Overview of Advanced LIGO

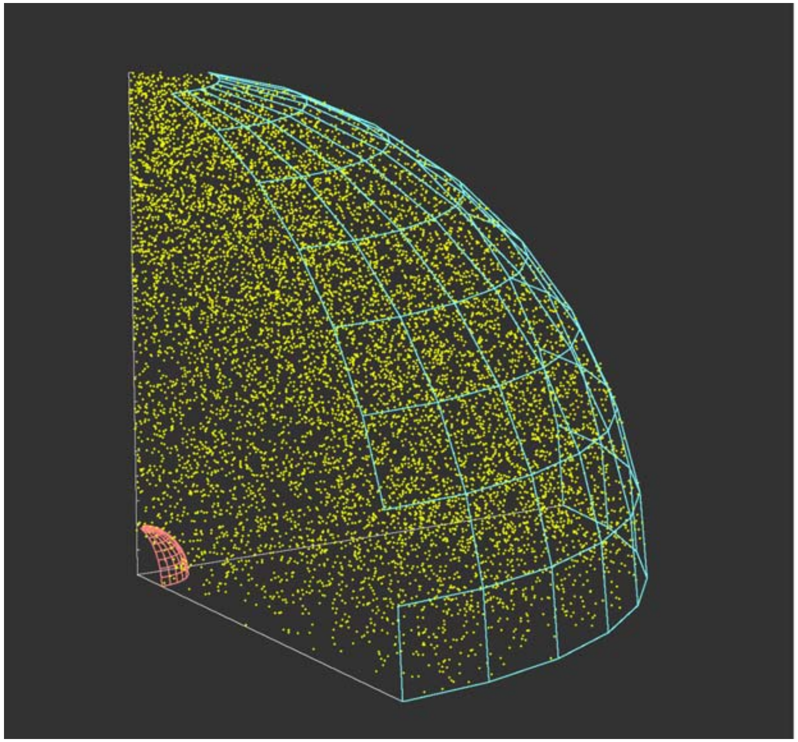
David Shoemaker
NSF Review of Advanced LIGO
11 June 2003

Advanced LIGO

- LIGO mission: detect gravitational waves and

  initiate GW astronomy

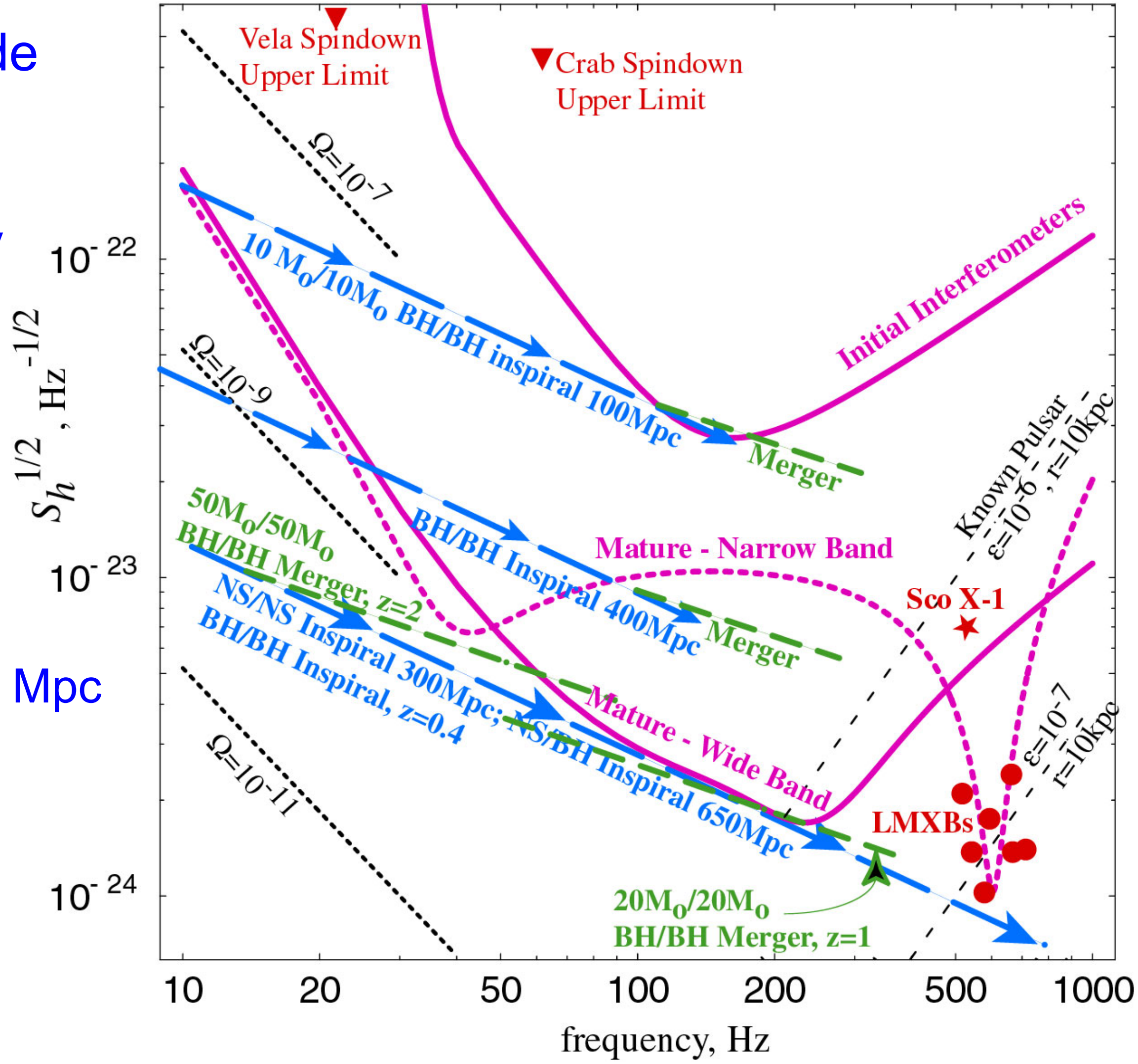
- Next detector
  - Should have assured detectability of known sources
  - Should be at the limits of reasonable extrapolations of detector physics and technologies
  - Must be a realizable, practical, reliable instrument
  - Should come into existence neither too early nor too late



→ **Advanced LIGO**

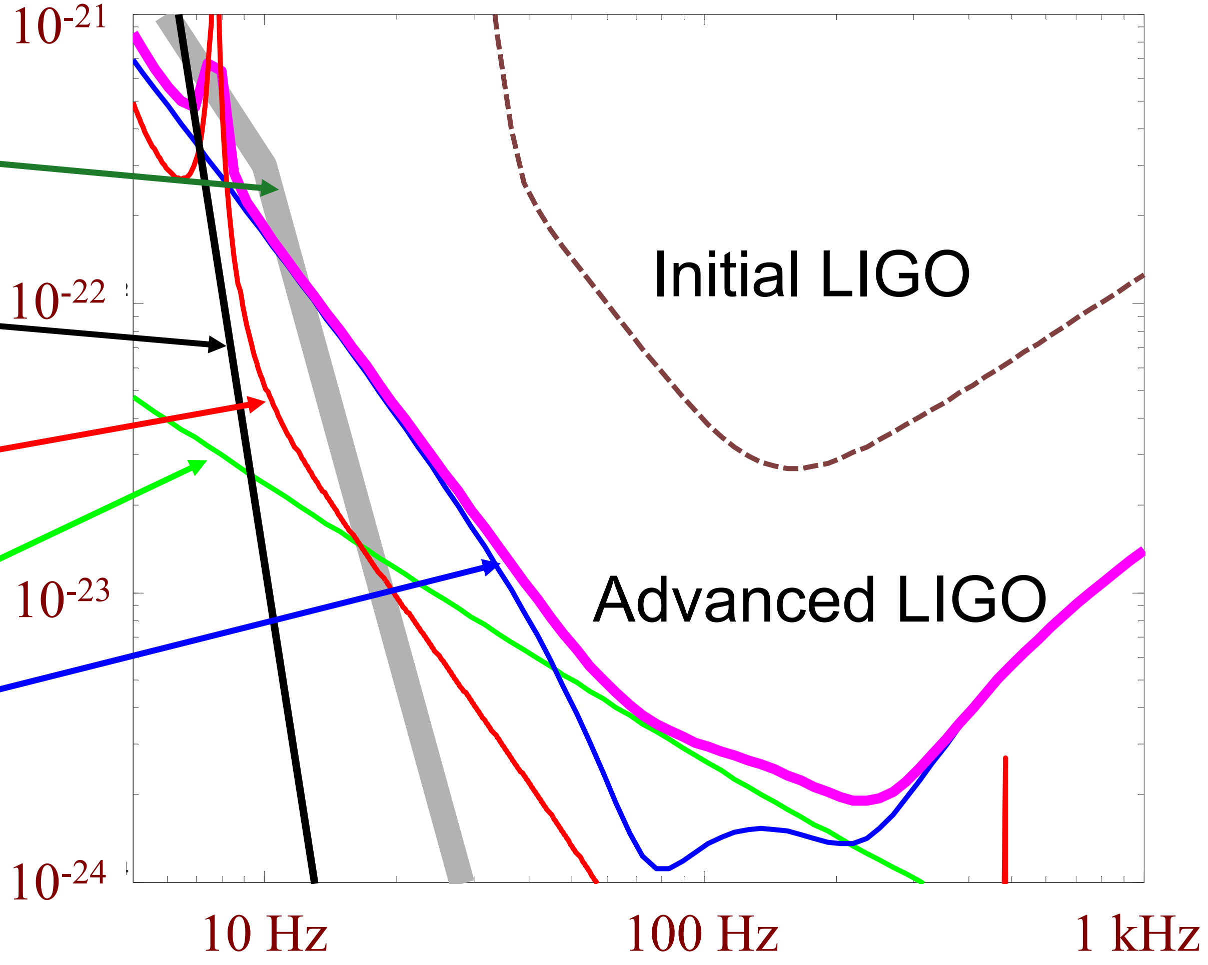
Initial and Advanced LIGO

- Factor 10 better amplitude sensitivity
  - » (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



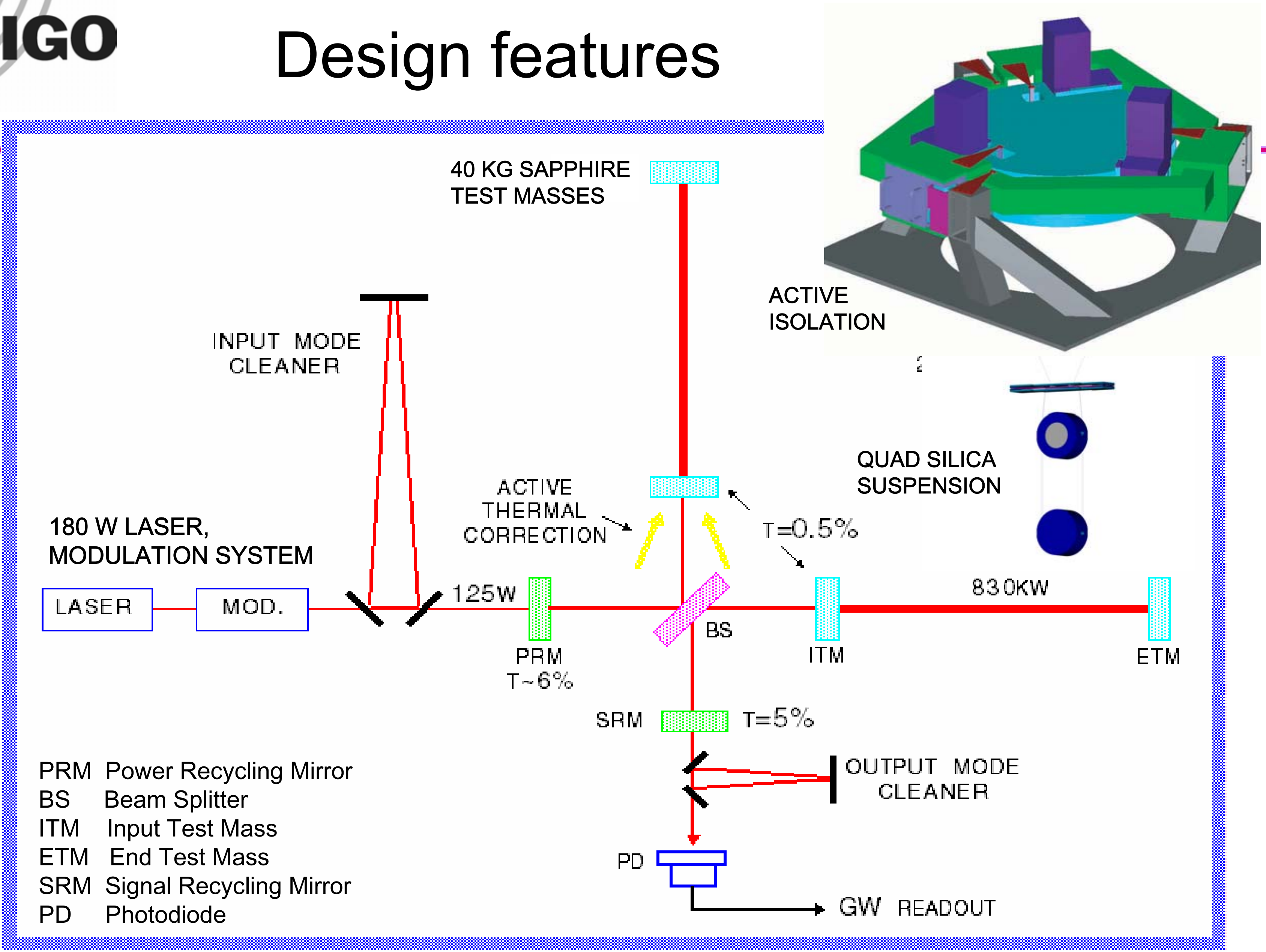
Anatomy of the projected Adv LIGO detector performance

- 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



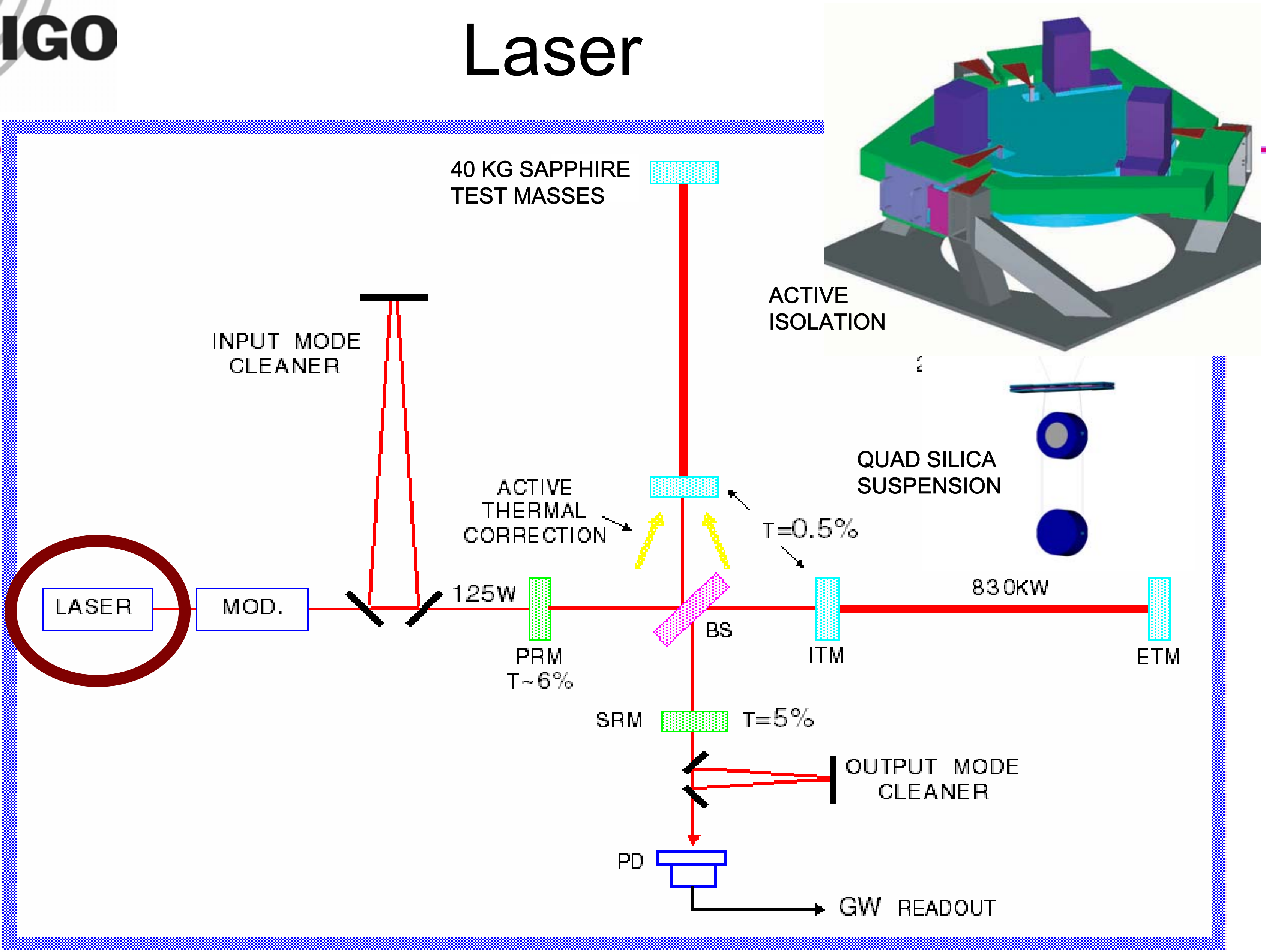
- Advanced LIGO's Fabry-Perot Michelson Interferometer is a platform for all currently envisaged enhancements to this detector architecture

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
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INPUT MODE
CLEANER
QUAD SILICA
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T=0.5%
LASER
MOD.
125W
830KW
PRM
T~6%
BS
ITM
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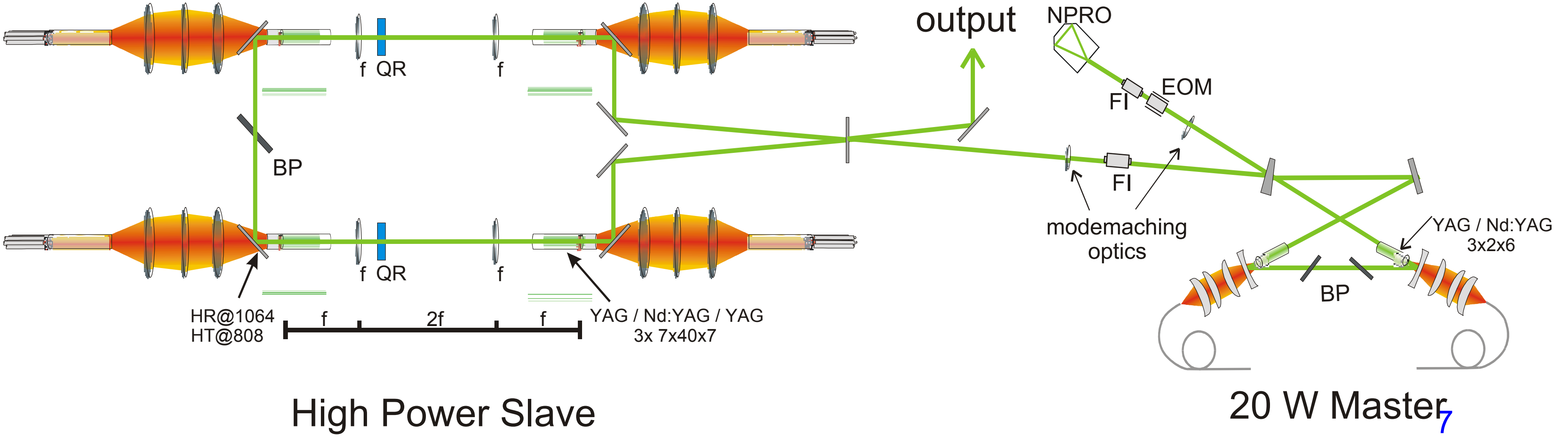
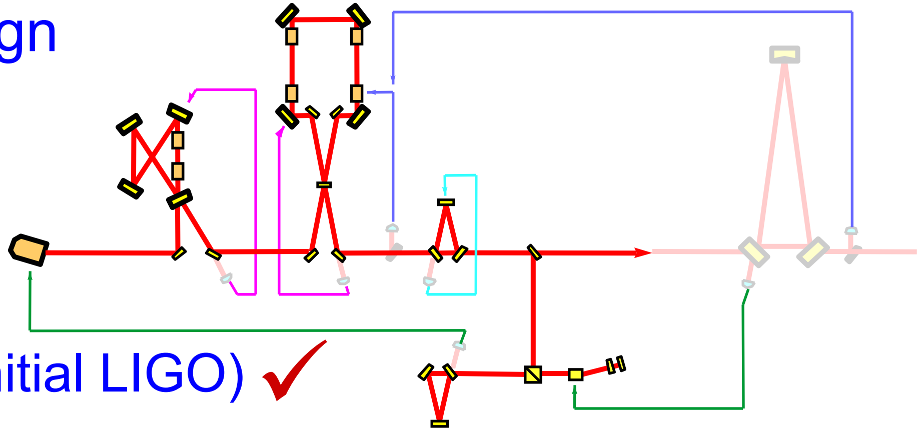
T=5%
OUTPUT MODE
CLEANER
PD
GW READOUT

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
  - 2002: 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 87 W ✓

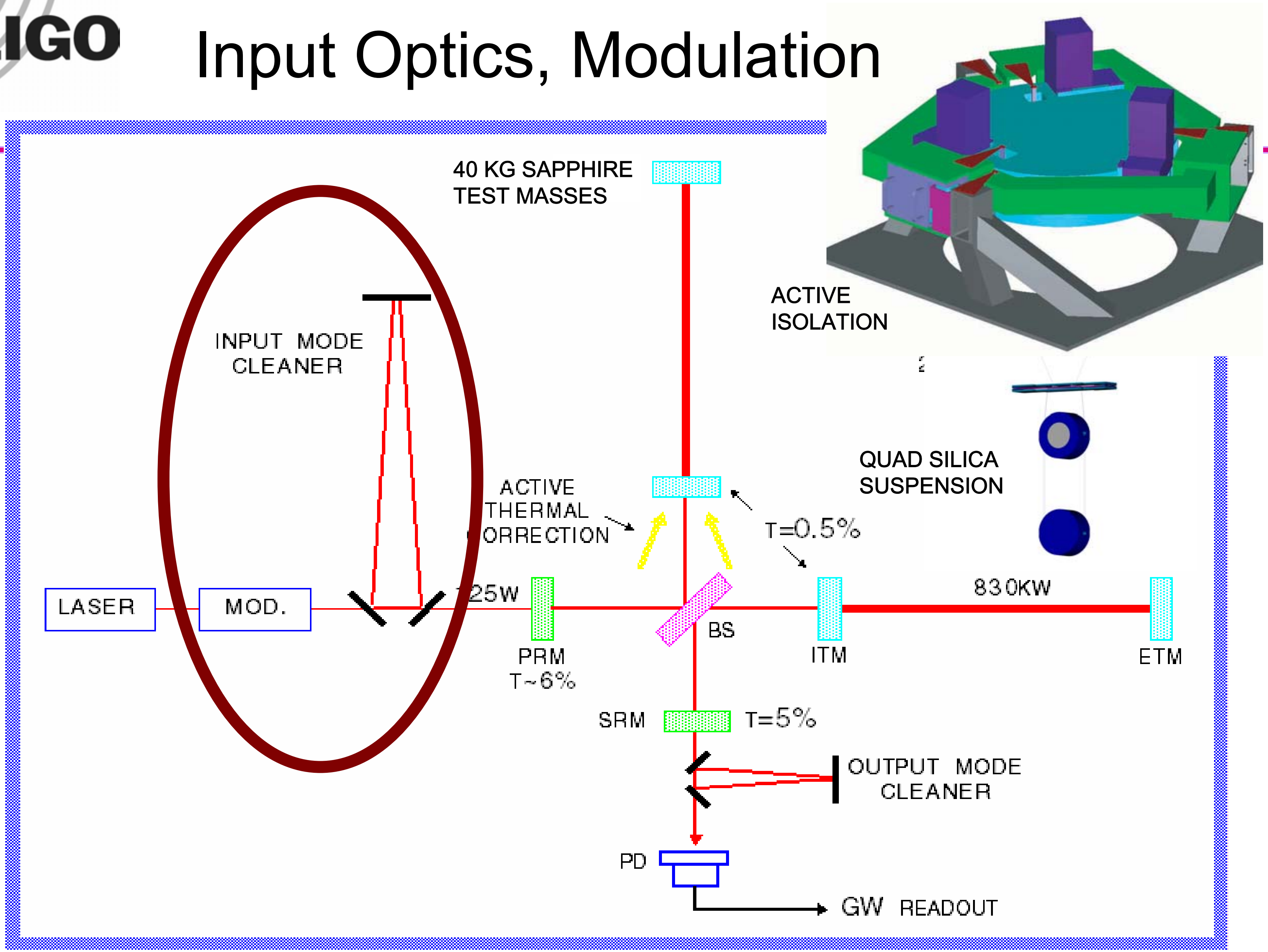


Pre-stabilized laser



- 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 in-vacuum photodiode, 2x10^{-9} ΔP/P at 10 Hz required (1x10^{-8} at 10 Hz demonstrated) ✓
- Max Planck Institute, Hannover leading the Pre-stabilized laser development – Willke
  - » Close interaction with Laser Zentrum Hannover
  - » Experience with GEO-600 laser, reliability, packaging
  - » Germany contributing laser to Advanced LIGO

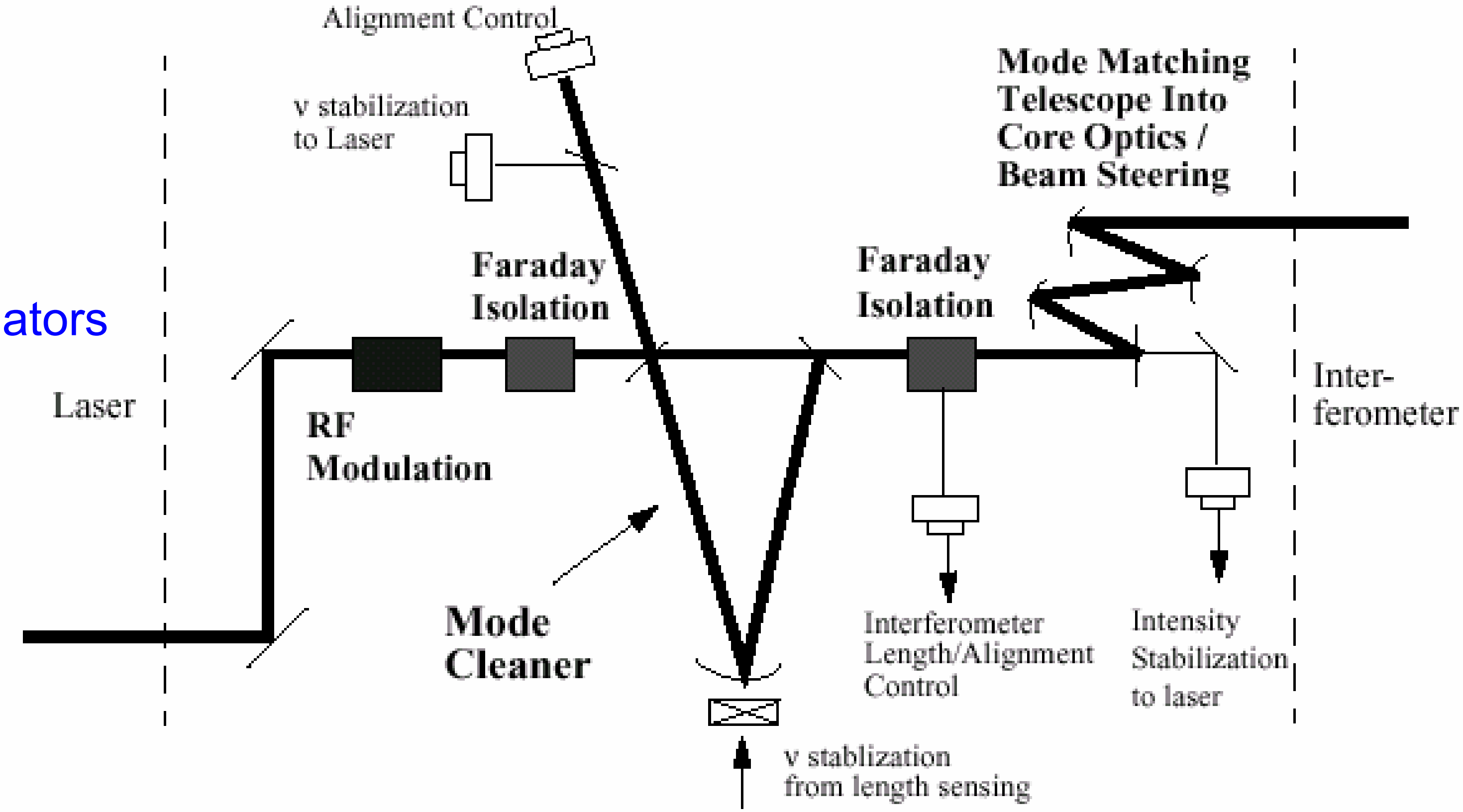
Input Optics, Modulation



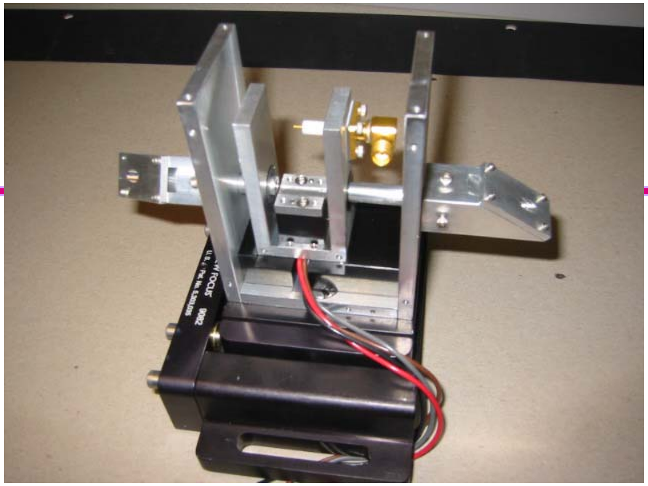
Input Optics

- 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

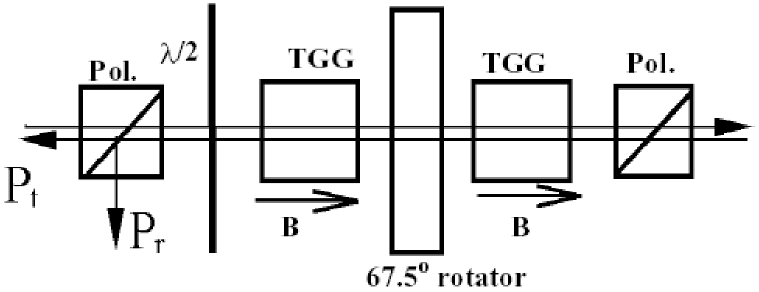
- Challenges:
  - » Modulators
  - » Faraday Isolators

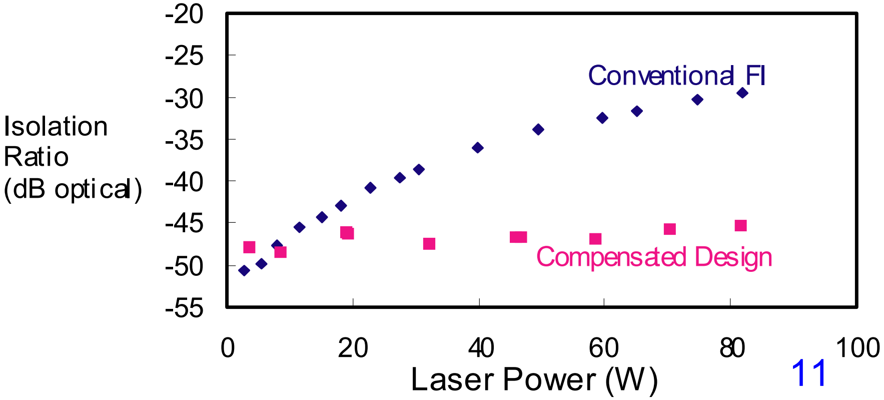


Input Optics

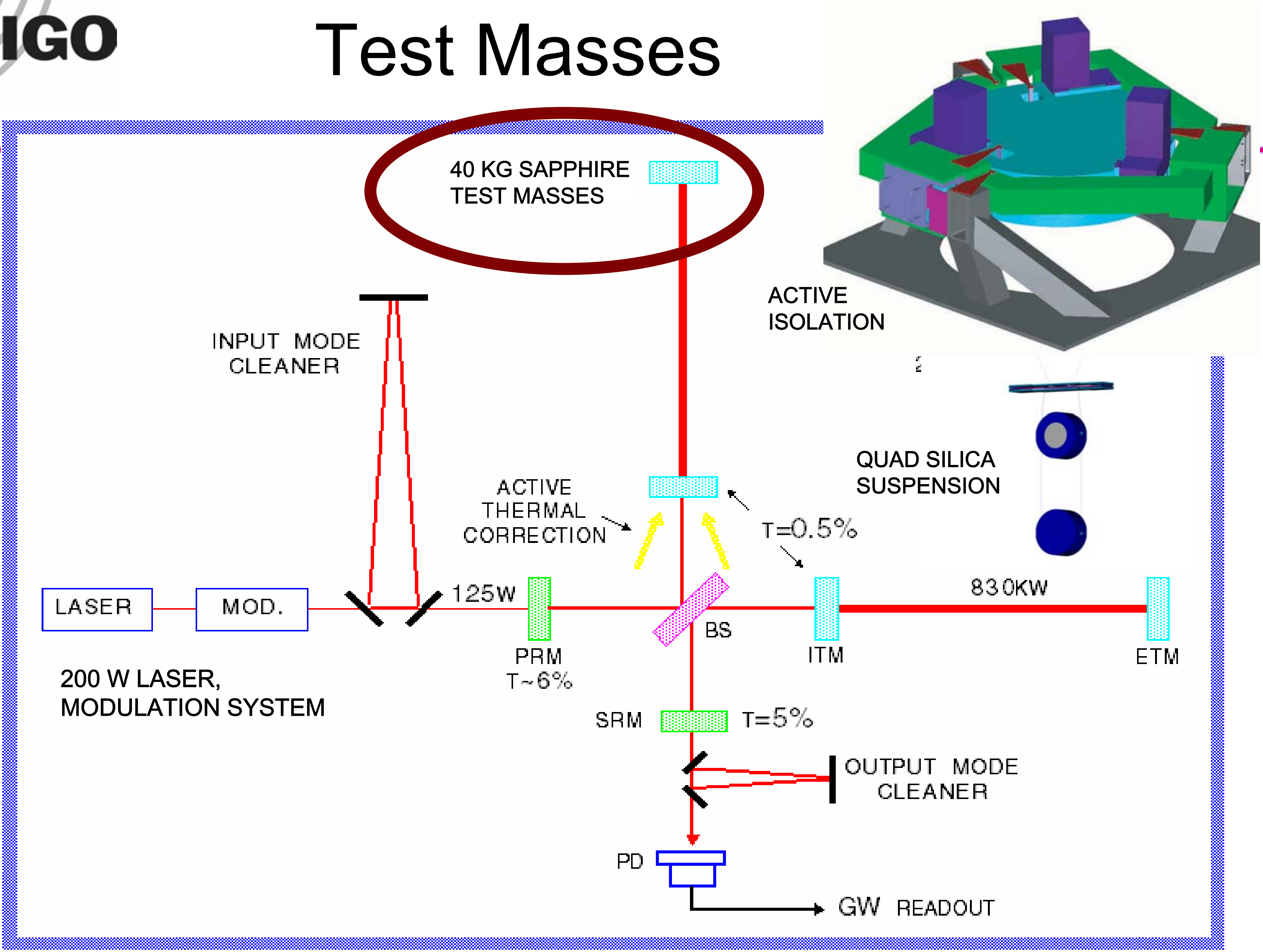


- University of Florida leading development effort -- Reitze
  - » As for initial LIGO
- 2002: High power rubidium tantanyl phosphate (RTP) electro-optic modulator developed
  - » Long-term exposure at Advanced LIGO power densities, with no degradation ✓
- 2003: Faraday isolator from IAP-Nizhny Novgorod
  - » thermal birefringence compensated
  - » Ok to 80 W – more powerful test laser being installed at Livingston





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

Test Masses / Core Optics

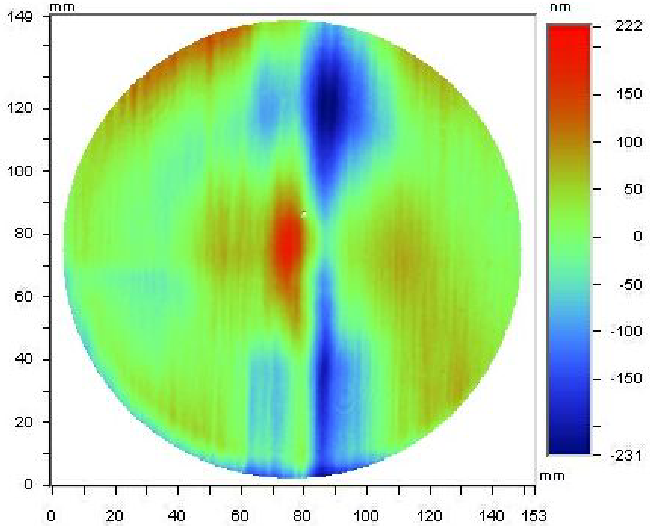
- Absolutely central mechanical *and* optical element in the detector
  - 830 kW; <1ppm loss; <20ppm scatter
  - 2×10^8 Q; 40 kg; 32 cm dia
- 1999 White Paper: Sapphire as test mass/core optic material; development program launched
- Low mechanical loss, high density, high thermal conductivity all desirable 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

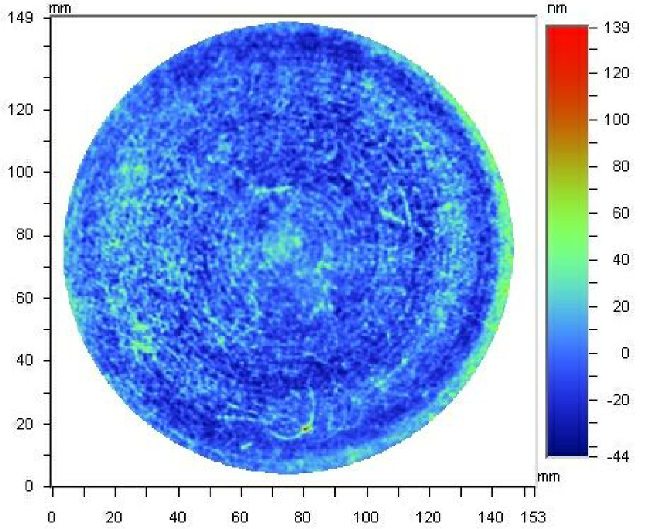
Core Optics

- 2002: Fabrication of Sapphire:
  - » 4 full-size Advanced LIGO boules grown ✓ (Crystal Systems); 31.4 x 13 cm; two acquired
- 2003: Mechanical losses: requirement met ✓
  - » recently measured at 200 million (uncoated)
- 2002: Bulk Homogeneity: requirement met
  - » Sapphire as delivered has 50 nm-rms distortion
  - » Goodrich 10 nm-rms compensation polish ✓
- 2001: 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: Bulk Absorption:
  - » Uniformity needs work
  - » Average level ~60 ppm, 40 ppm desired
  - » Annealing shown to reduce losses

Compensation Polish

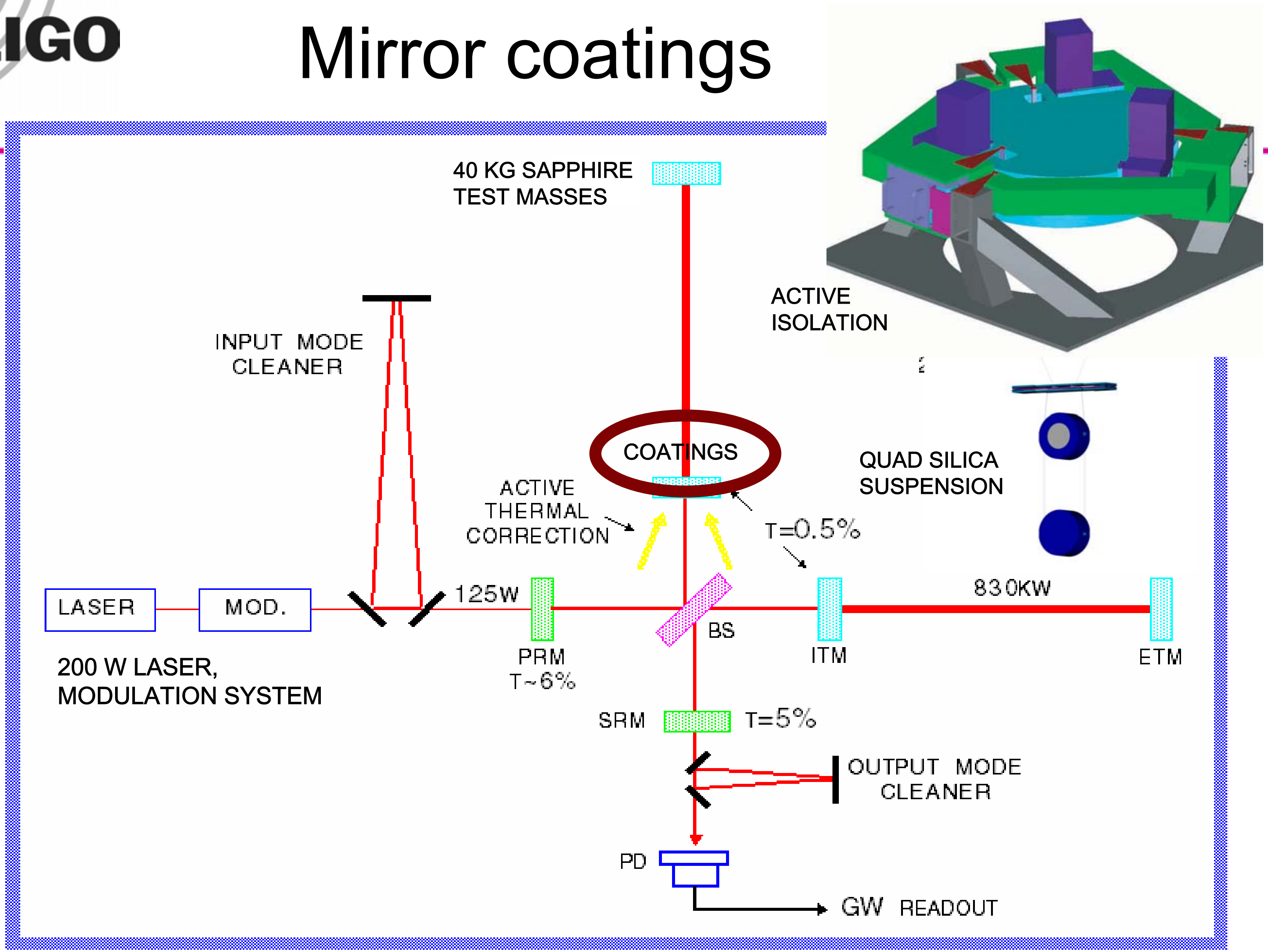


before



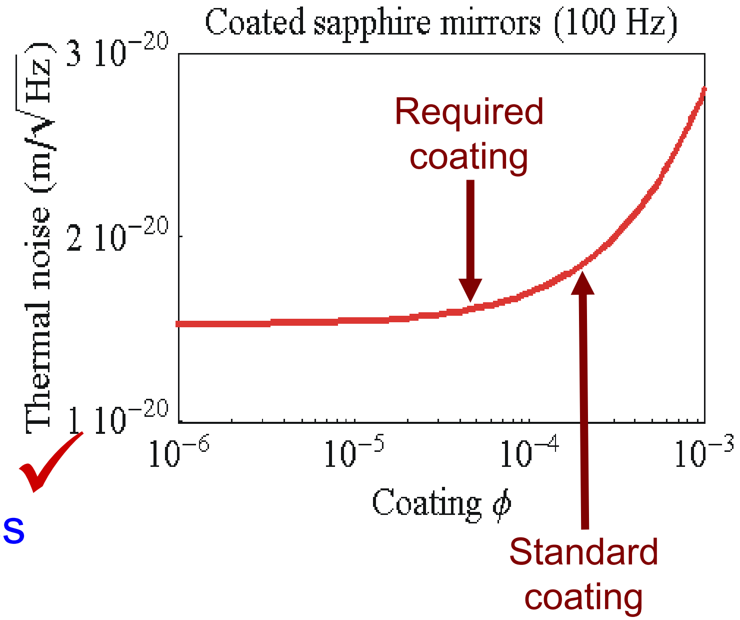
after

Mirror coatings



Test Mass Coatings

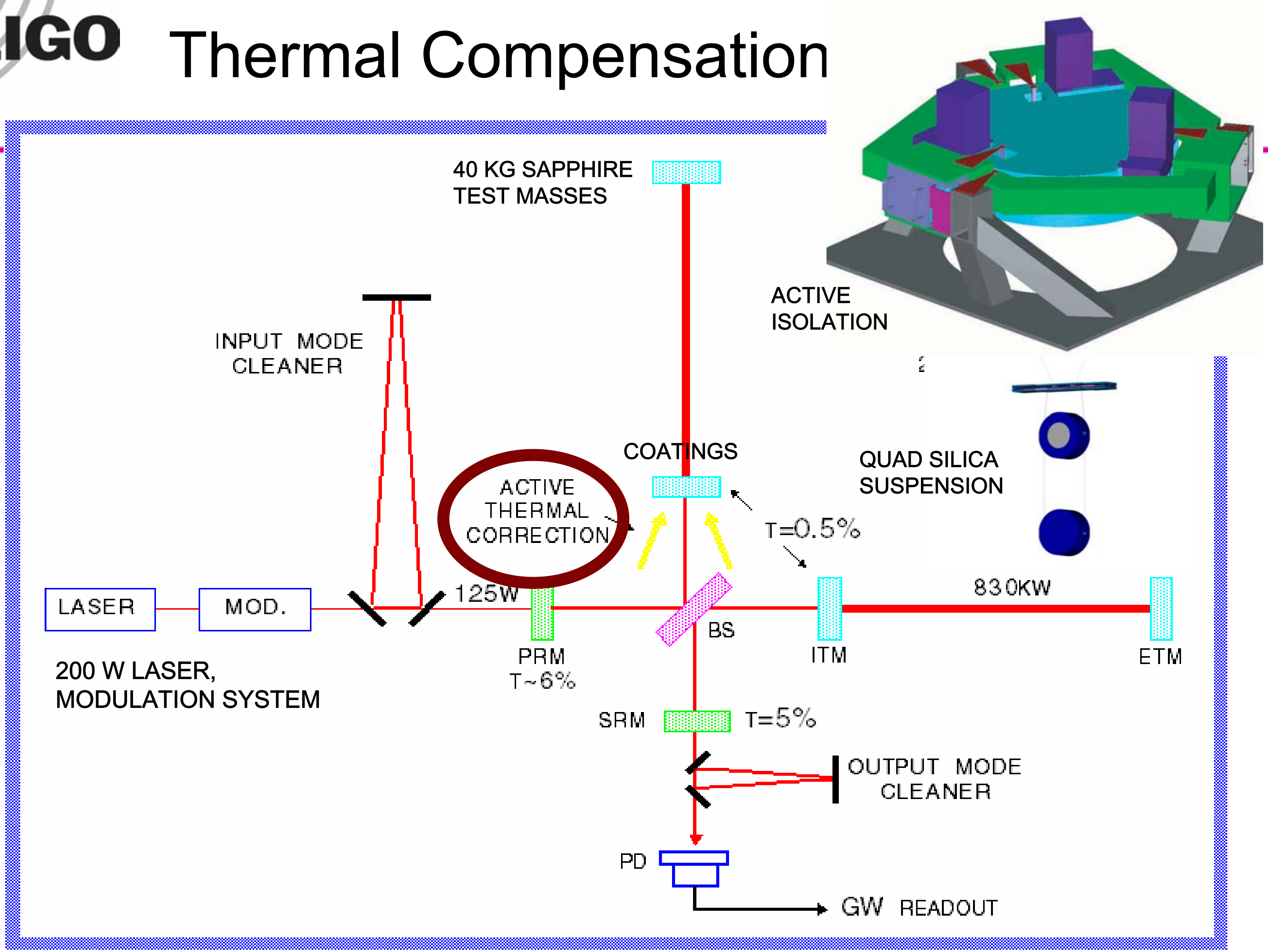
- Optical absorption (~0.5 ppm), scatter meet requirements for (good) conventional coatings
- R&D mid-2000: Thermal noise due to coating mechanical loss recognized; LSC program put in motion to develop low-loss coatings
  - » Series of coating runs – materials, thickness, annealing, vendors
  - » Measurements on a variety of samples
- 2001: Ta_2O_5 identified as principal source of loss ✓
- 2002: Test coatings show somewhat reduced loss
  - » Alumina/Tantala
  - » Doped Silica/Tantala
- Need ~5x reduction in loss to make compromise to performance minimal
- 2003: Expanding the coating development program ✓
  - » RFP out to 5 vendors; expect to select 2
- Direct measurement via special purpose TNI interferometer – lab tour
- First to-be-installed coatings needed in ~2.5 years – sets the time scale



Required coating

Standard coating

Thermal Compensation



40 KG SAPPHIRE TEST MASSES

ACTIVE ISOLATION

INPUT MODE CLEANER

COATINGS

QUAD SILICA SUSPENSION

ACTIVE THERMAL CORRECTION

T=0.5%

LASER

MOD.

125W

830KW

BS

ITM

ETM

200 W LASER, MODULATION SYSTEM

PRM T~6%

SRM

T=5%

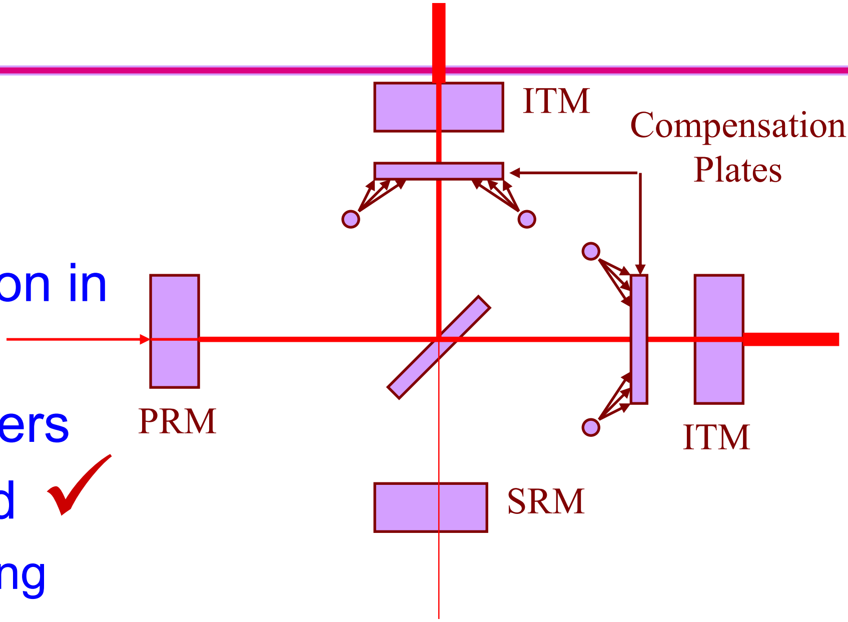
OUTPUT MODE CLEANER

PD

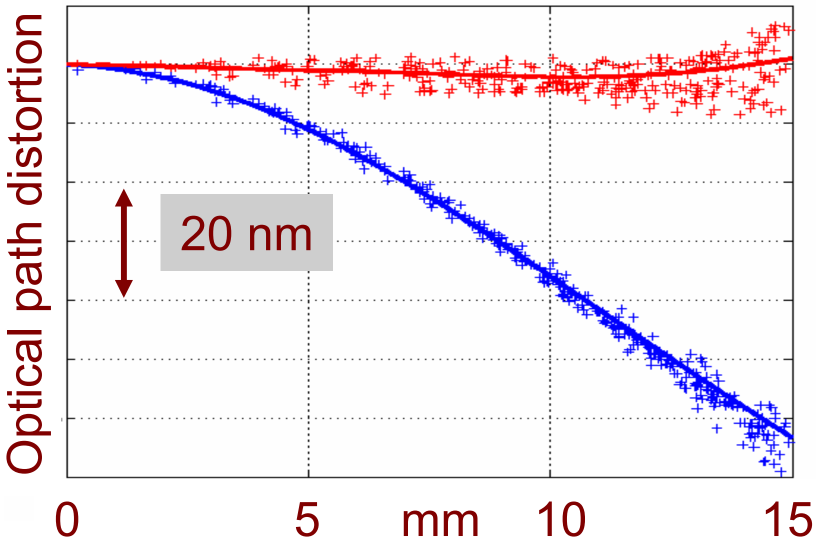
GW READOUT

Active Thermal Compensation

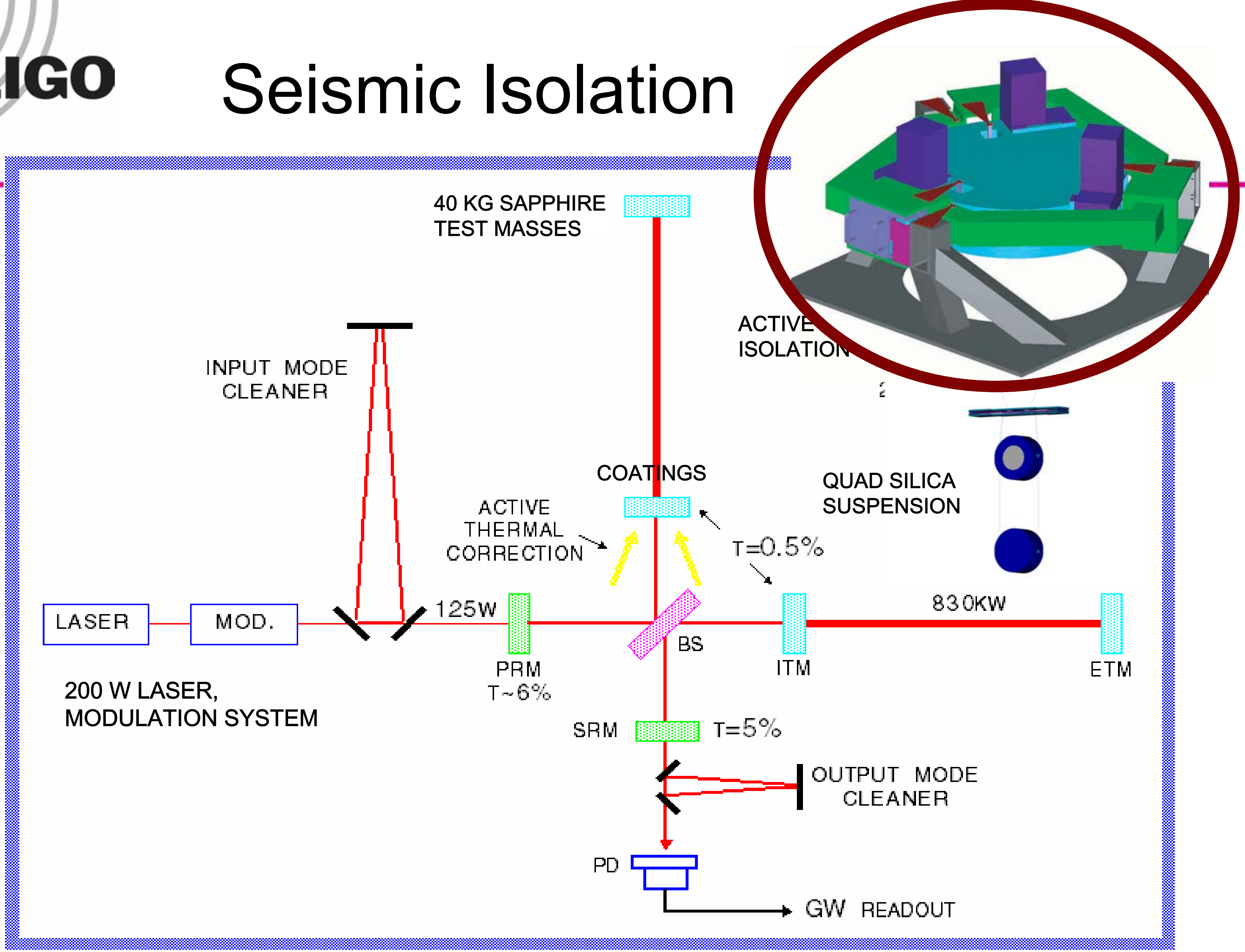
- 1999 White Paper: Need recognized, concept laid out
- Removes excess ‘focus’ due to absorption in coating, substrate
- Allows optics to be used at all input powers
- 2002: Initial R&D successfully completed ✓
    - Quasi-static ring-shaped additional heating
    - Scan to complement irregular absorption
- Sophisticated thermal model (‘Melody’) ✓ developed to calculate needs and solution
- 2003: Gingin facility (ACIGA) readying tests with Lab suspensions, optics
- Application to initial LIGO in preparation



Shielded ring compensator test

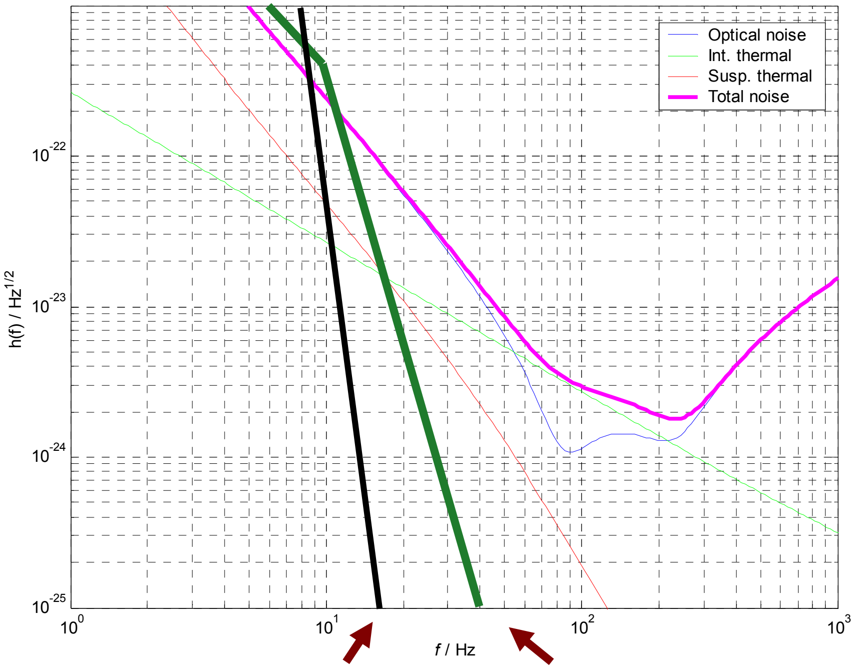


Seismic Isolation



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

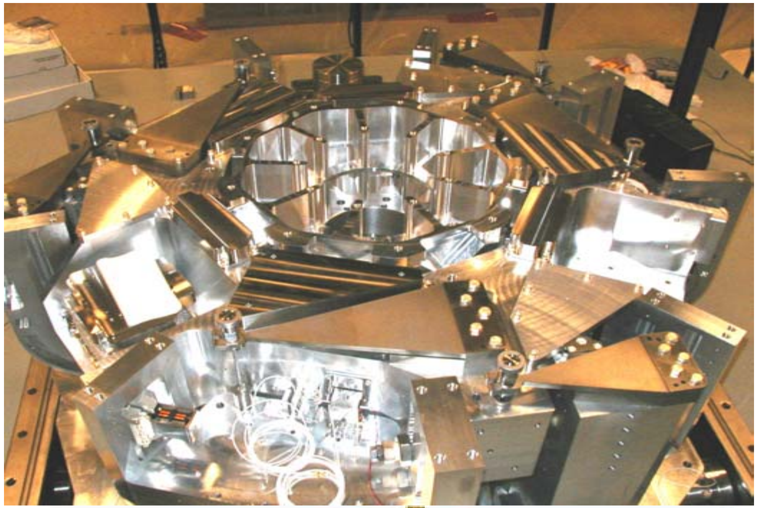


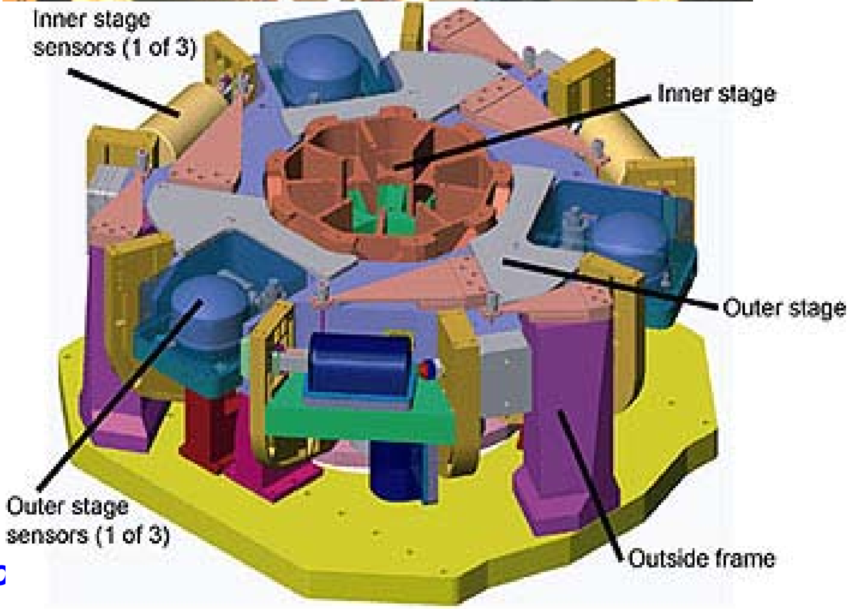
Seismic contribution

Newtonian background

Isolation: Two-stage platform

- 2000: Choose an active approach: ✓
  - » high-gain servo systems, two stages of 6 degree-of-freedom each
  - » Allows extensive tuning of system after installation, operational modes
  - » Dynamics decoupled from suspension systems
- Lead at LSU – Giaime
- 2003: Stanford Engineering Test Facility Prototype fabricated ✓
  - » Mechanical system complete
  - » Instrumentation being installed
  - » First measurements indicate excellent actuator – structure alignment
- 2003: RFP for final Prototypes released ✓



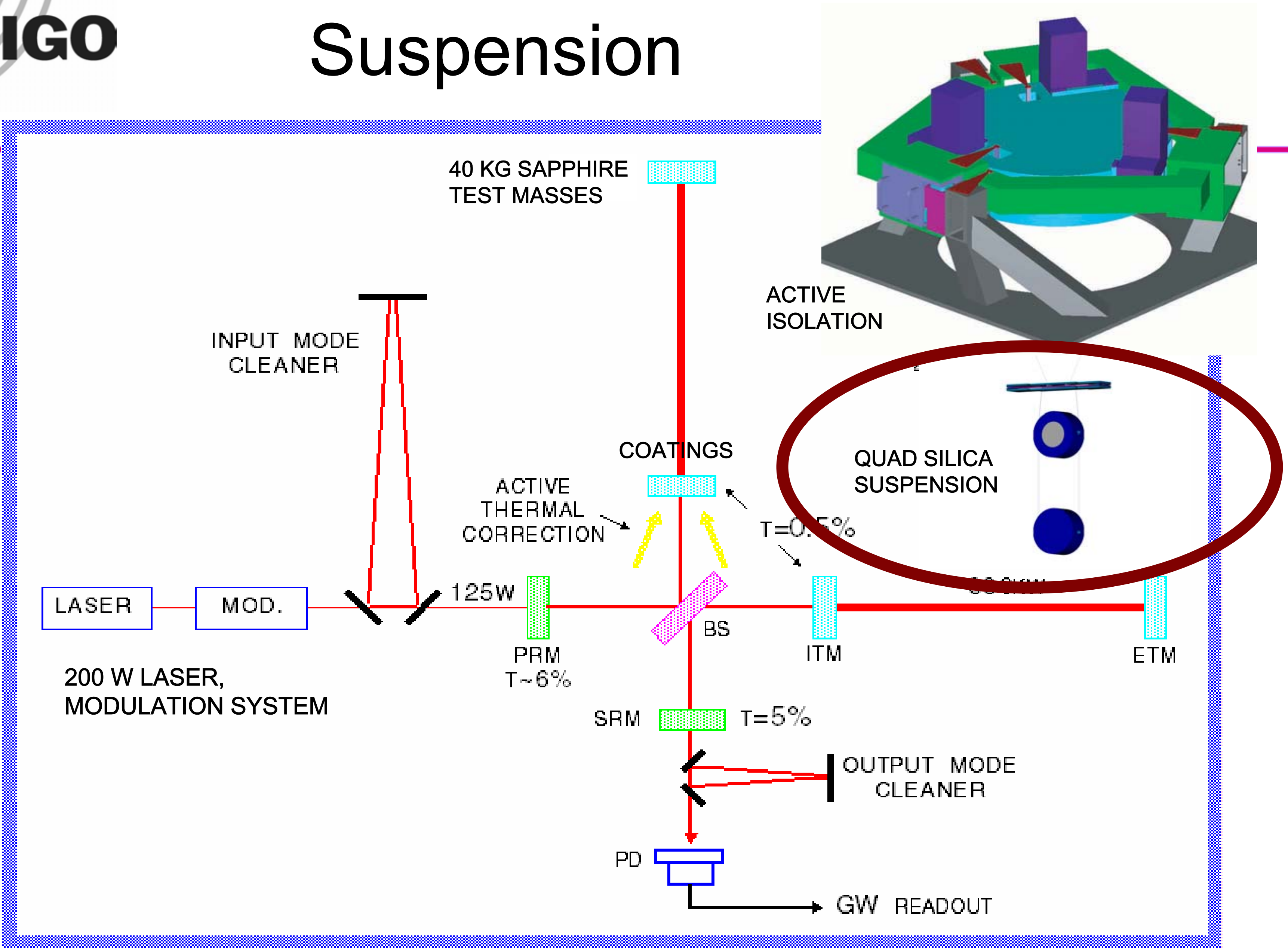


Isolation: Pre-Isolator

- External stage of low-frequency pre-isolation (→ ~1 Hz)
  - » Tidal, microseismic peak reduction
  - » DC Alignment/position control and offload from the suspensions
  - » 1 mm pp range
- Lead at Stanford – Lantz
- 2003: Prototypes in test and evaluation at MIT for early deployment at Livingston in order to reduce the cultural noise impact on initial LIGO
  - » System performance exceeds ✓ Advanced LIGO requirements

LIGO Laboratory

Suspension



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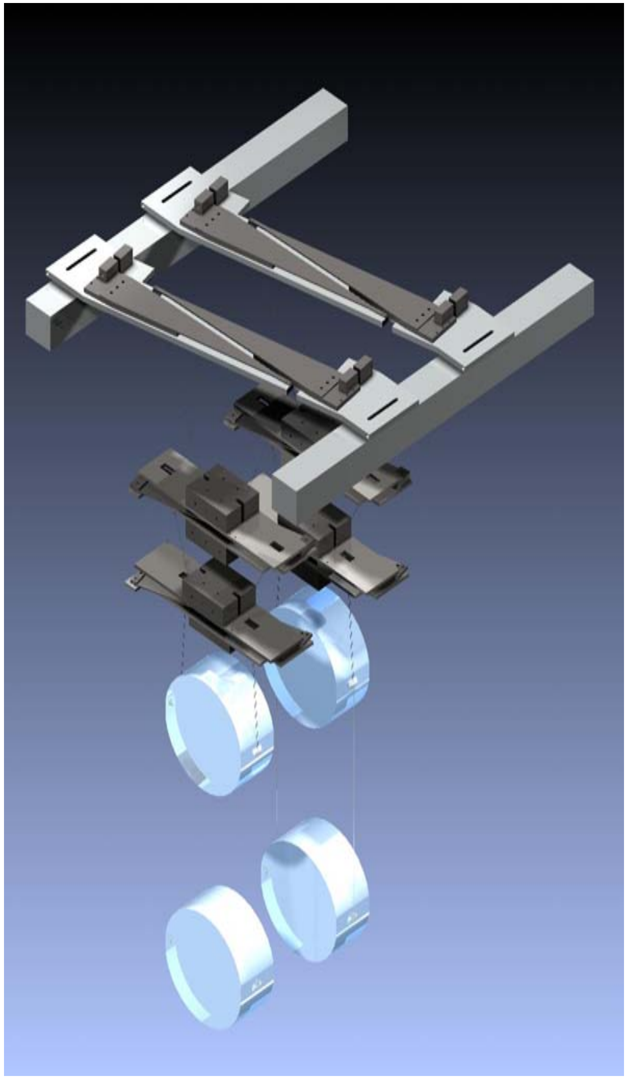
GW READOUT

Suspensions: Test Mass Quads

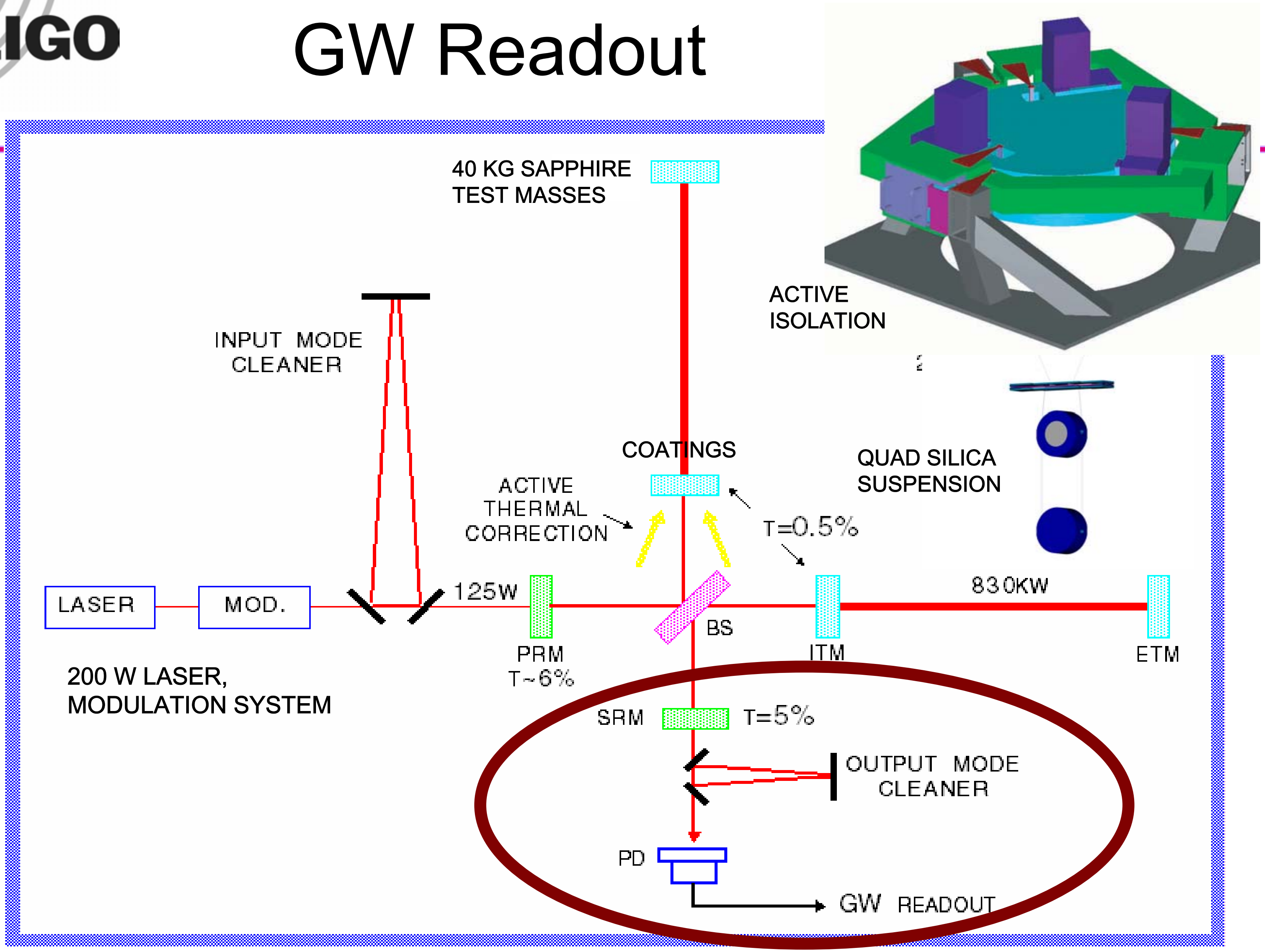
- 1999 White Paper: Adopt GEO600 monolithic suspension assembly
- Requirements:
  - minimize suspension thermal noise
  - Complement seismic isolation
  - Provide actuation hierarchy
- 2000: Quadruple pendulum design chosen
  - Fused silica fibers, bonded to test mass
  - Leaf springs (VIRGO origin) for vertical compliance
- Success of GEO600 a significant comfort ✓
  - 2002: All fused silica suspensions installed
- PPARC funding approved: significant financial, technical contribution; quad suspensions, electronics, and some sapphire substrates ✓
  - U Glasgow, Birmingham, Rutherford
  - Quad lead in UK – Cantley, Strain, Hough



Suspensions: Triples

- Triple suspensions for auxiliary optics
  - Relaxed performance requirements
- Uses same fused-silica design, control hierarchy
- 2003: Prototype of Mode Cleaner ✓ triple suspension fabricated
  -- lab tour
- To be installed in LASTI fall-2003
  - Fit tests
  - Controls/actuation testing

GW Readout



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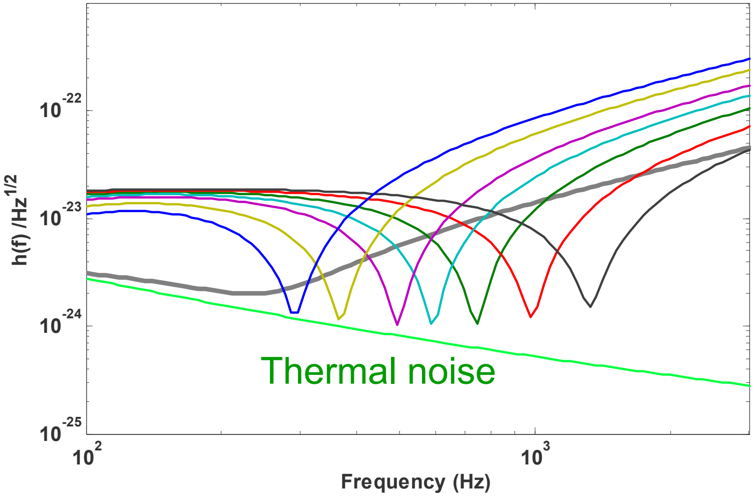
GW READOUT

GW readout, Systems

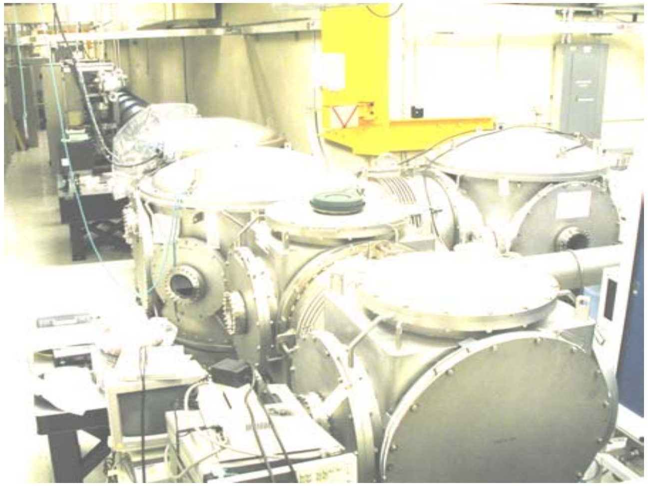
- 1999 White Paper: Signal recycled Michelson Fabry-Perot configuration
  - » Offers flexibility in instrument response, optimization for technical noises
  - » Can also provide narrowband response
  - » Critical advantage: can distribute optical power in interferometer as desired



- 2000: 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
- Caltech 40m prototype in construction, early testing – lab tour
  - » Complete end-to-end test of readout, controls, data acquisition

System testing

- Initial LIGO experience: thorough testing off-site necessary
- Very significant feature in Advanced LIGO plan: testing of accurate prototypes in context
- Two major facilities:
  - » MIT LASTI facility – full scale tests of seismic isolation, suspensions, laser, mode Cleaner
  - » Caltech 40m interferometer – sensing/controls tests of readout, engineering model for data acquisition, software – lab tour
- Support from LSC testbeds
  - » Gingin – thermal compensation
  - » Glasgow 10m – readout
  - » Stanford ETF – seismic isolation
  - » GEO600 – much more than a prototype!



Scope of proposal

- Upgrade of the detector
  - All interferometer subsystems
  - Data acquisition and control infrastructure
- Upgrade of the laboratory data analysis system
  - Observatory on-line analysis
  - Caltech and MIT campus off-line analysis and archive
- Virtually no changes in the infrastructure
  - Buildings, foundations, services, 4km arms unchanged
  - Present vacuum quality suffices for Advanced LIGO – 10^{-7} torr
  - Move 2km test mass chambers to 4km point at Hanford
  - Replacement of ~15m long spool piece in vacuum equipment

Upgrade of all three interferometers

- In discovery phase, tune all three to broadband curve
  - » 3 interferometers nearly doubles the event rate over 2 interferometers
  - » Improves non-Gaussian statistics
  - » Commissioning on other LHO IFO while observing with LHO-LLO pair
- In observation phase, the same IFO configuration can be tuned to increase low or high frequency sensitivity
  - » sub-micron shift in the operating point of one mirror suffices
  - » third IFO could e.g.,
    - – observe with a narrow-band VIRGO
    - – focus alone on a known-frequency periodic source
    - – focus on a narrow frequency band associated with a coalescence, or BH ringing of an inspiral detected by other two IFOs

Reference design

- Baseline is to upgrade the 3rd interferometer from 2km to 4km
    - » Cost is modest and sensitivity gain supports discovery
    - » Will certainly want maximum sensitivity later
- Baseline is a nearly simultaneous upgrade of both sites
    - » Could stagger quite significantly to maintain the network – with an equally significant delay in completion and coincidence observations by the two LIGO sites
- Baseline is to employ Sapphire as the test mass material
    - » Fused silica a strong fallback

Timing of Advanced LIGO

- Direct observation of gravitational waves is a compelling scientific goal, and Advanced LIGO will be a crucial element
  - Revolutionary increase in sensitivity over first generation instruments
  - Strong astrophysical support for Advanced LIGO signal strengths
- Delaying Advanced LIGO likely to create a significant gap in the field – at least in the US
  - Can lose the team of instrument scientists
  - Running costs of an over-exploited instrument represents lost opportunity
- Our LSC-wide R&D program is in concerted motion
  - Appears possible to meet program goals
- We are well prepared
  - Reference design well established, confirmation growing through R&D
- Timely for International partners that we move forward now

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
- Now: This proposal is for fabrication, installation
- Long-lead purchases planned for 2004, real start 2005
  - Sapphire Test Mass material, seismic isolation fabrication
  - 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

Advanced LIGO

- Initial instruments, data establishing the field of interferometric GW detection
- Advanced LIGO promises exciting astrophysics
- Substantial progress in R&D, design
- Still a few good problems to solve
- A broad community effort, international support
- Ready to make transition from R&D to Project

- Advanced LIGO can lead the field to maturity

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