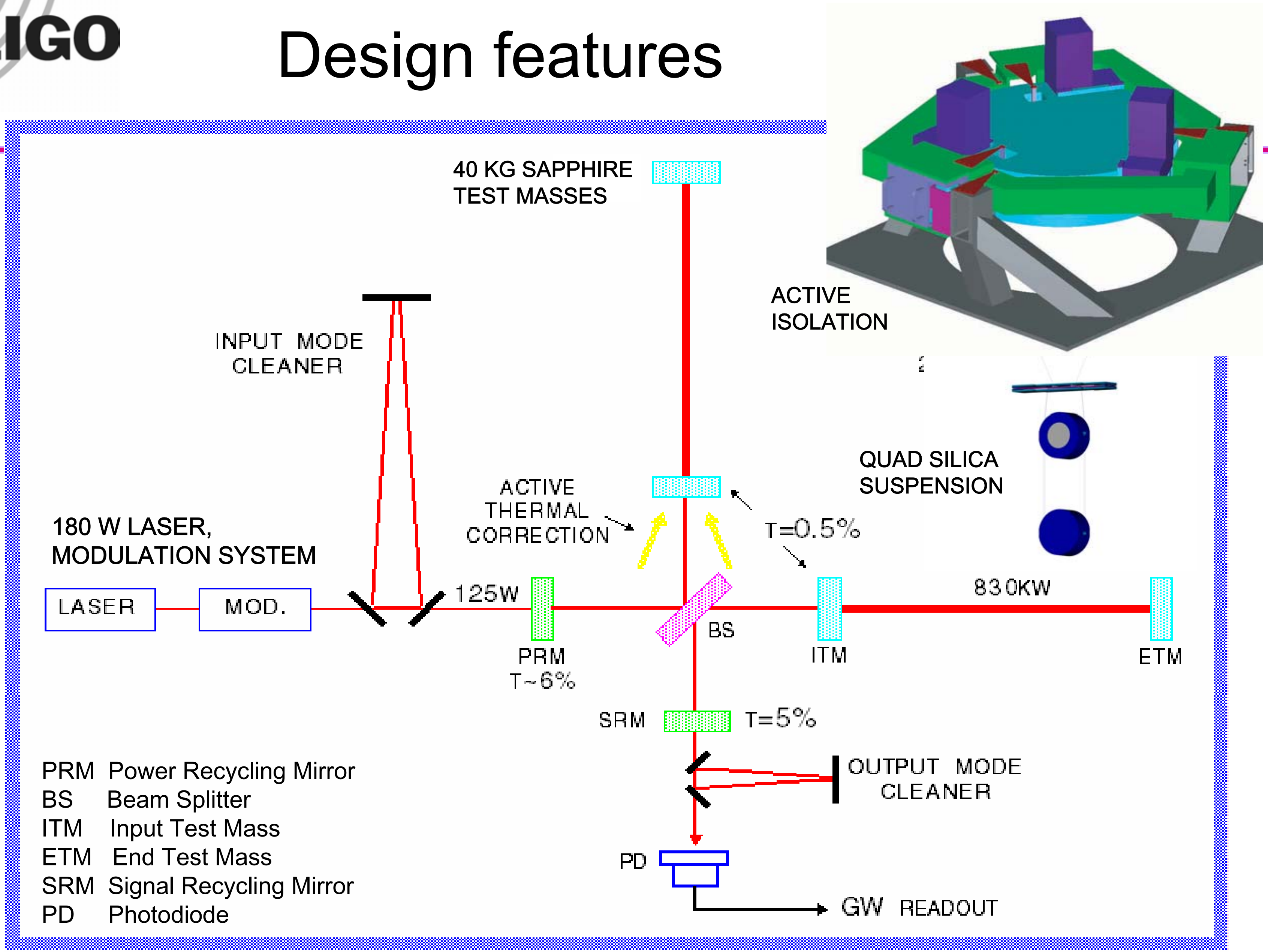
Stray forces on test masses

- Most Important: Make the interferometer long!
  - Scaling of thermal noise, seismic, technical
  - Cross-coupling from vertical to horizontal – 4km not far from ideal
- Thermal noise
  - ½ kT of noise per mode
  - Coupling to motion according to fluctuation-dissipation theorem
  - Gather the energy into a narrow band via low mechanical losses, place resonances outside of measurement band by choosing the right geometry
- Initial LIGO: fused silica substrates, attachments made to limit increases in loss, steel suspension wire
- Seismic Noise
  - Due to seismic activity, oceans, winds, and people
- Initial LIGO: cascaded lossy oscillators, analog of multipole low-pass filter – and now also an active pre-isolator in preparation

Managing Stray forces in Advanced LIGO

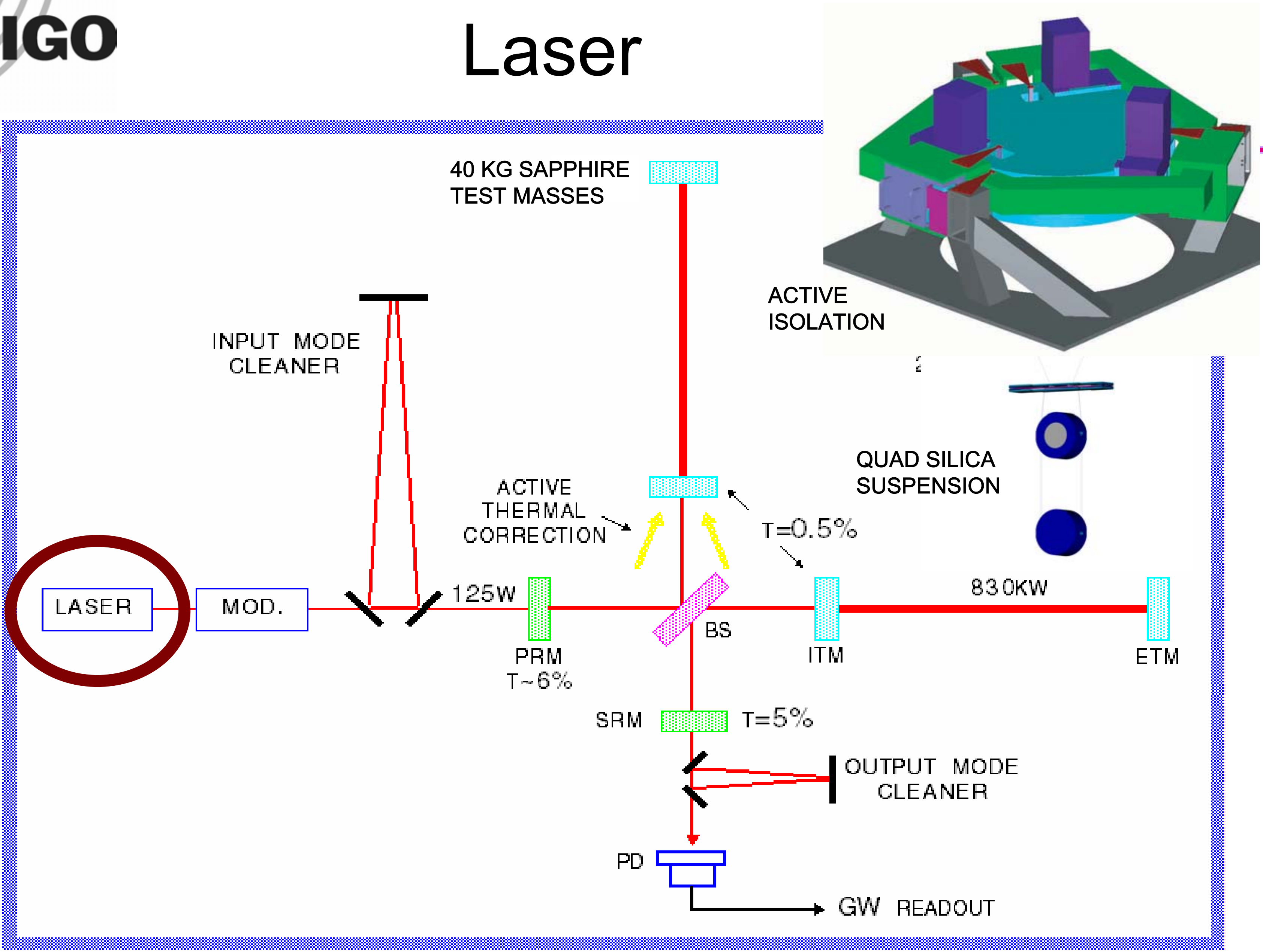
- Seismic Isolation: use servo-control techniques and low-noise seismometers to ‘slave’ optics platform to inertial space
  - Decreases motion in the gravitational-wave band to a negligible level
  - Decreases motion in ‘controls’ band, moving forces away from test mass
- Suspension thermal noise: all-silica fiber construction
  - Intrinsically low-loss material
  - Welded and ‘contacted’ construction also very low loss
- Substrate thermal noise: use monolithic Sapphire
  - High Young’s modulus
  - Low mechanical loss
  - (fallback: very low-loss silica)
- Optical coating thermal noise: develop low-loss materials and techniques
  - Area of active development

Design features



PRM	Power Recycling Mirror
BS	Beam Splitter
ITM	Input Test Mass
ETM	End Test Mass
SRM	Signal Recycling Mirror
PD	Photodiode

Laser


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
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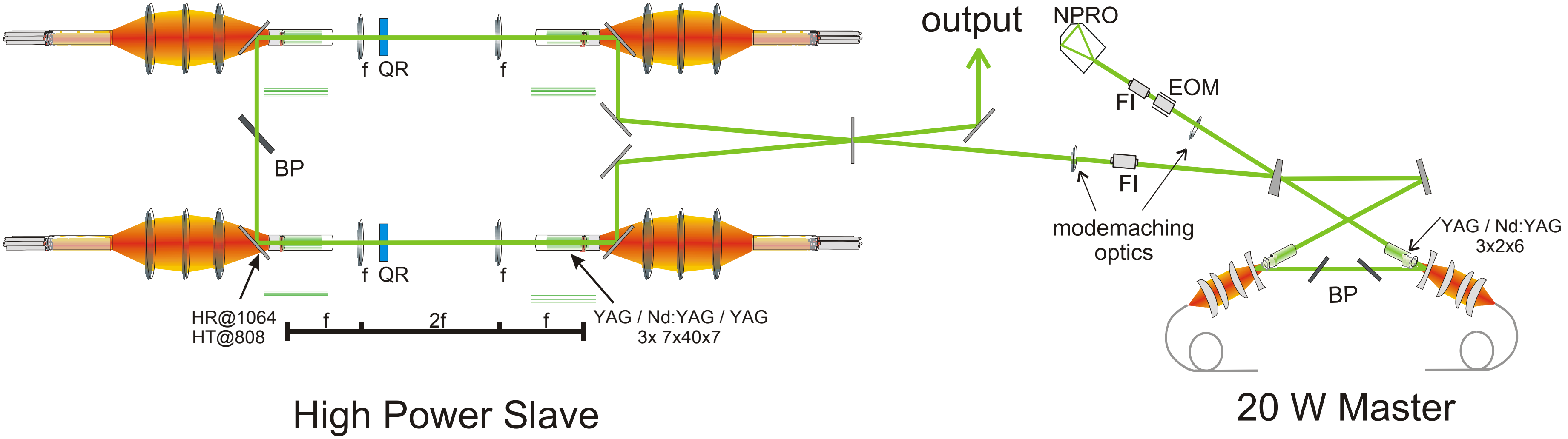
T=5%
OUTPUT MODE CLEANER
PD
GW READOUT

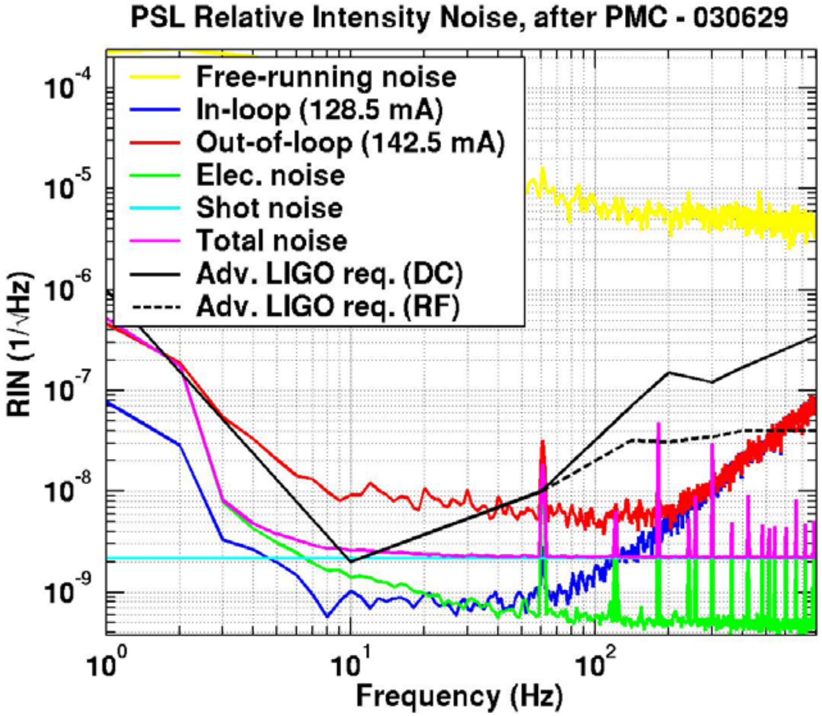
Pre-stabilized Laser

- Require the maximum power compatible with optical materials
  - » 1999 White Paper: 180 W at output of laser, leads to 830 kW in cavities
  - » Continue with Nd:YAG, 1064 nm
  - » Three approaches studied by LSC collaboration – stable/unstable slab oscillator (Adelaide), slab amplifier (Stanford), end-pumped rod oscillator (Laser Zentrum Hannover (LZH)); evaluation concludes that all three look feasible
  - » Choose the end-pumped rod oscillator, injection locked to an NPRO
  - » 2003: Prototyping well advanced – ½ of Slave system has developed 114 W, 87 W single frequency, M^2 1.1, polarization 100:1



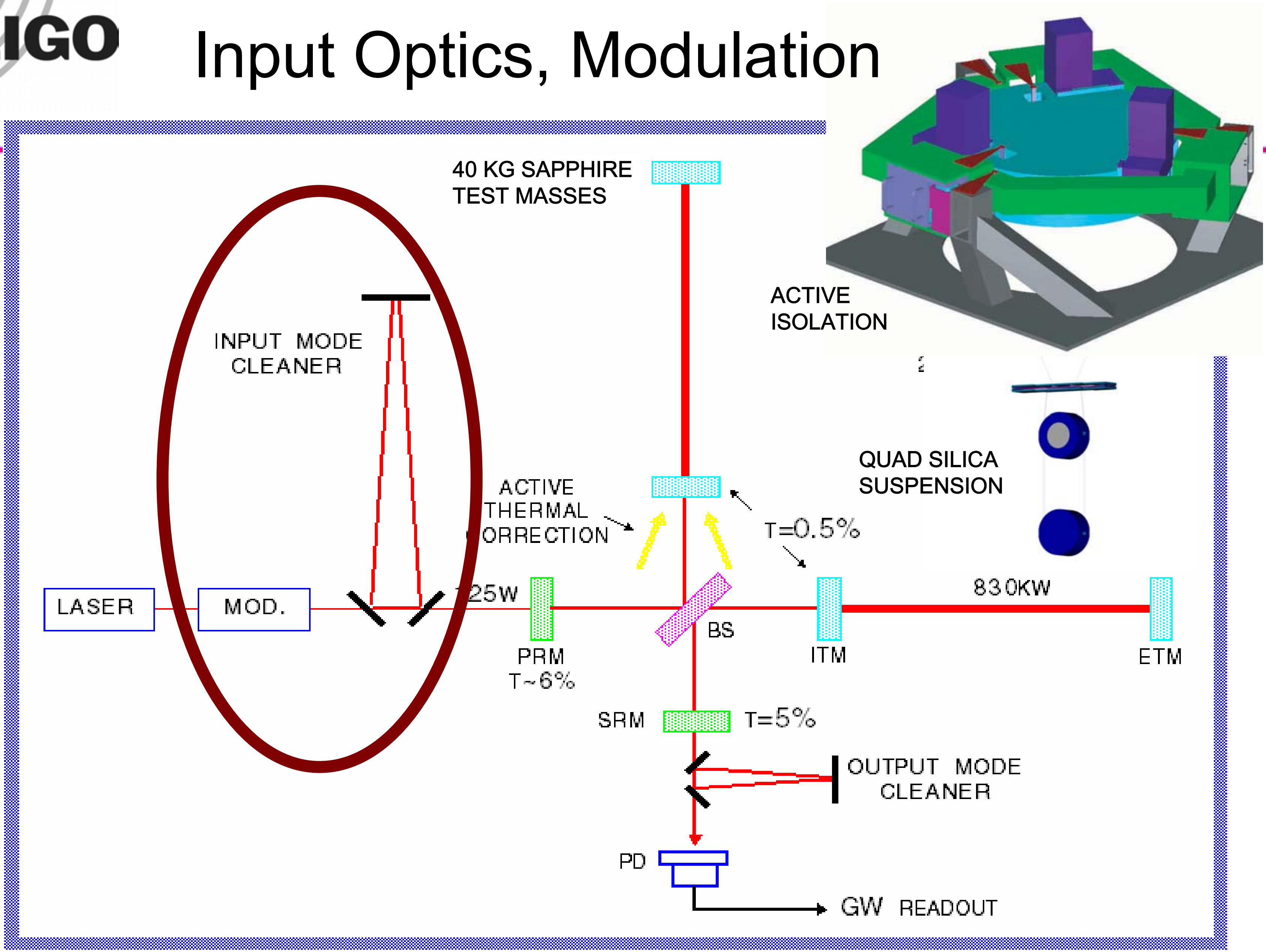
Pre-stabilized laser

- Overall subsystem system design similar to initial LIGO
  - » Frequency stabilization to fixed reference cavity, 10 Hz/Hz$^{1/2}$ at 10 Hz required (10 Hz/Hz$^{1/2}$ at 12 Hz seen in initial LIGO)
  - » Intensity stabilization to 2x10^{-9} ΔP/P at 10 Hz required
  - » 2003: 1x10^{-8} at 10 Hz demonstrated



- Max Planck Institute, Hannover leading the Pre-stabilized laser development
  - » Close interaction with Laser Zentrum Hannover
  - » Experience with GEO-600 laser, reliability, packaging
  - » German GEO Group contributing laser to Advanced LIGO

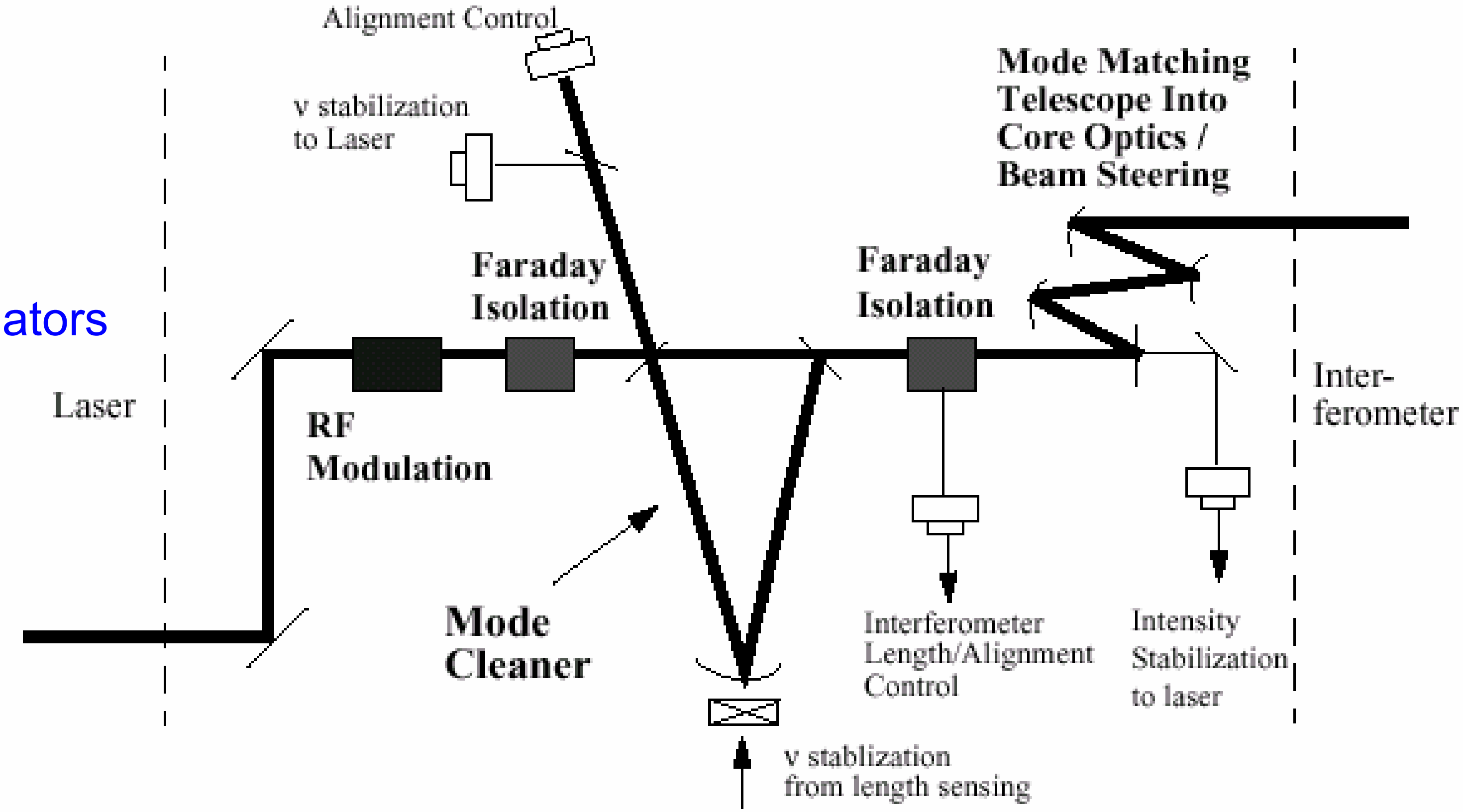
Input Optics, Modulation



Input Optics

- Provides phase modulation for length, angle control (Pound-Drever-Hall)
- Stabilizes beam position, frequency with suspended mode-cleaner cavity
- Matches into main optics (6 cm beam) with suspended telescope
- 1999 White Paper: Design similar to initial LIGO but 20x higher power

- Challenges:
  - » Modulators
  - » Faraday Isolators



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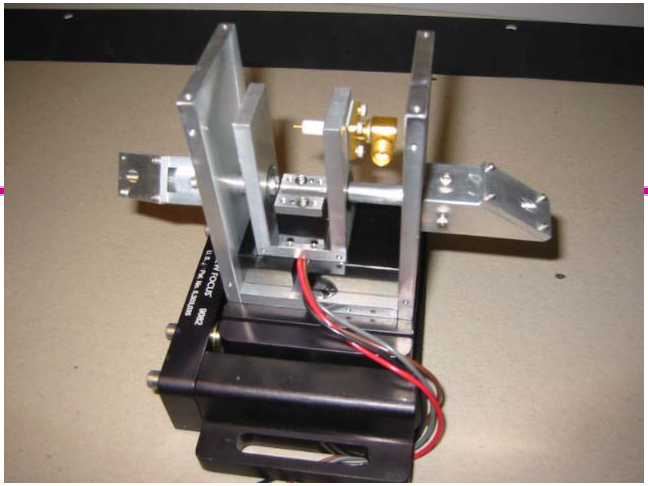
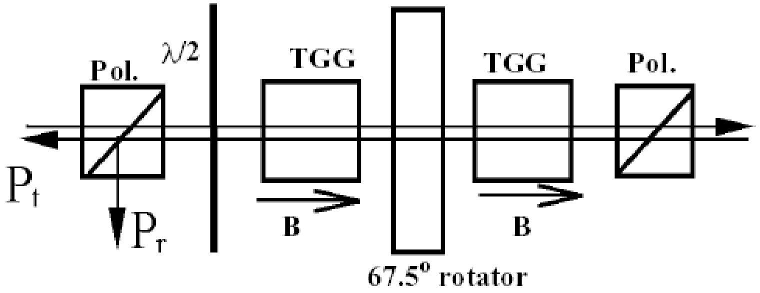
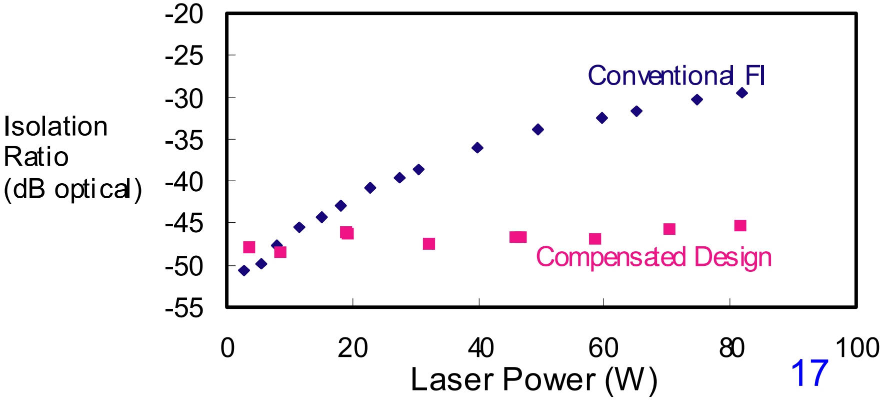
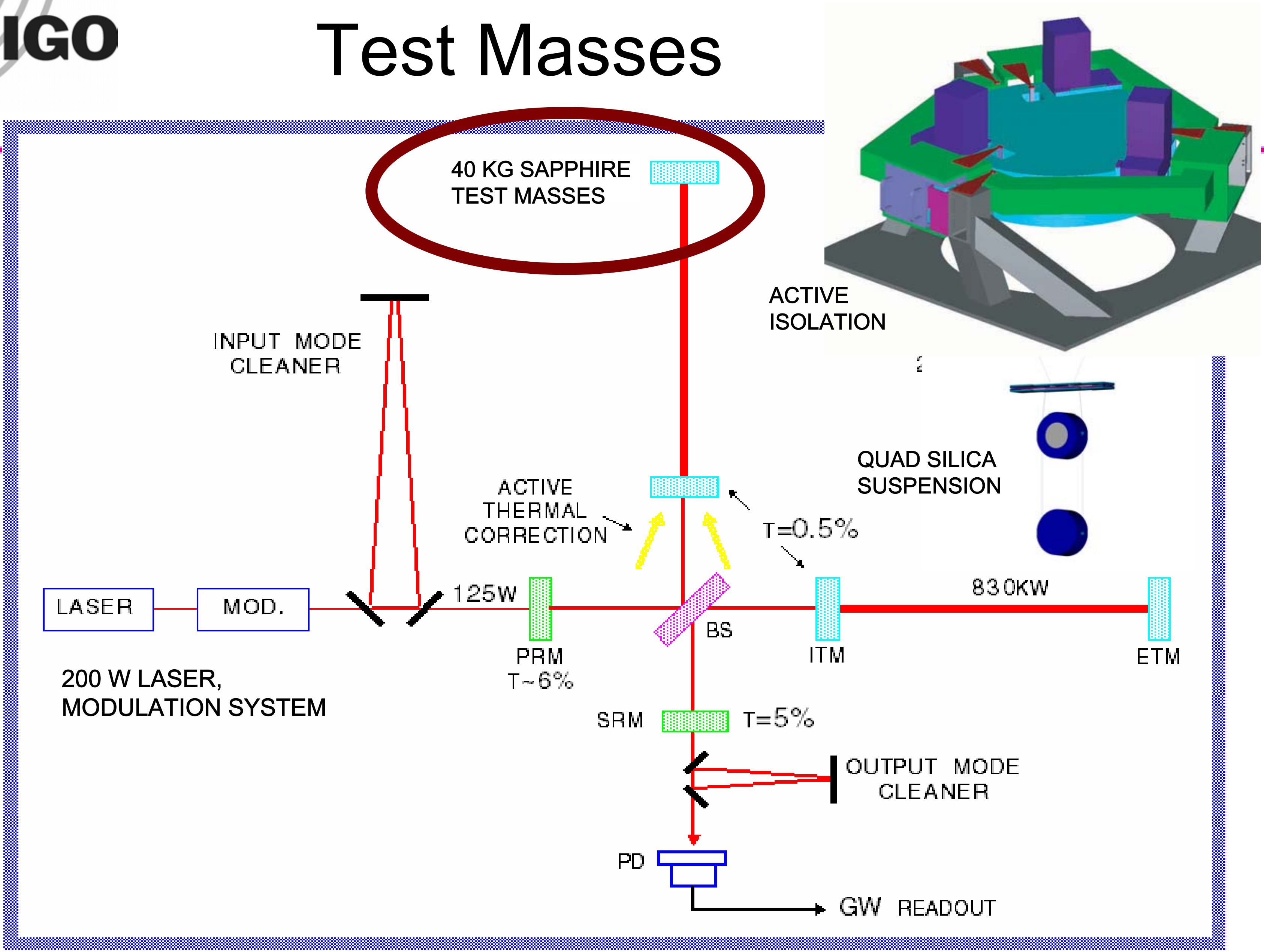


- University of Florida leading development effort
  - » As for initial LIGO
  - » 2003: LIGO Lab developing controls, suspensions (see later…)
- 2003: Faraday isolator from IAP-Nizhny Novgorod
  - » thermal birefringence compensated
  - » Ok to 80 W – more powerful test laser to be installed at Livingston for further tests





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

ITM

ETM

PRM T~6%

200 W LASER, MODULATION SYSTEM

SRM

T=5%

OUTPUT MODE CLEANER

PD

GW READOUT

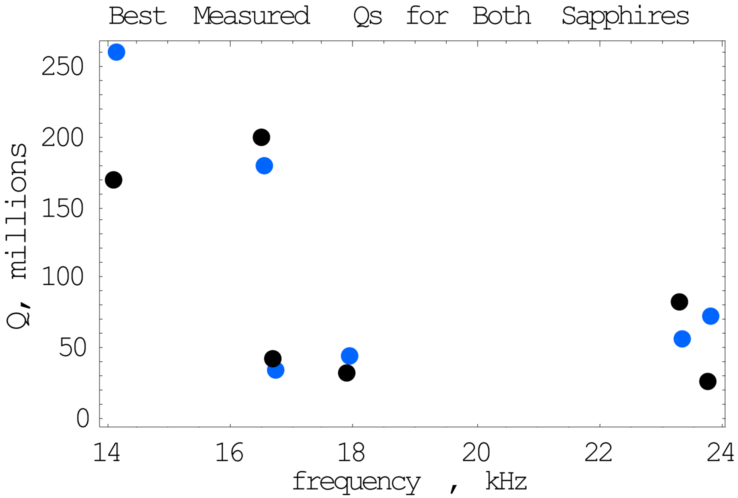
Test Masses / Core Optics

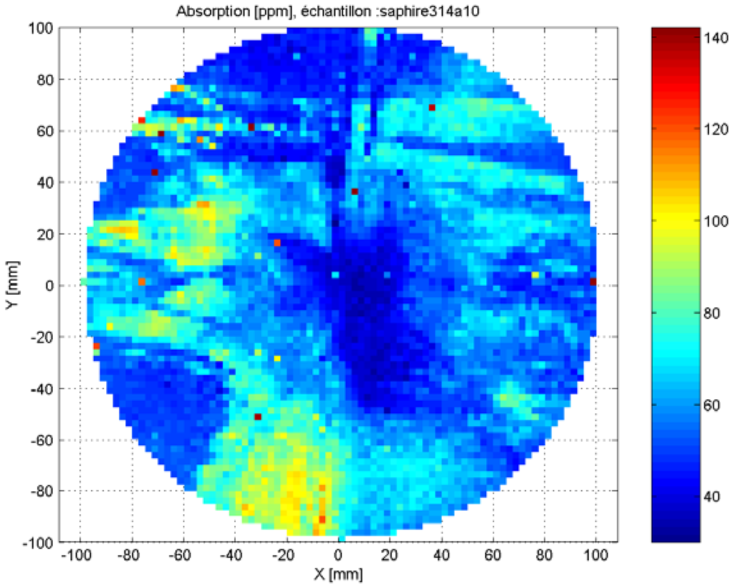
- Absolutely central mechanical *and* optical element in the detector
  - » 830 kW; <1ppm loss; <20ppm scatter
  - » 2×10^8 Q; 40 kg; 32 cm dia
- 1999 White Paper: Sapphire as test mass/core optic material; development program launched
- Low mechanical loss, high Young's modulus, high thermal conductivity all desirable attributes of sapphire
- Fused silica remains a viable fallback option
- Significant progress in program
  - » Industrial cooperation
  - » Characterization by very active LSC working group

Full-size Advanced LIGO sapphire substrate

Sapphire Core Optics

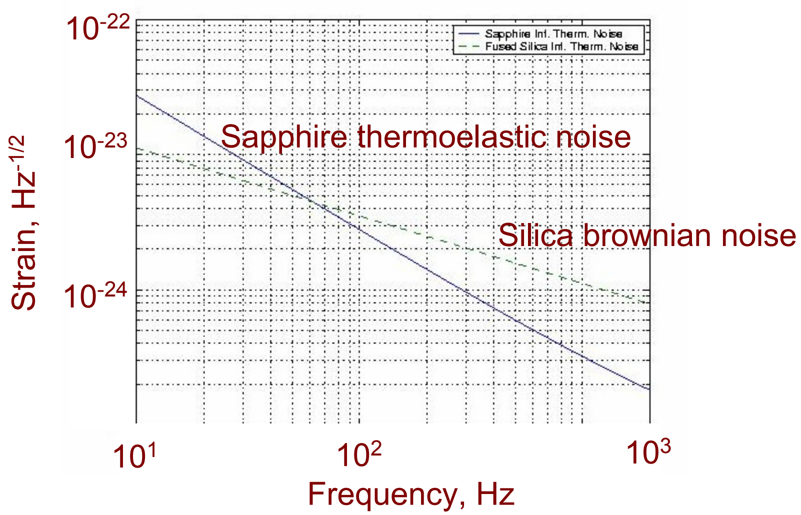
- Fabrication of Sapphire:
  - » Full-size Advanced LIGO boules grown (Crystal Systems); 31.4 x 13 cm
- Bulk Homogeneity: requirement met
  - » Sapphire as delivered has 50 nm-rms distortion
  - » Goodrich 10 nm-rms compensation polish
- Polishing technology:
  - » CSIRO has polished a 15 cm diam sapphire piece:
1.0 nm-rms uniformity over central 120 mm (requirement is 0.75 nm)
- 2003: Mechanical losses: requirement met
  - » Highest Q measured at <250 million
  - » Program to identify possible anisotropies in losses well underway: finite-element modeling
with Q measurements of many modes
- 2003: Bulk Absorption:
  - » Measured; uniformity needs work
  - » Average level ~60 ppm, 40 ppm desired

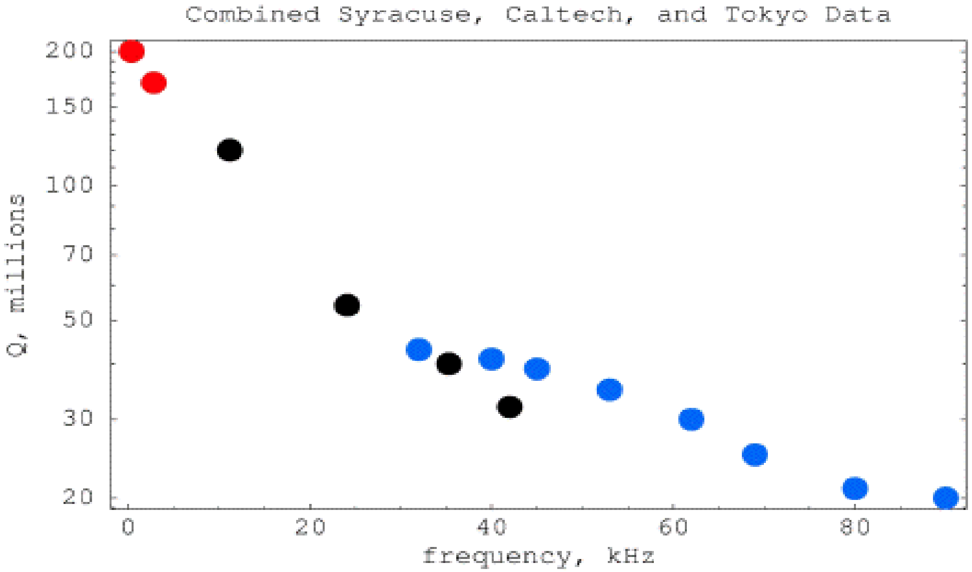




Backup: Fused Silica

- Alternative test mass material
- Familiar; fabrication, polishing, coating processes well refined
- Disadvantages:
  - » Overall thermal noise may be higher
  - » Thermal noise signature not as well suited to Adv LIGO
  - » Lower Young’s modulus leads to higher coating thermal noise
  - » More expensive (!)
- Development program to reduce mechanical losses, understand frequency dependence
  - » Annealing proven on small samples, needs larger sample tests and optical post-metrology
- strong backup – reduction in sensitivity would be minimal for current parameters



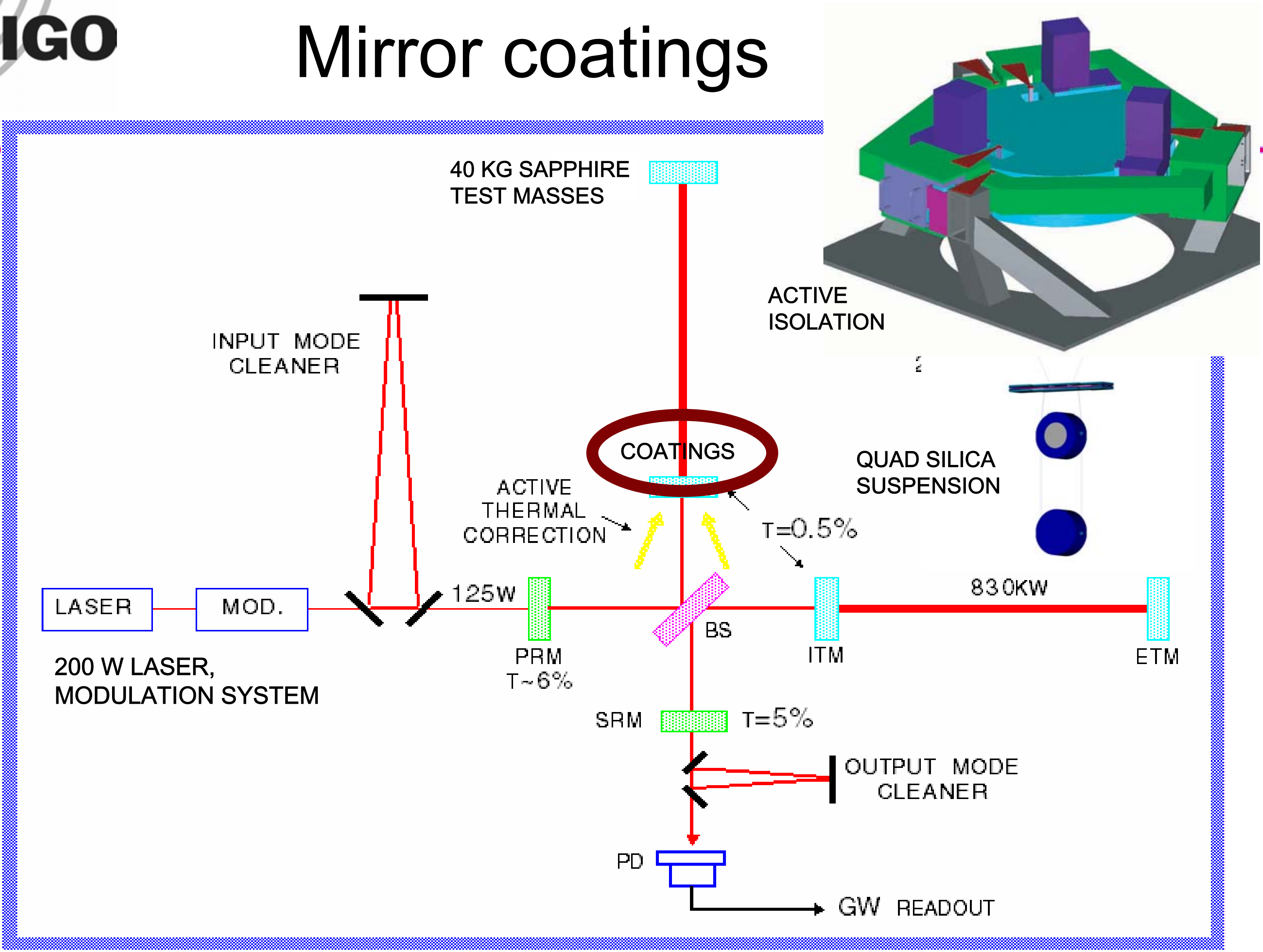


Test Mass downselect

- Remaining tests/models:
  - Absorption in second sample of sapphire
  - Scattering tests (inclusions)
  - Q tests of other sapphire samples (with polished barrel)
  - Annealing of small samples of both sapphire (absorption) and silica (mechanical losses)
  - Models of interferometer performance with absorption maps

- April 2004 for evaluation
  - Set to match suspension development plan
  - Could lead to requiring further actions
  - Believe we are close to adopting sapphire

Mirror coatings



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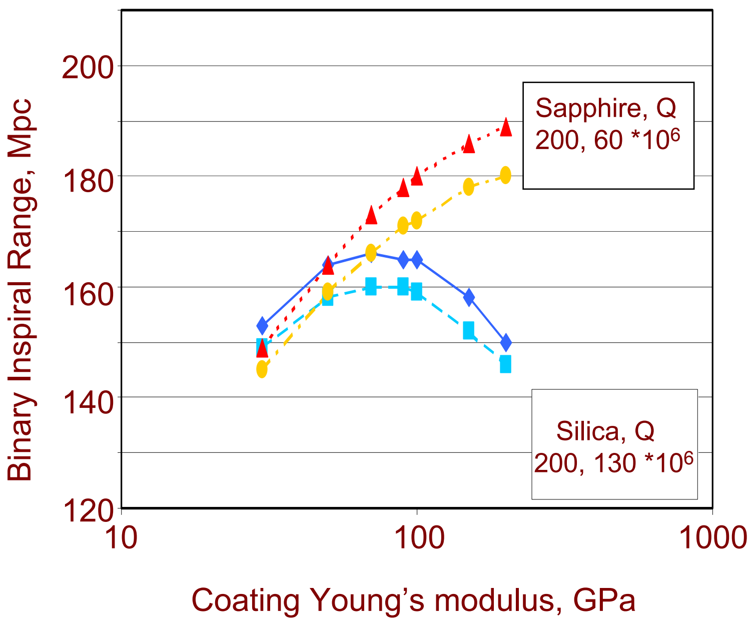
PD

GW READOUT

Test Mass Coatings

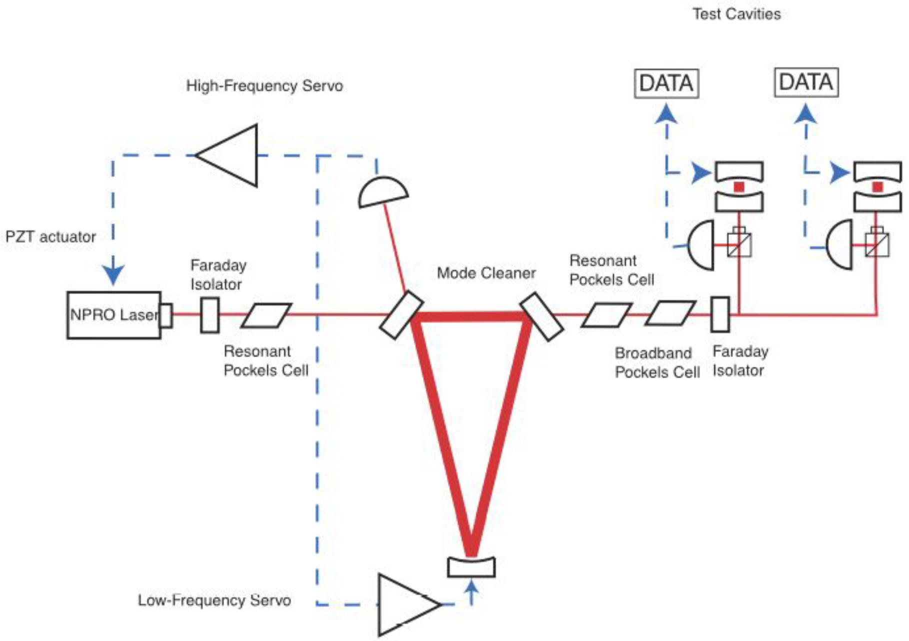
- Optical absorption (~0.5 ppm) requirements met by (good) conventional coatings
- R&D mid-2000: Thermal noise due to coating mechanical loss recognized; LSC program put in motion to develop low-loss coatings
  - » Series of coating runs – materials, thickness, annealing, vendors
  - » Measurements on a variety of samples
- Ta_2O_5 identified as principal source of loss
  - » Typical good coating φ=3-5e-4
- Test coatings show somewhat reduced loss
  - » Alumina/Tantala
  - » Doped Silica/Tantala
  - » Best (one sample) to date: φ=8e-5; 2e-4 reproducible
- Need ~5x reduction in loss to reduce current ~20% compromise to a negligible level

Coating loss $\varphi = 5 * 10^{-5}$

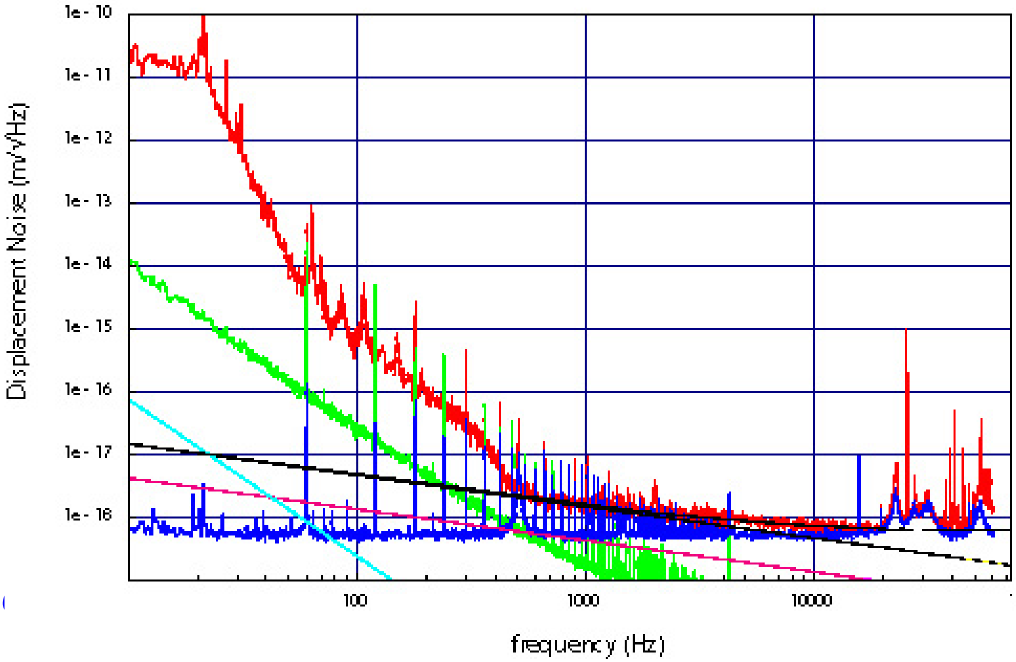


Direct measurement

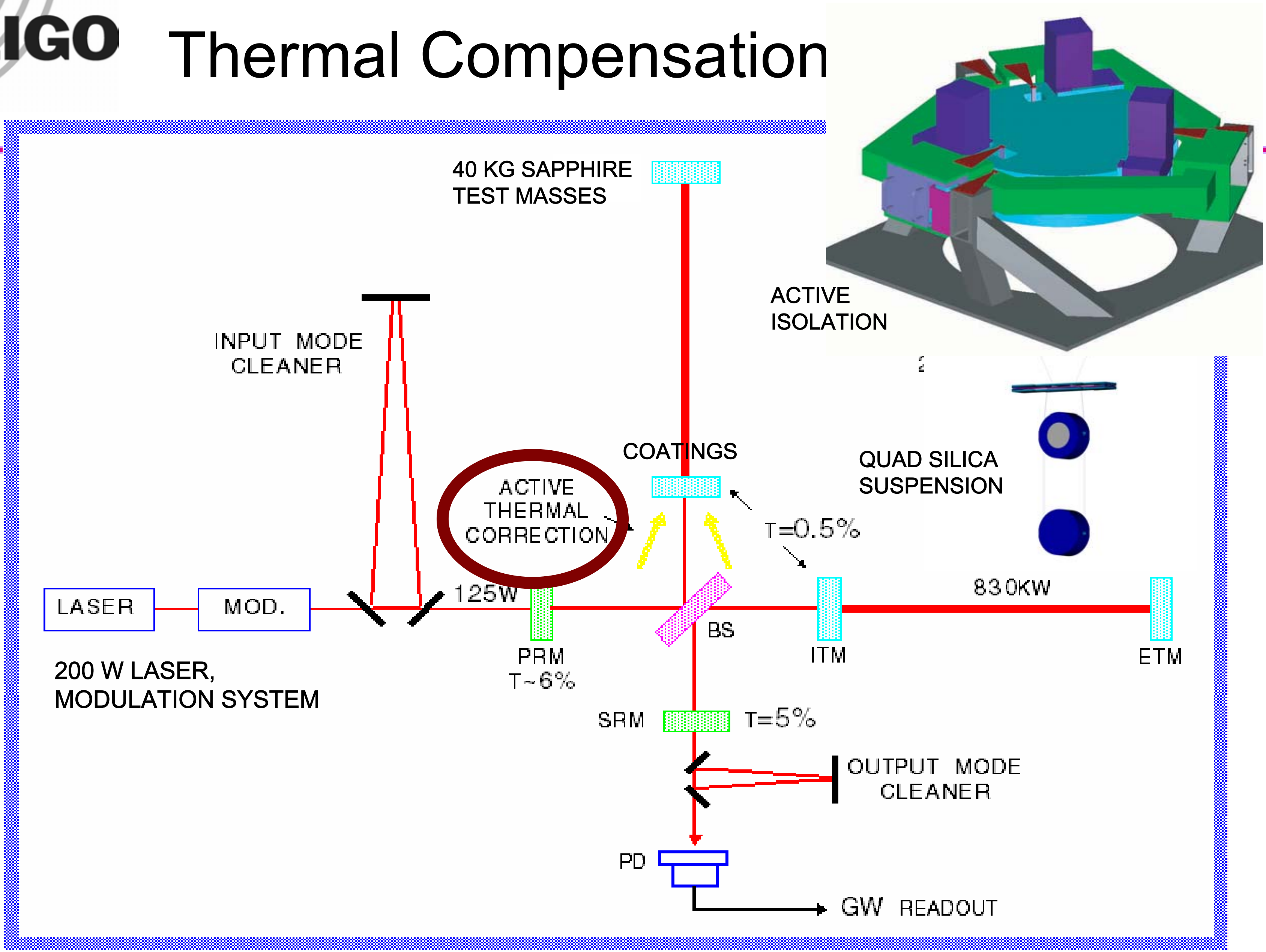
- Thermal Noise Interferometer (TNI) designed to measure coating and substrate thermal noise
- Presently set up with fused silica substrates with conventional coatings
- 2003: Recent results appear to show confirmation of models for anticipated coating losses; similar confirmation from Japanese experiment
- Sapphire substrates for measurement of thermoelastic noise ready



TNI noise floor 10/23/03

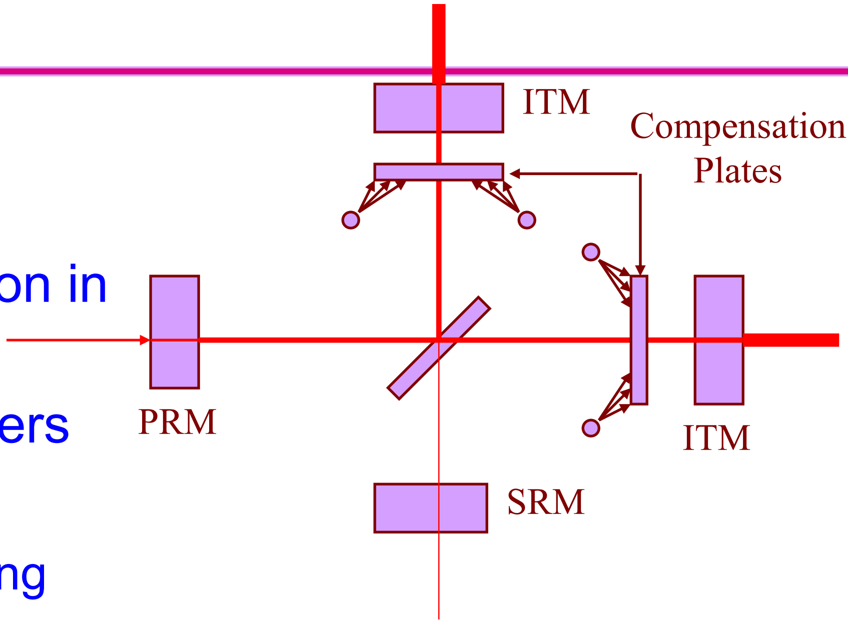


Thermal Compensation

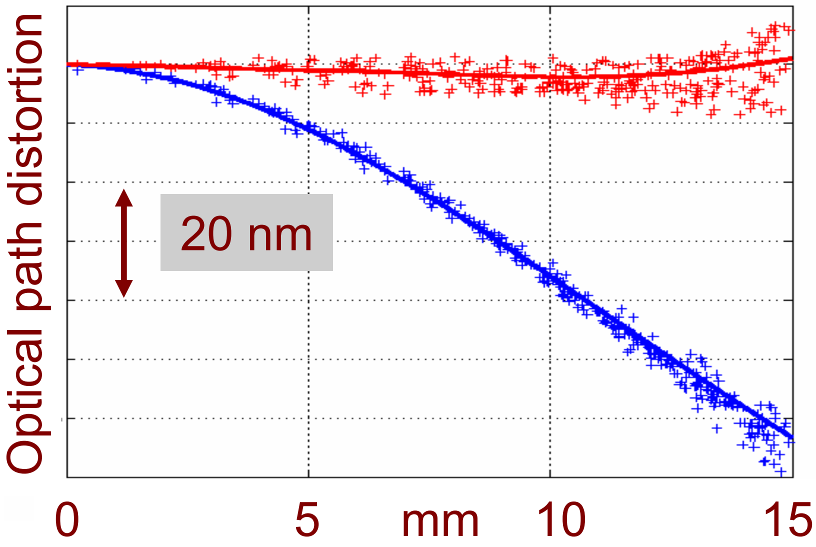


Active Thermal Compensation

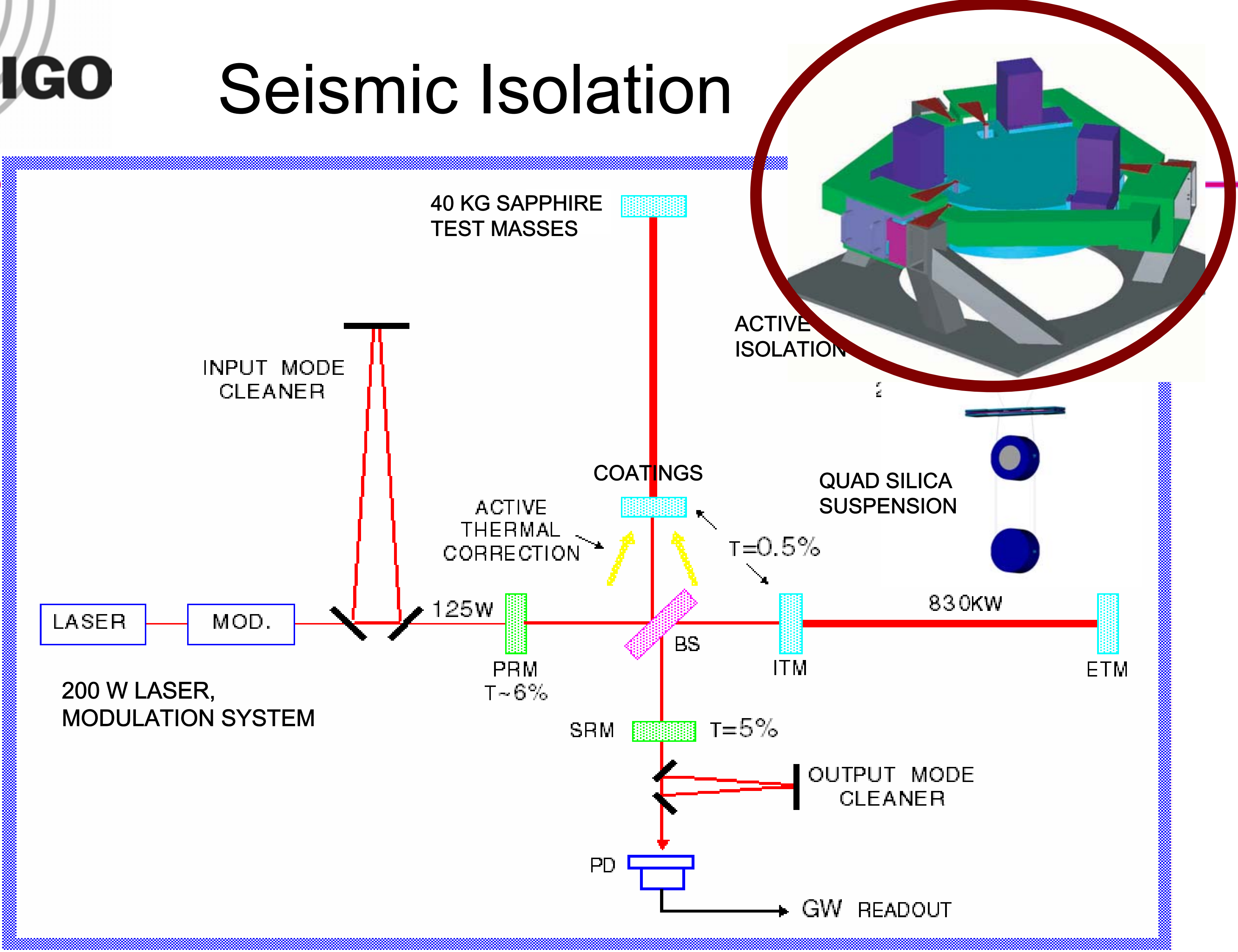
- 1999 White Paper: Need recognized, concept laid out
- Removes excess 'focus' due to absorption in coating, substrate
- Allows optics to be used at all input powers
- Initial R&D successfully completed
  - » Quasi-static ring-shaped additional heating
  - » Scan to complement irregular absorption
- Sophisticated thermal model ('Melody') developed to calculate needs and solution
- 2003: Gingin facility (ACIGA) readying tests with Lab suspensions, optics
- 2003: Application to initial LIGO in preparation



Shielded ring compensator test



Seismic Isolation



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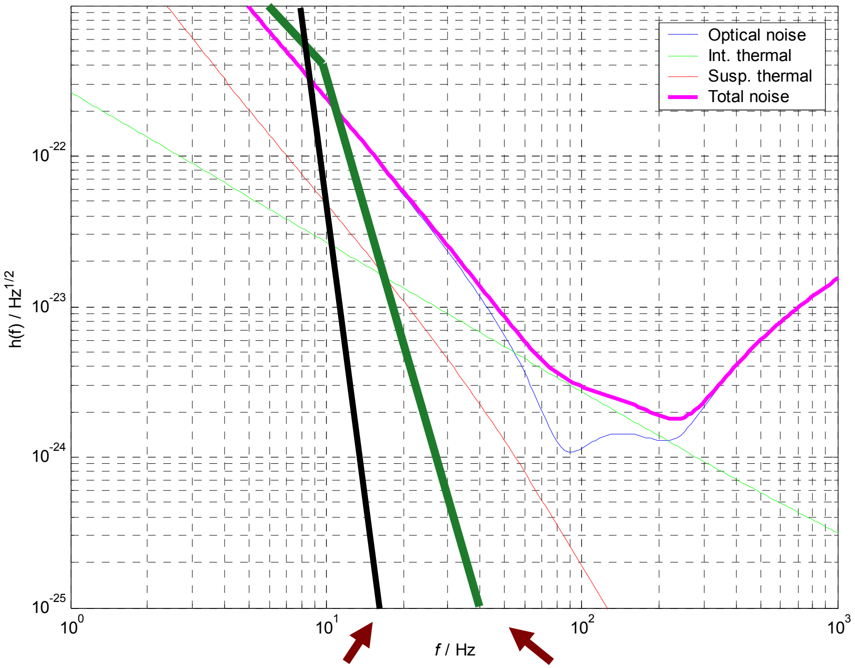
GW READOUT

Isolation: Requirements

- 1999 White Paper: Render seismic noise a negligible limitation to GW searches
  - » Newtonian background will dominate for frequencies less than ~15 Hz
  - » Suspension and isolation contribute to attenuation
- 1999 White Paper: Reduce or eliminate actuation on test masses
  - » Actuation source of direct noise, also increases thermal noise
  - » Acquisition challenge greatly reduced
  - » In-lock (detection mode) control system challenge is also reduced

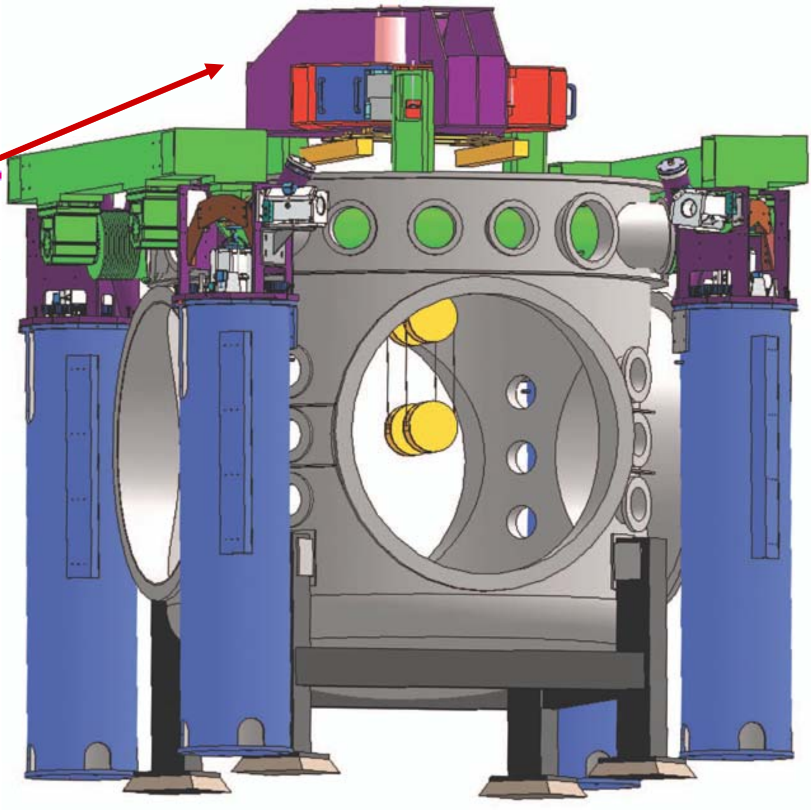


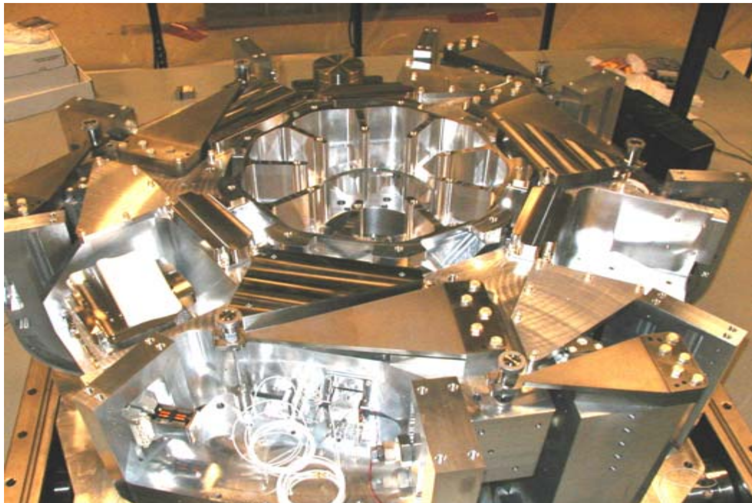
Seismic contribution

Newtonian background

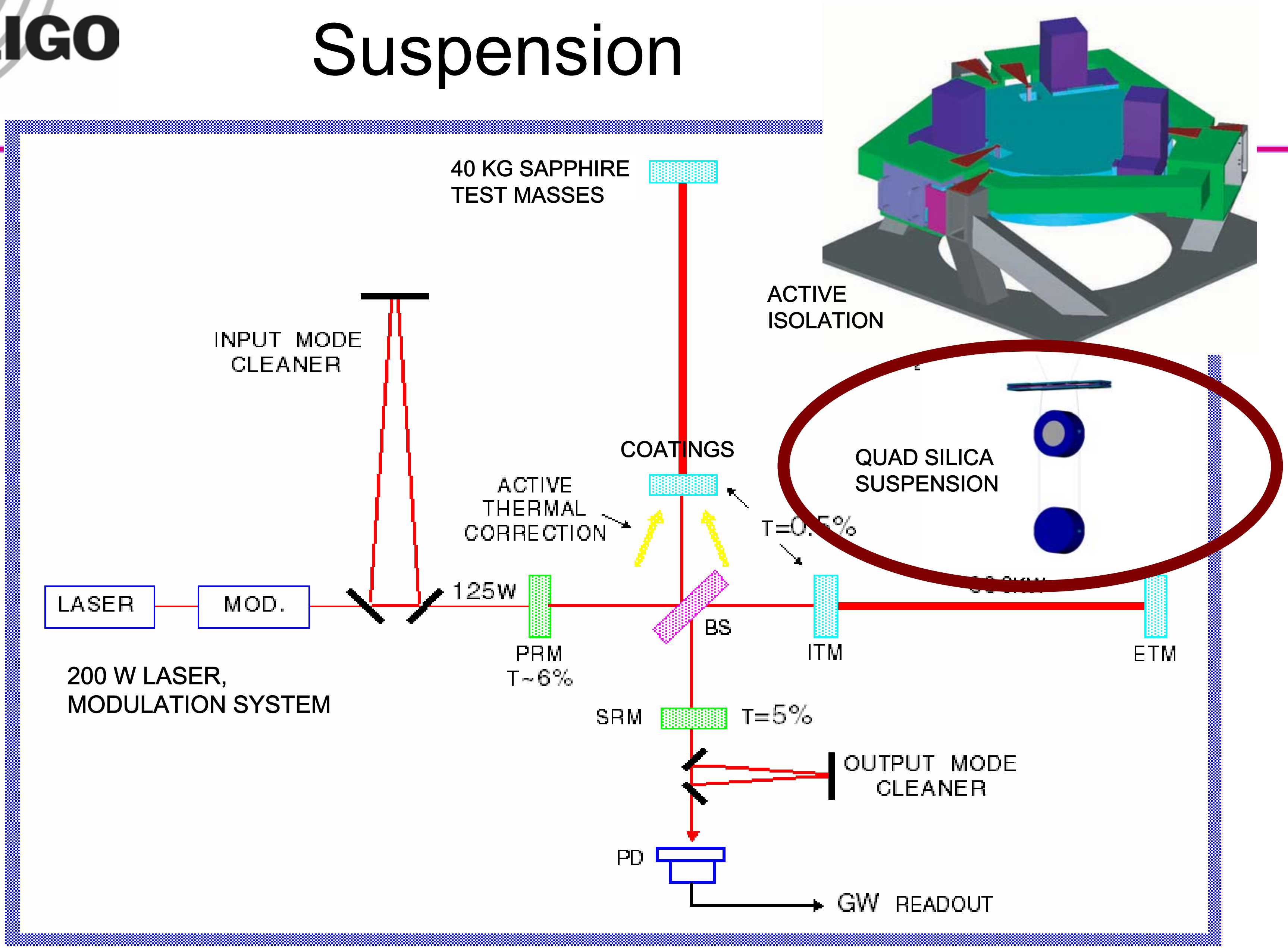
Isolation: multi-stage solution

- Choose an active approach:
  - » high-gain servo systems, two stages of 6 degree-of-freedom each
  - » External hydraulic actuator pre-isolator
  - » Allows extensive tuning of system after installation, operational modes
  - » Dynamics decoupled from suspension systems
- Lead at LSU
- 2003: External pre-isolator Prototypes in test and evaluation at MIT
  - » early deployment at Livingston in order to reduce the cultural noise for initial LIGO
  - » System performance meets initial needs, exceeds Advanced LIGO requirements
- 2003: Stanford Engineering Test Facility Prototype fabricated, in test
  - » First measurements indicate excellent actuator–structure alignment, rigidity
- 2003: Vendor chosen for final Prototypes





Suspension



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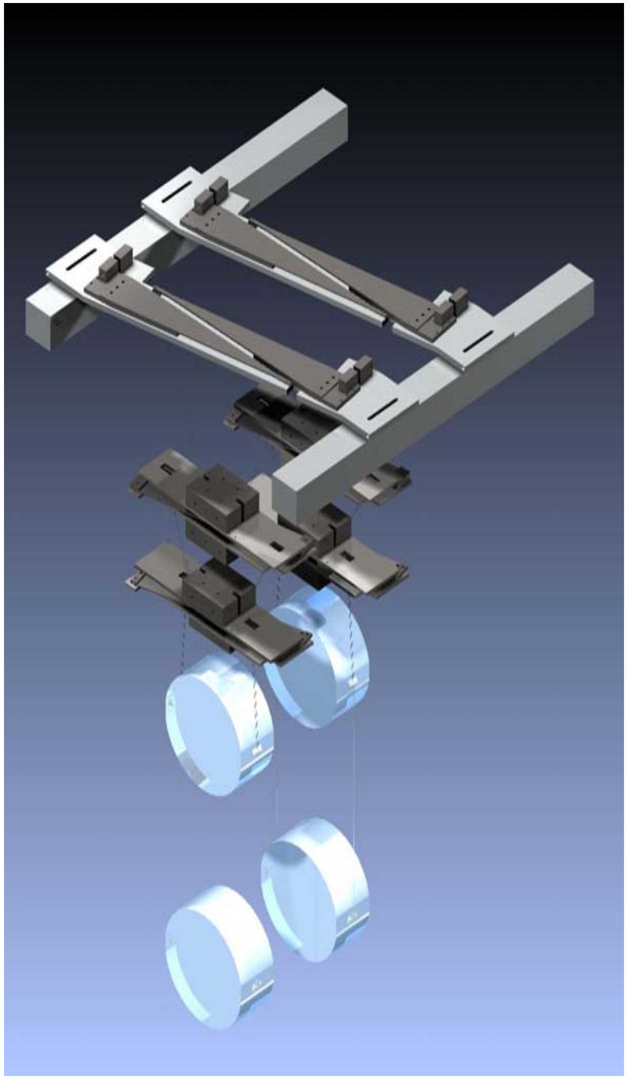
Suspensions: Test Mass Quads

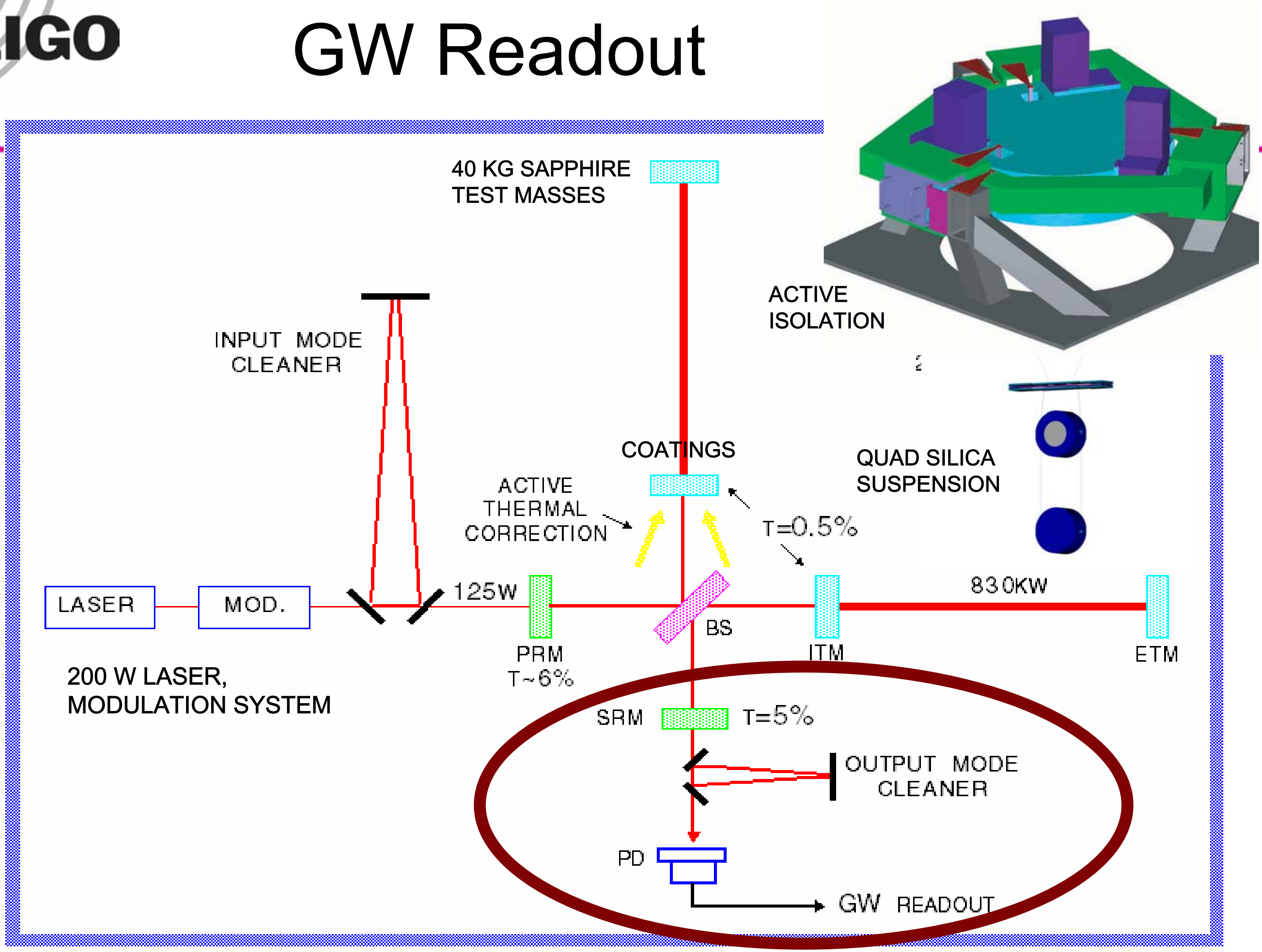
- 1999 White Paper: Adopt GEO600 monolithic suspension assembly
- Requirements:
  - » minimize suspension thermal noise
  - » Complement seismic isolation
  - » Provide actuation hierarchy
- Quadruple pendulum design chosen
  - » Fused silica fibers, bonded to test mass
  - » Leaf springs (VIRGO origin) for vertical compliance
- Success of GEO600 a significant comfort
  - » All fused silica suspensions installed
  - » Ultimately tests to ~12x Adv LIGO at 40 Hz
- 2003: PPARC funding approved!
  - » significant
    financial, technical contribution;
    quad suspensions, electronics, and some
    sapphire substrates
  - » U Glasgow, Birmingham, Rutherford
  - » Quad lead in UK



Suspensions: Triples

- Triple suspensions for auxiliary optics
  - Relaxed performance requirements
- Uses same fused-silica design, control hierarchy
- 2003: Mode Cleaner suspension design completed, prototype triple suspension fabricated, stand-alone testing underway
- To be installed in LASTI Spring-2004
  - Fit tests
  - Controls/actuation testing
- 2003: Recycling mirror design started

GW Readout



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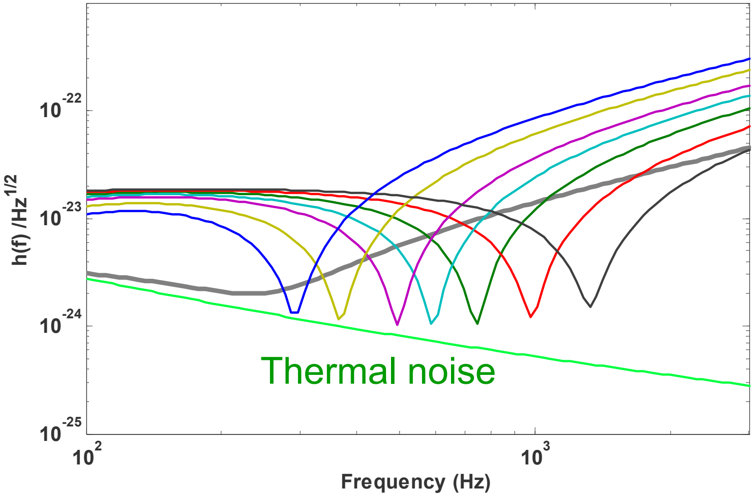
GW READOUT

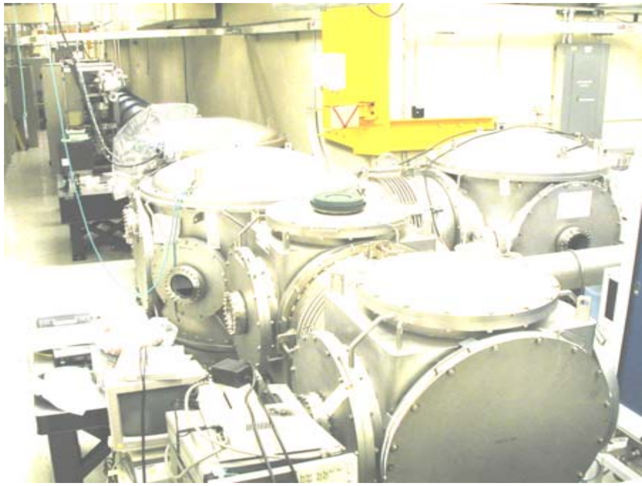
GW readout, Systems



- 1999 White Paper: Signal recycled Michelson Fabry-Perot configuration
  - » Offers flexibility in instrument response, optimization for technical noises
  - » Can also provide narrowband response
  - » Critical advantage: can distribute optical power in interferometer as desired
- Three table-top prototypes give direction for sensing, locking system
- 2003: Glasgow 10m prototype: control matrix elements confirmed
- 2003: Readout choice – DC rather than RF for GW sensing
  - » Offset ~ 1 picometer from interferometer dark fringe
  - » Best SNR, simplifies laser, photodetection requirements
- 2003: Caltech 40m prototype in testing
  - » Complete end-to-end test of readout, controls, data acquisition

System testing

- Initial LIGO experience: thorough testing off-site necessary
- Very significant feature in R&D plan: testing of accurate prototypes in context
- Two major facilities:
  - » MIT LASTI facility – full scale tests of seismic isolation, suspensions, laser, mode Cleaner
  - » 2003: pre-isolator development, intensity stabilization for AdL, frequency servos
  - » Caltech 40m interferometer – sensing/controls tests of readout, engineering model for data acquisition, software
  - » 2003: completion of construction phase
- Support from LSC testbeds
  - » Gingin – thermal compensation
  - » Glasgow 10m – readout
  - » Stanford ETF – seismic isolation
  - » GEO600 – much more than a prototype!



Baseline plan

- Initial LIGO Observation at design sensitivity 2004 – 2006
  - » Significant observation within LIGO Observatory
  - » Significant networked observation with GEO, VIRGO, TAMA
- Structured R&D program to develop technologies
  - » Conceptual design developed by LSC in 1998
  - » Cooperative Agreement carries R&D to Final Design
- 2003: Proposal for fabrication, installation
  - » NSF considering proposal and timeline
- Proposal calls for project start in 2005
  - » Sapphire Test Mass material, seismic isolation fabrication long leads
  - » Prepare a ‘stock’ of equipment for minimum downtime, rapid installation
- Start installation in 2007
  - » Baseline is a staggered installation, Livingston and then Hanford
- Coincident observations by 2010
  - » At an advanced level of commissioning

Advanced LIGO R&D

- Answering Charge – Progress in the following domains:

- Laser: in 2003,
  - selected baseline power head design,
  - supported prototyping of design, observe >1/2 final power goal in ½ of system.
  - Demonstrated intensity stabilization to requirements at 40 Hz and higher, within factor of 5 at most stringent frequency (10 Hz)
- Substrates: in 2003,
  - Received full-size 40 kg, 32 cm diameter sapphire substrates
  - Found mechanical losses in these substrates to meet requirements
  - Characterized absorption in these substrates, supported successful annealing techniques on smaller pieces to reduce absorption – scaling up now
  - New high Q measurements of small (200e6) and LIGO-sized (120e6) of fused silica; supported annealing on small pieces to reduce mechanical losses – scaling up now
- Coatings, in 2003,
  - Refined models for coating thermal noise
  - Observed coating thermal noise in two experiments, consistent with theory
  - Measured and supported measurements of mechanical losses on trial coatings
  - Developed strategy for coating development, put plan into motion