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Advanced LIGO Subsystems

NSF Review of the Advanced LIGO Project
31 May 2006

Dennis Coyne, Caltech
Peter Fritschel, MIT

AGENDA

Part 1: Dennis Coyne

- **Advanced LIGO Technical Overview**
- **Subsystem Breakdown**
- **Subsystem Overviews:**
  - » **Control & Data System (CDS) Infrastructure**
    - – **Data Acquisition (DAQ, WBS 4.09)**
    - – **Data Computing System (DCS, WBS 4.12)**
  - » **Isolation:**
    - – **Seismic Isolation (SEI, WBS 4.02)**
    - – **Suspensions (SUS, WBS 4.03)**
  - » **Integration**
    - – **Systems Engineering (SYS, WBS 4.14.5)**
    - – **Facility Modifications & Preparation (FMP, WBS 4.01)**
    - – **Installation & System Test (INS, WBS 4.13)**

AGENDA

Part 2: Peter Fritschel

- » **Lasers & Optics**
  - – **Pre-Stabilized Laser (PSL, WBS 4.04)**
  - – **Input Optics (IO, WBS 4.05)**
  - – **Core Optic Components (COC, WBS 4.06)**
  - – **Auxiliary Optics System (AOS, WBS 4.07)**
- » **Global Interferometer Controls**
  - – **Interferometer Sensing & Controls (ISC, WBS 4.08)**

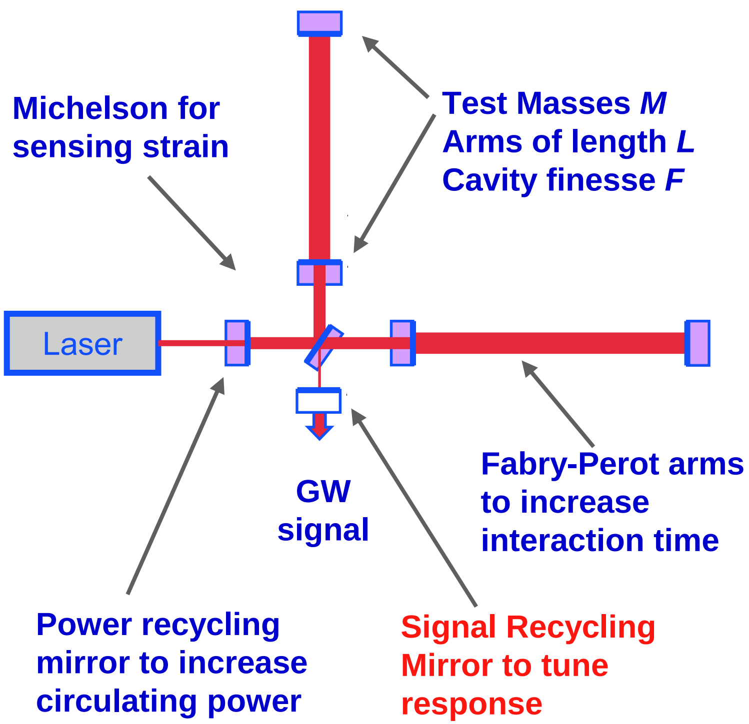
- **Open Trade Studies/Options**
- **Performance**
- **System Test Beds**

Advanced LIGO Detector Improvements

Retain infrastructure, vacuum chambers, and Initial LIGO layout of power recycled interferometer

- Recombined Fabry-Perot Michelson
  - Signal recycling (increase sensitivity & add tunability)
- ~20x higher input power (lower shot noise)
- 40 kg masses (lower photon pressure noise)
- Fused Silica Suspension (lower thermal noise)
- Active seismic isolation, quadruple pendulum suspensions (lower frequency response)
- Leads to:
  - Increased Thermal Compensation
  - Improved Scattered Light Control
  - Addition of Output Optical Filtering (Mode Cleaner)
  - Seismically isolated, in-vacuum detection
  - Increased Control Complexity
  - Modifications to the Vacuum Envelope

ADVANCED LIGO LAYOUT



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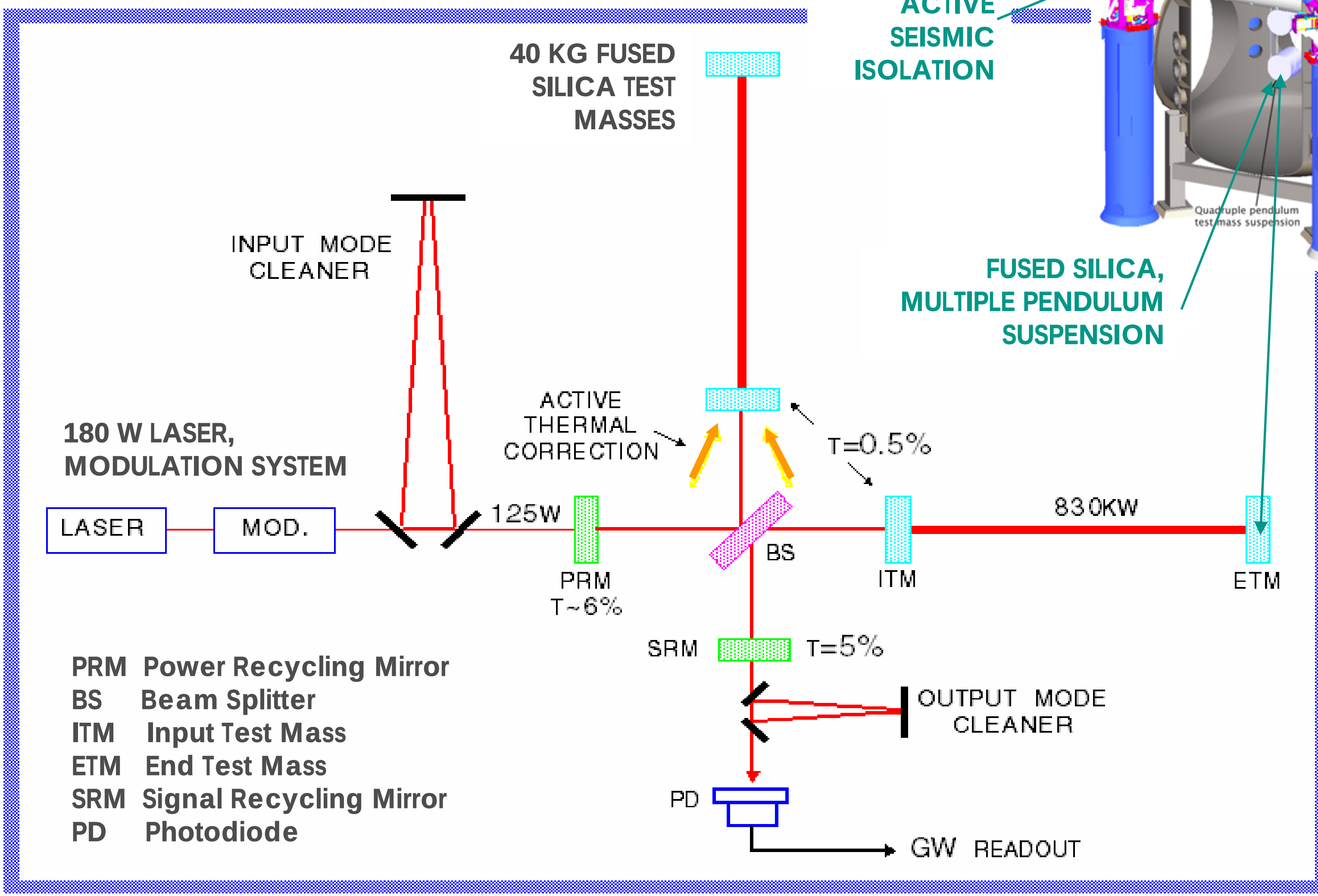
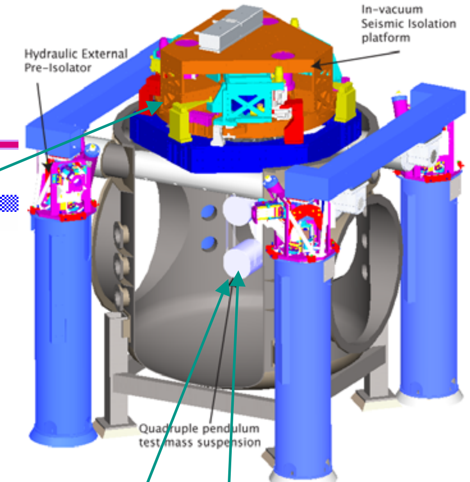
Advanced LIGO Design Features



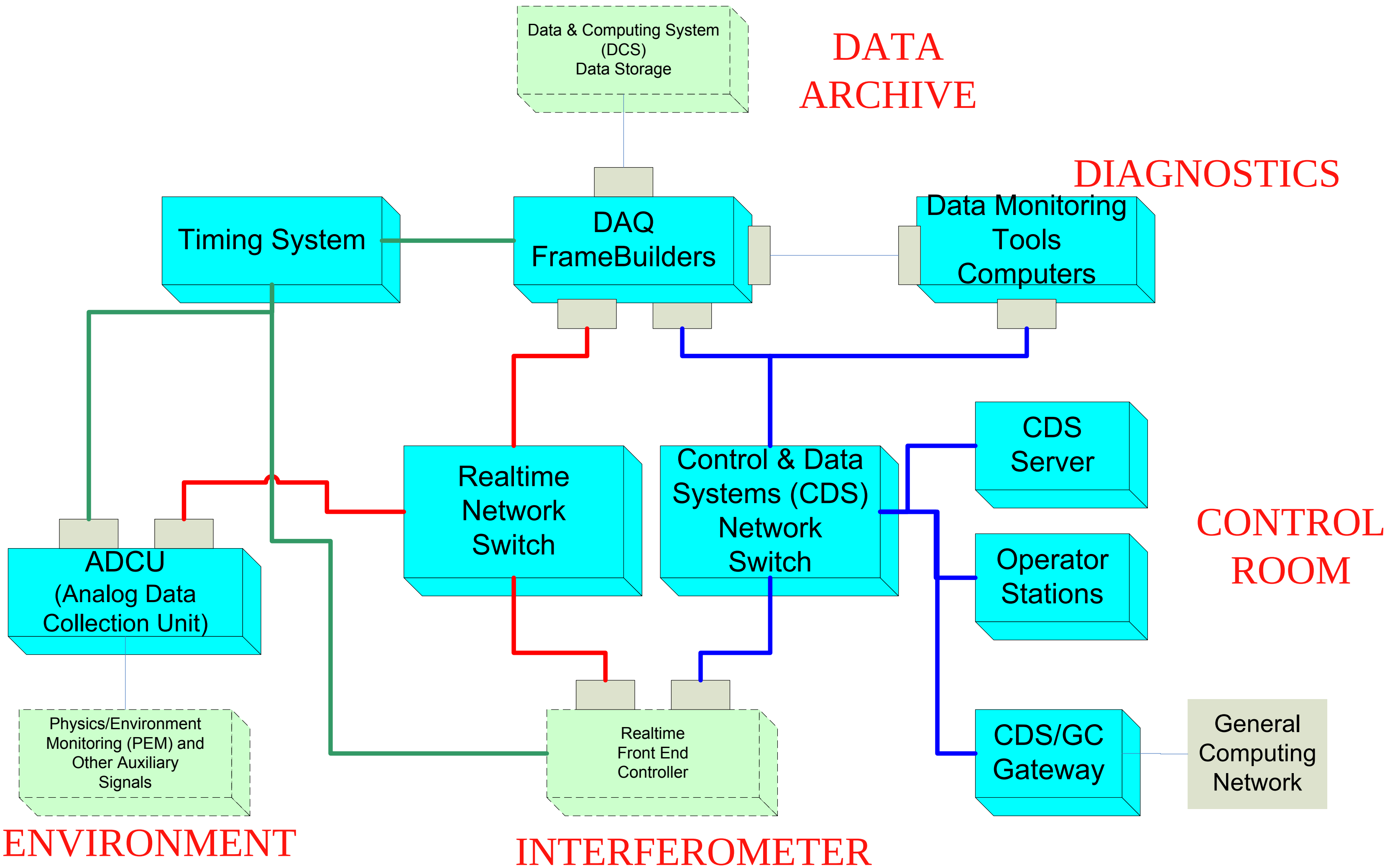


PRM Power Recycling Mirror
BS Beam Splitter
ITM Input Test Mass
ETM End Test Mass
SRM Signal Recycling Mirror
PD Photodiode

Control & Data System Infrastructure: DAQ Subsystem

- Data Acquisition System Infrastructure
  - receive, digitize, format and store data
  - “FrameBuilder”
- Networking infrastructure
- Interferometer Supervisory Controls
- Control Room Equipment
- Timing System
- Mass Storage Systems
- Diagnostics Monitoring and Test Tools (computers & software)
- Control & Data System Test Stand for each Observatory

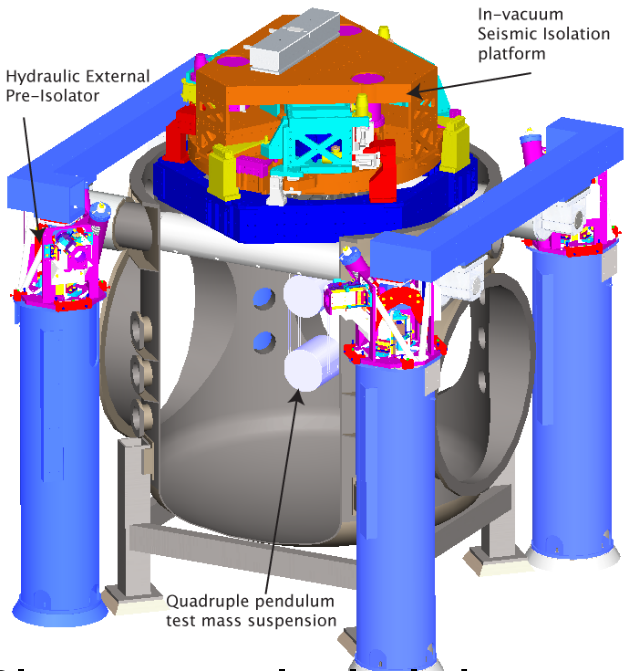
DAQ Block Diagram



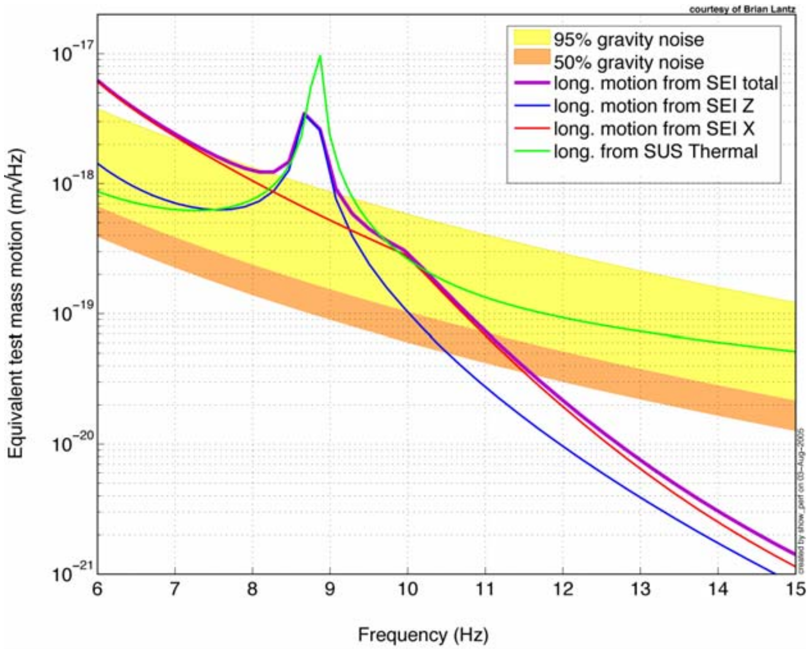
Data Computing System

- **Data Archival**
  - » **30 Mb/s raw data rate for 3 interferometers**
    - – **1.8 PB/year storage (3 copies)**
  - » **Data striped across disks in cluster (RAID)**
    - – **10 TB per node – 14.5 PB aggregate**
  - » **Utilize existing tape robots (with upgrades) for "salt mine" archive**
- **Data Distribution**
  - » **Existing LIGO WAN expected to handle AdL bandwidth**
  - » **Infrastructure built on grid technology**
- **Computing**
  - » **Require ~5 TFLOPS, or ~10 x Initial LIGO FLOPS**
    - – **Longer templates for compact object binary inspiral detection using Weiner filtering techniques**
  - » **Planned Configuration is ~10 x existing**
    - – **Planned: 23K+ CPUs, >51 THz, 1456 nodes, >10 Gbps switch, SMP data servers**
    - – **Current: 2.3K CPUs, 5.6 THz**

Seismic Isolation: Multi-Stage Solution



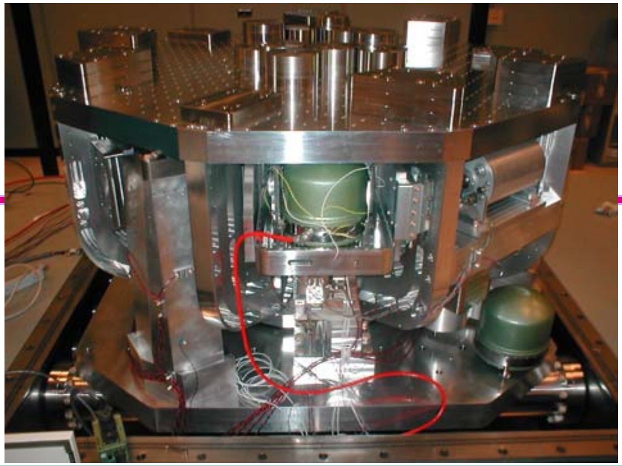
- **Render seismic noise a negligible limitation to GW searches**
  - » Both suspension and isolation systems contribute to attenuation
  - » Newtonian background will dominate for frequencies less than ~15 Hz
- **Reduce actuation forces on test masses**



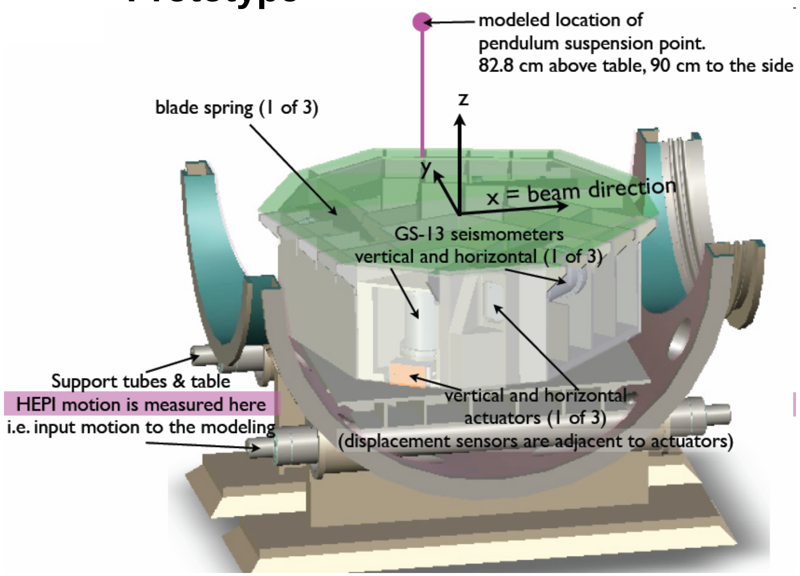
- **Choose an active isolation approach:**
  - » 3 stages of 6 degree-of-freedom each
  - » Hydraulic External Pre-Isolation (HEPI)
  - » Two Active Stages of Internal Seismic Isolation
- **Increase number of passive isolation stages in suspensions**
  - » From single suspensions in initial LIGO to quadruple suspensions for Adv. LIGO

Seismic Isolation (SEI)

- **BSC Chamber Design**
  - » **Full Scale Prototype is being assembled at LASTI**
  - » **Installation & Test this year with Quadruple Pendulum Suspension Prototype**
  - » **Modeling based on ~2/3 Scale "Technology Demonstrator" at Stanford's Engineering Test Facility (ETF) indicates Performance Meets Requirements**
- **HAM Chamber design**
  - » **Modeling indicates a Single Stage Internal Seismic Isolation (ISI) System meets Requirements**
  - » **Full Scale Design to be completed for LASTI Prototype**

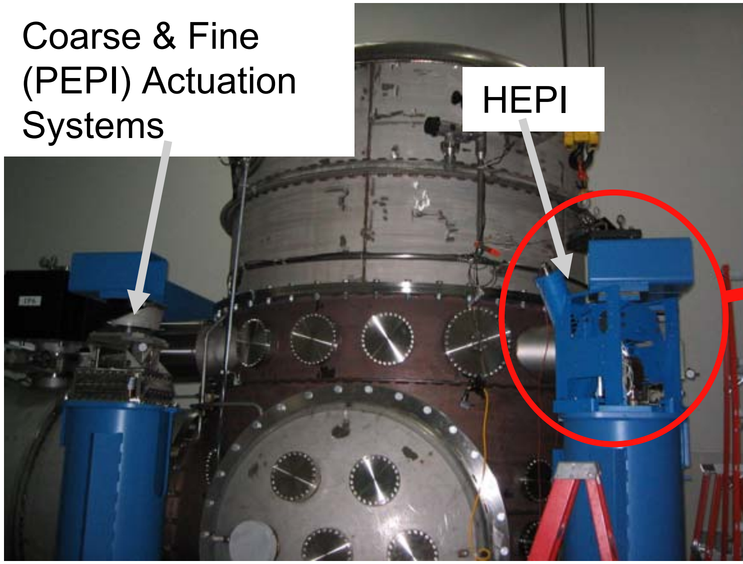


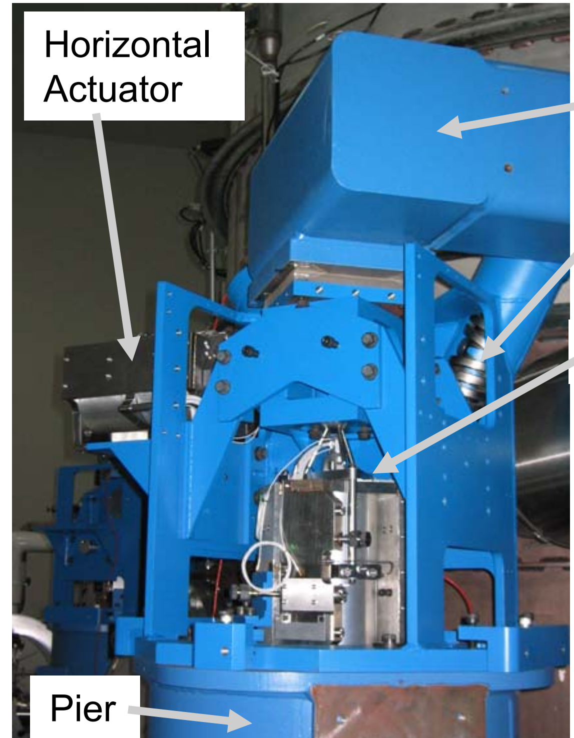
SEI Technology Demonstrator at the Stanford Engineering Test Facility (ETF)



Requirement	HAM Chamber Value	BSC Chamber Value
Payload mass	510 kg	800 kg
Range	± 1 mm, ± 0.5 mrad	± 1 mm, ± 0.5 mrad
Optics table noise	4×10^{-11} m/√Hz (@10 Hz)	3×10^{-13} m/√Hz (@10 Hz)
Angular noise	100 nrad RMS	10 nrad RMS

Seismic Isolation, HEPI Subsystem Installation at LIGO Livingston Observatory





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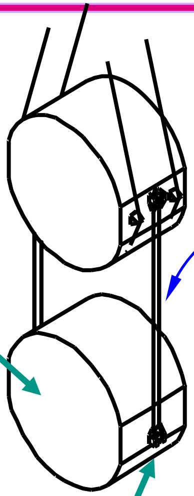
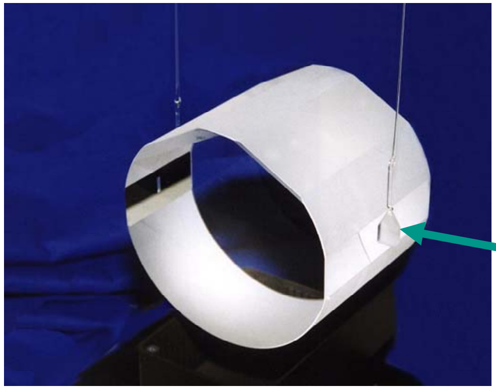
Thermal Noise Suppression Suspension Subsystem (SUS) Design

- **Minimize noise from damping controls and global control actuation**
- **Minimise thermal noise from pendulum modes**
  - » Thermally induced motion of the test masses sets the sensitivity limit in the range ~10 — 100 Hz
  - » Required noise level at each of the main optics is 10^{-19} m/√Hz at 10 Hz, falling off at higher frequencies



Test mass with mirror coating

Silica fibres



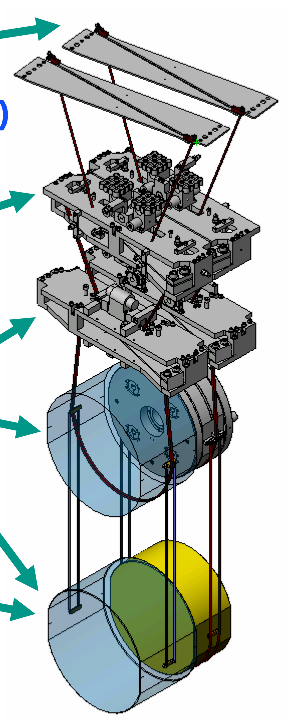
Silicate bonds

Optics Table Interface (Seismic Isolation System)

Damping Controls

Hierarchical Global Controls

Electrostatic Actuation

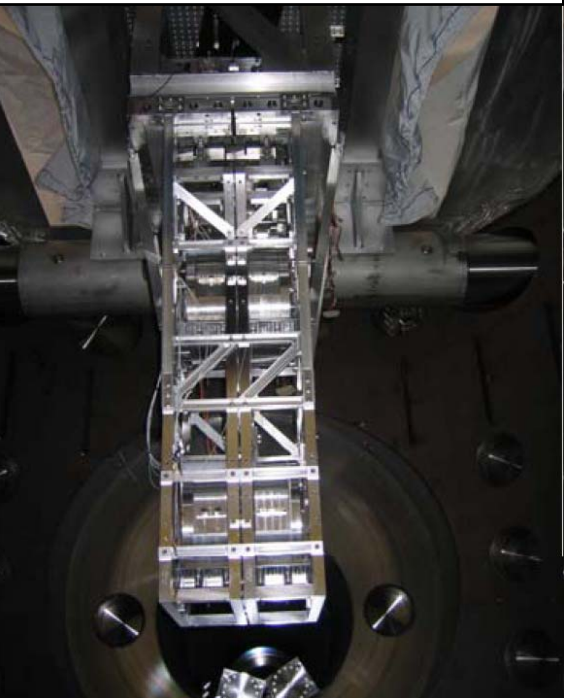


- **Choose quadruple pendulum suspensions for the main optics and triple pendulum suspensions for less critical cavity optics**
- **Create quasi-monolithic pendulums using fused silica ribbons to suspend 40 kg test mass**

Suspensions Update
(Combined US and UK Effort)

- **Test Mass (Quad) Suspension**
  - » **'Controls' Prototype installed at LASTI & under Test**
  - » **Preliminary Results in June for Concurrent "Noise" Prototype Development**
  - » **The UK Group delivers the "Noise" Prototype (essentially final design) in early 2007**

Quad Suspension in LASTI BSC Chamber

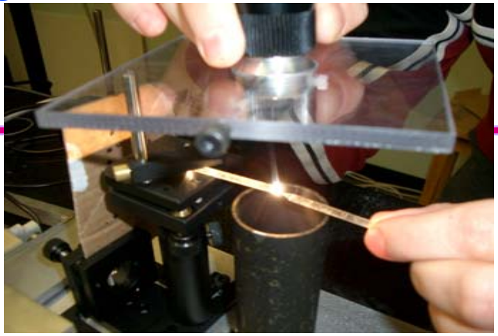


Triple Suspension in LASTI HAM Chamber

- Mode Cleaner (Triple) Suspension
  - »LASTI Testing of controls prototype completed
  - »Performance as expected
  - »Model-measurement comparison caught some model shortcomings & an as-built difference
  - »Final "Noise" Prototype is next

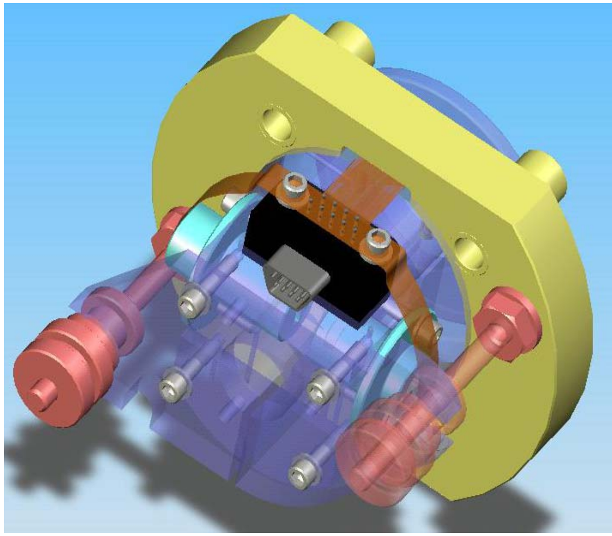
- **Other suspensions (extensions of existing designs):**
  - **Recycling mirror (triple) –full design**
  - **Beamsplitter (triple) –conceptual design**
  - **Folding Mirror (triple) –conceptual design**
  - **Output mode cleaner (double) –conceptual design underway**
  - **Mode matching telescopes, steering mirrors etc (single) – modified LIGO 1 suspensions**

New Elements/Aspects of the "Noise" Prototype, Quadruple Suspension



Welding 3mm silica rod with 9W CO_2 laser

- **Silica Fiber/Ribbon Pulling**
  - » **R&D on computer controlled CO_2 laser system proceeding well**
  - » **Fibers up to 570 mm long, 184 ± 5 microns diameter (15 microns dia. repeatability)**
  - » **3 GPa breaking stress (factor of safety ≈ 4)**
- **Fiber/Ribbon Welding**
  - » **Fiber & ribbon welding demonstrated**
  - » **Working to improve welded strength**
- **Electronics**
  - » **Improved Optical Sensing & Electro-Magnetic actuator (OSEM) assembly**
  - » **New Control & Data Systems (CDS), Bus & Network Topology at LASTI implemented to support Seismic & Suspension Prototype Testing**



Modified Hybrid
OSEM Design

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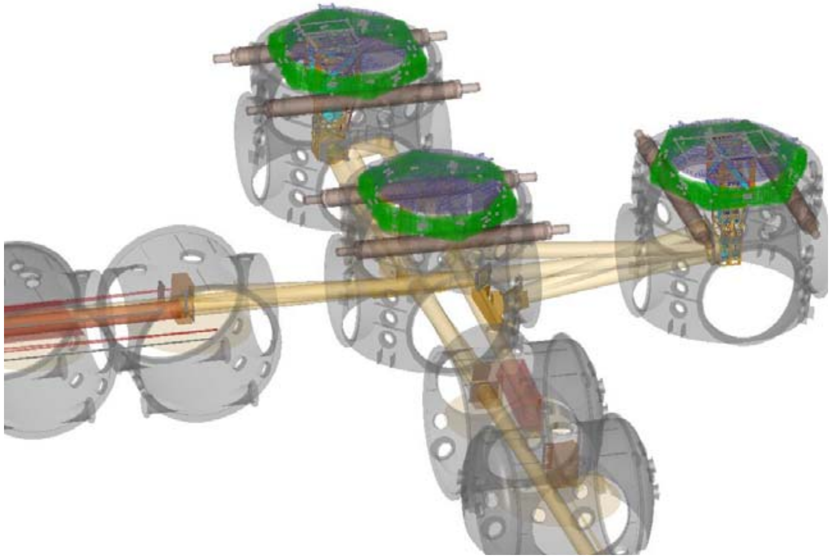
Systems Engineering

- Systems Engineering is Level-Of-Effort in the Construction Phase
- Maintain Interface Control Documentation (ICD)
- Continue Modeling/Simulation
- Maintain technical configuration management
- Define integrated test plans & procedures
- Review/Approve Subsystem acceptance test plans, test reports, EMI/EMC & grounding implementation, …

•3D, Integrated Opto-mechanical layout captured in SolidWorks CAD

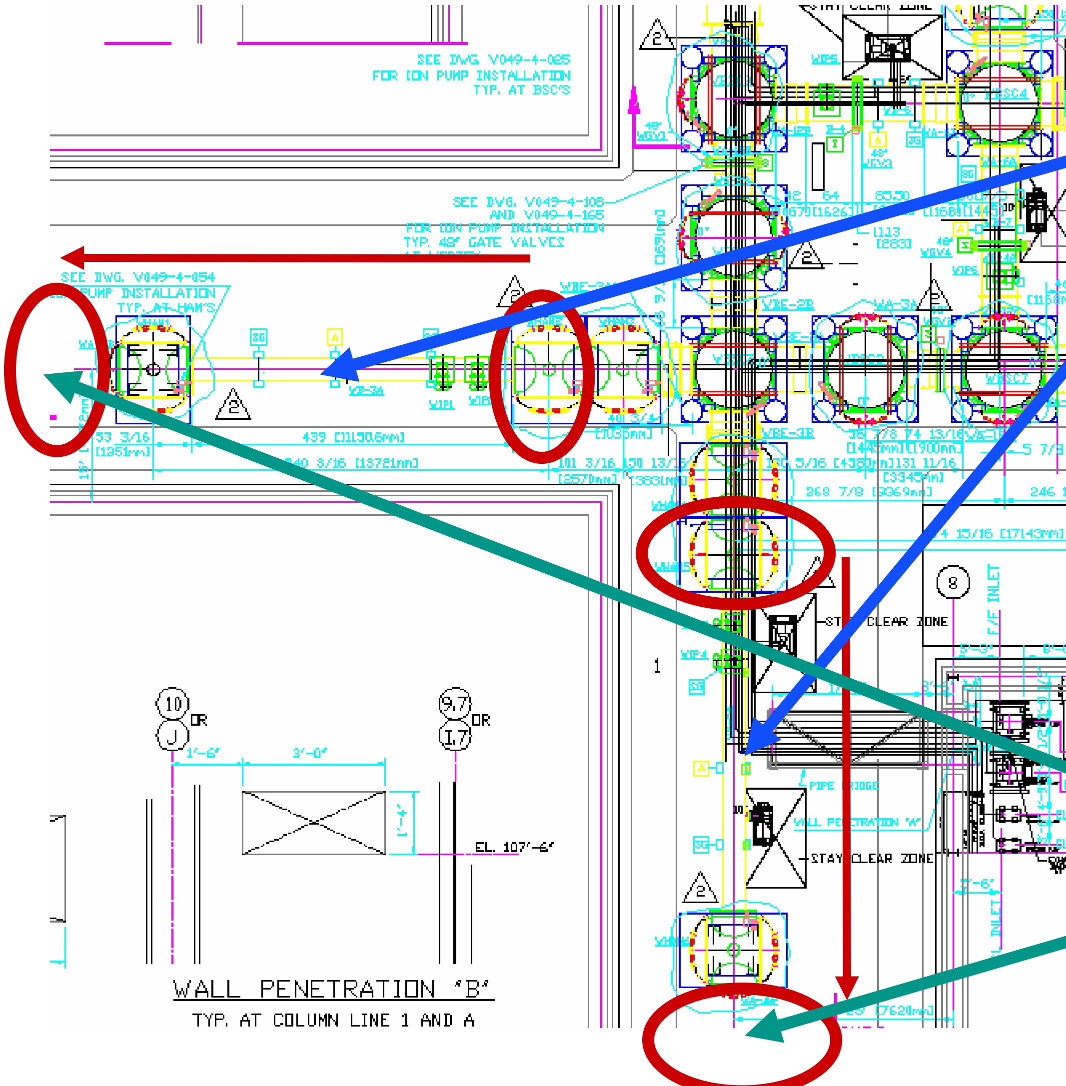
•Optical layout defined with Zemax

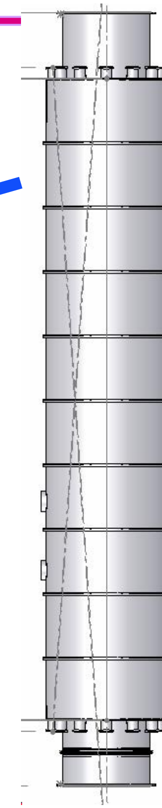


Facility Modifications & Preparations (FMP)

- Plan for Installation, Logistics and Staging
- Procure new Vacuum System components
  - » 2K to 4K conversion
  - » large diameter mode cleaner tubes
  - » Relocation of 2 HAM chambers for each interferometer
- Procure more class 100 clean room space for assembly and installation
- Provide assembly workspace and storage
- Procure installation fixtures and tooling
- Refurbish existing optics lab space, purchase bake oven, cleaning supplies

ISC Read-out Tables in Vacuum & Larger Input & Output Mode Cleaner Tubes





Mode Cleaner Tube

End HAM Chambers Have Separate Vacuum System

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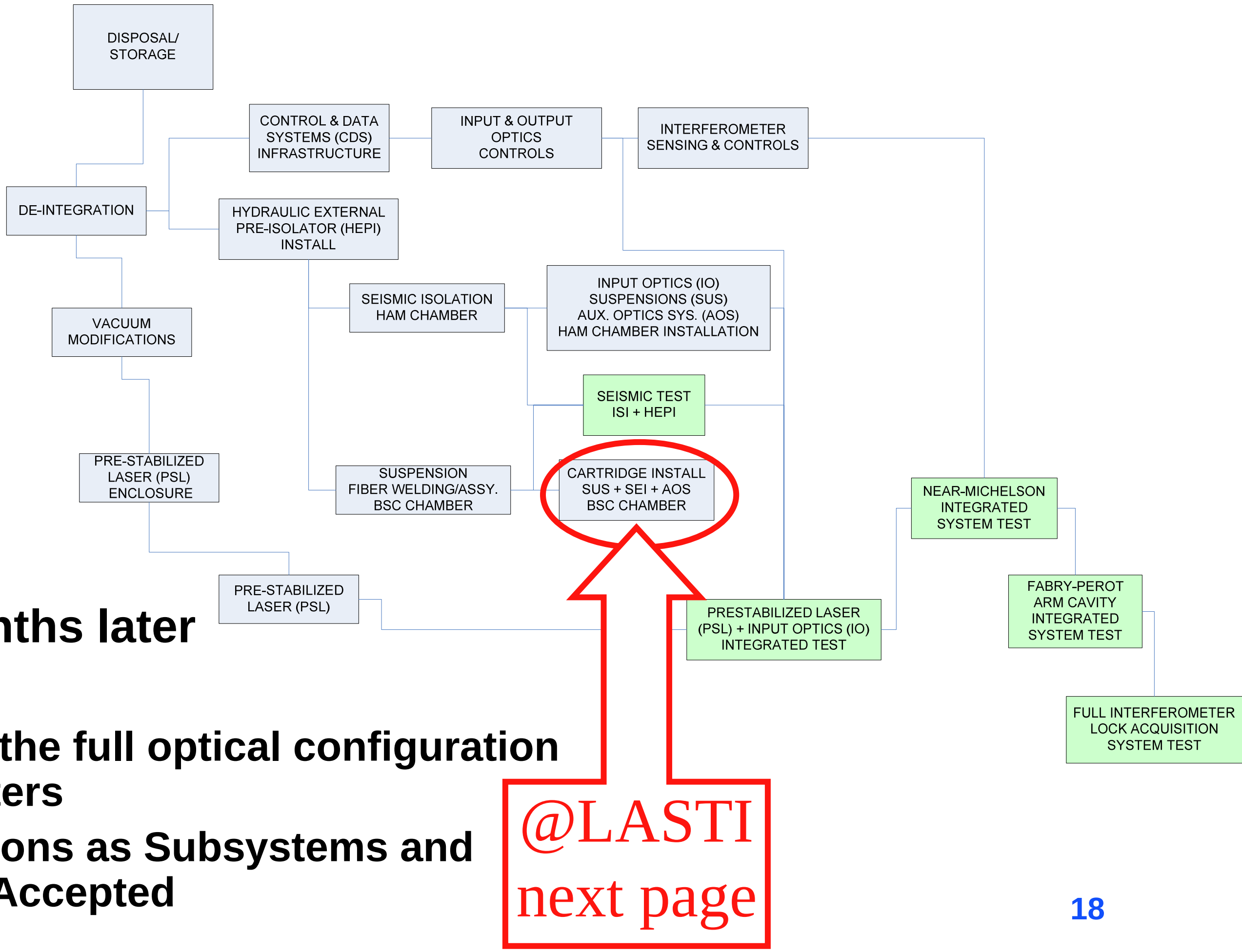
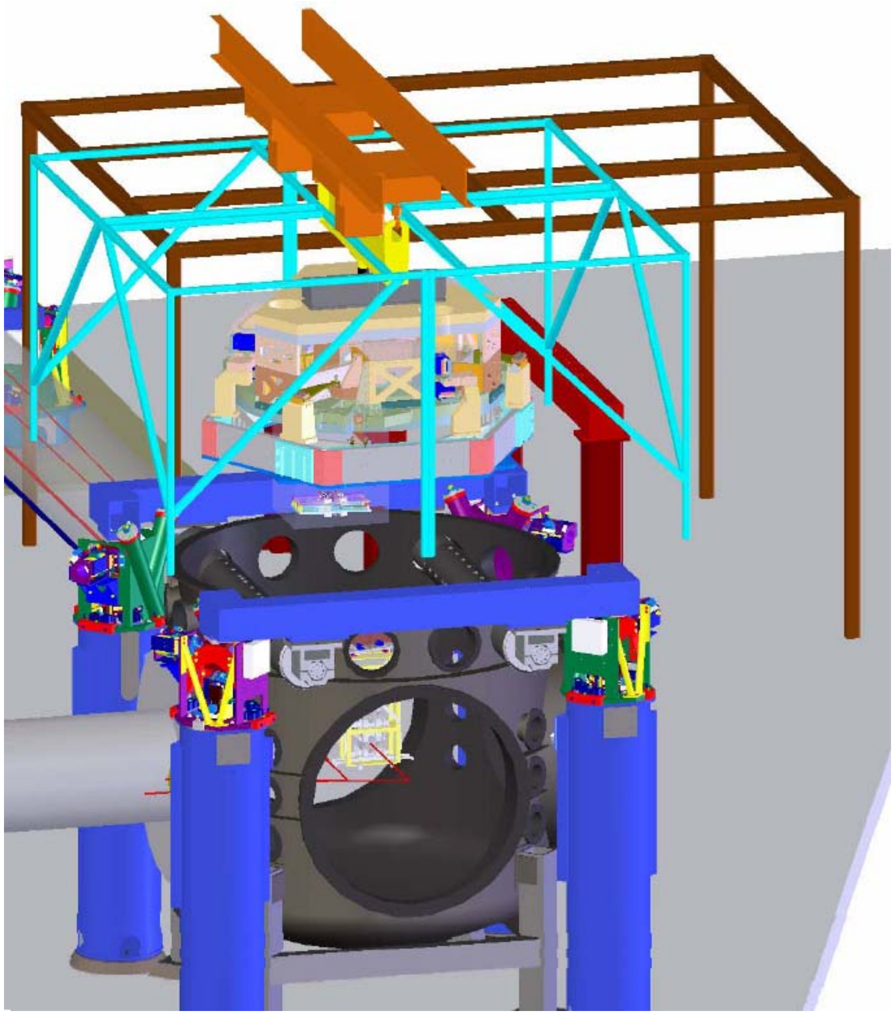
Installation (INS)

- **Basic Task Sequence per Interferometer:**
  - » **Removal**
  - » **Vacuum Equipment & Infrastructure Modifications**
  - » **Installation**
  - » **Testing**



- **Start at Livingston**
- **Hanford starts ~9 months later**
- **Duration is ~3 years**
  - » **Multi-hour “lock” in the full optical configuration for all 3 interferometers**
  - » **Transition to operations as Subsystems and Interferometers are Accepted**

BSC “Cartridge” Insertion into BSC Chamber @LASTI



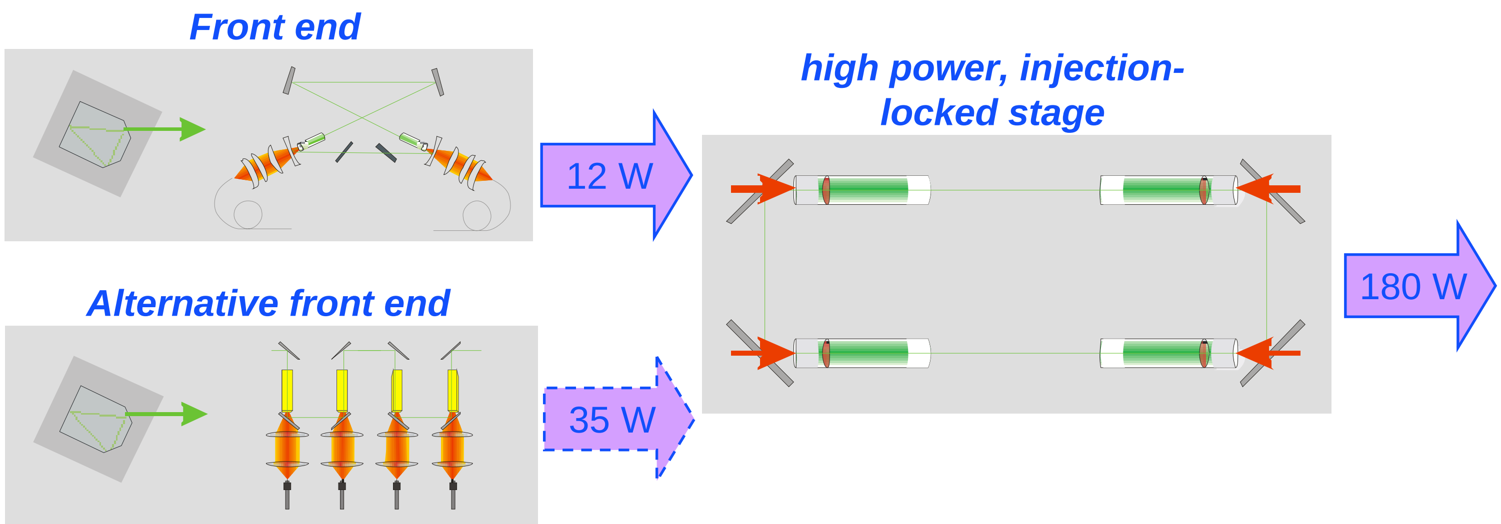
Advanced LIGO Subsystem Descriptions

NSF Review of Advanced LIGO Project

Dennis Coyne, Caltech
Peter Fritschel, MIT

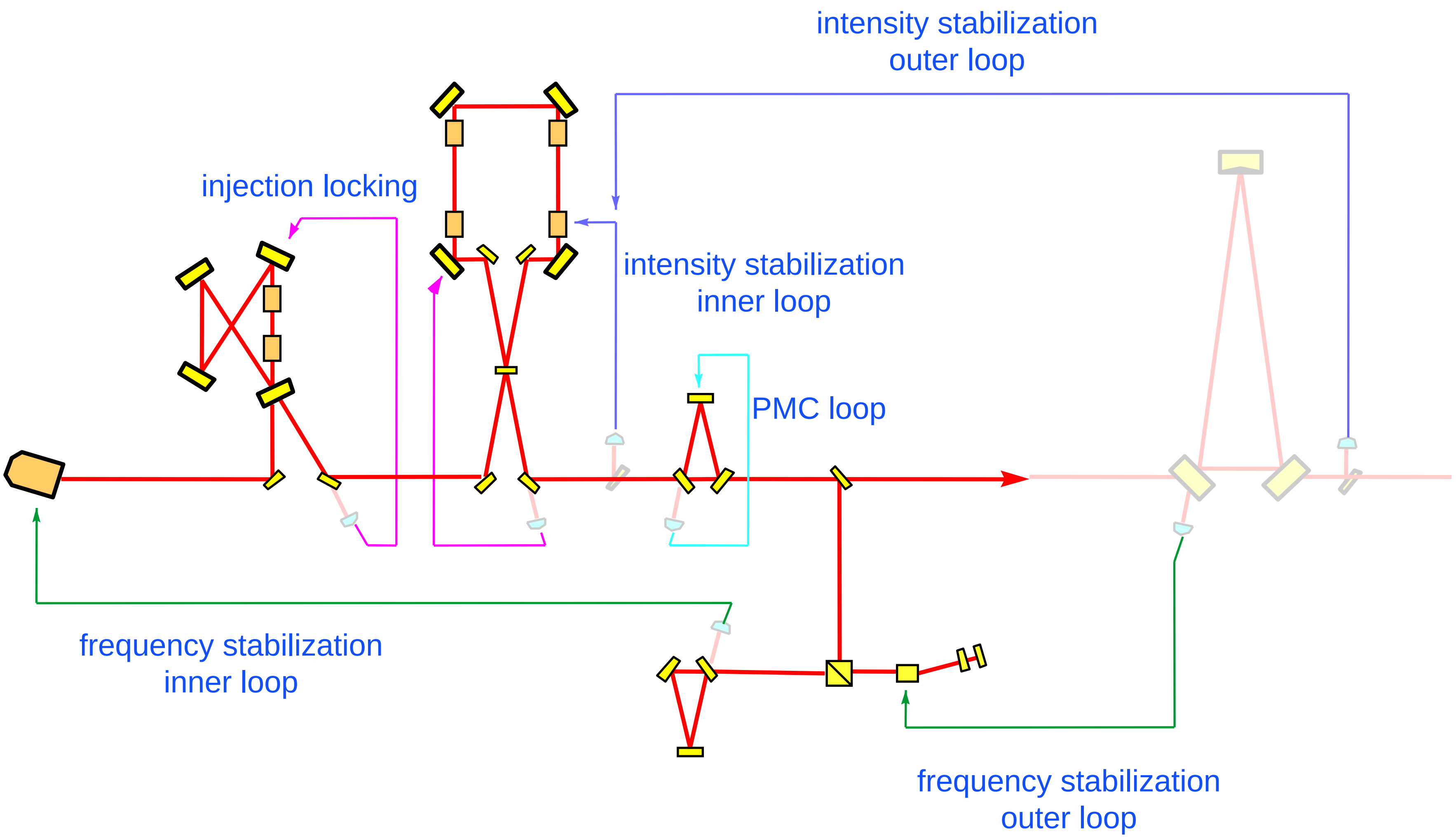
Pre-stabilized laser (PSL)

- **High power laser: 180 Watts**



- **Laser power stabilization**
- **Laser frequency pre-stabilization**
  - » Wideband frequency actuation for further stabilization
- **Pre-mode cleaner for spatial clean-up and high-frequency filtering**
- **Diagnostic tools**
- **Laser safety measures**

PSL: stabilization systems



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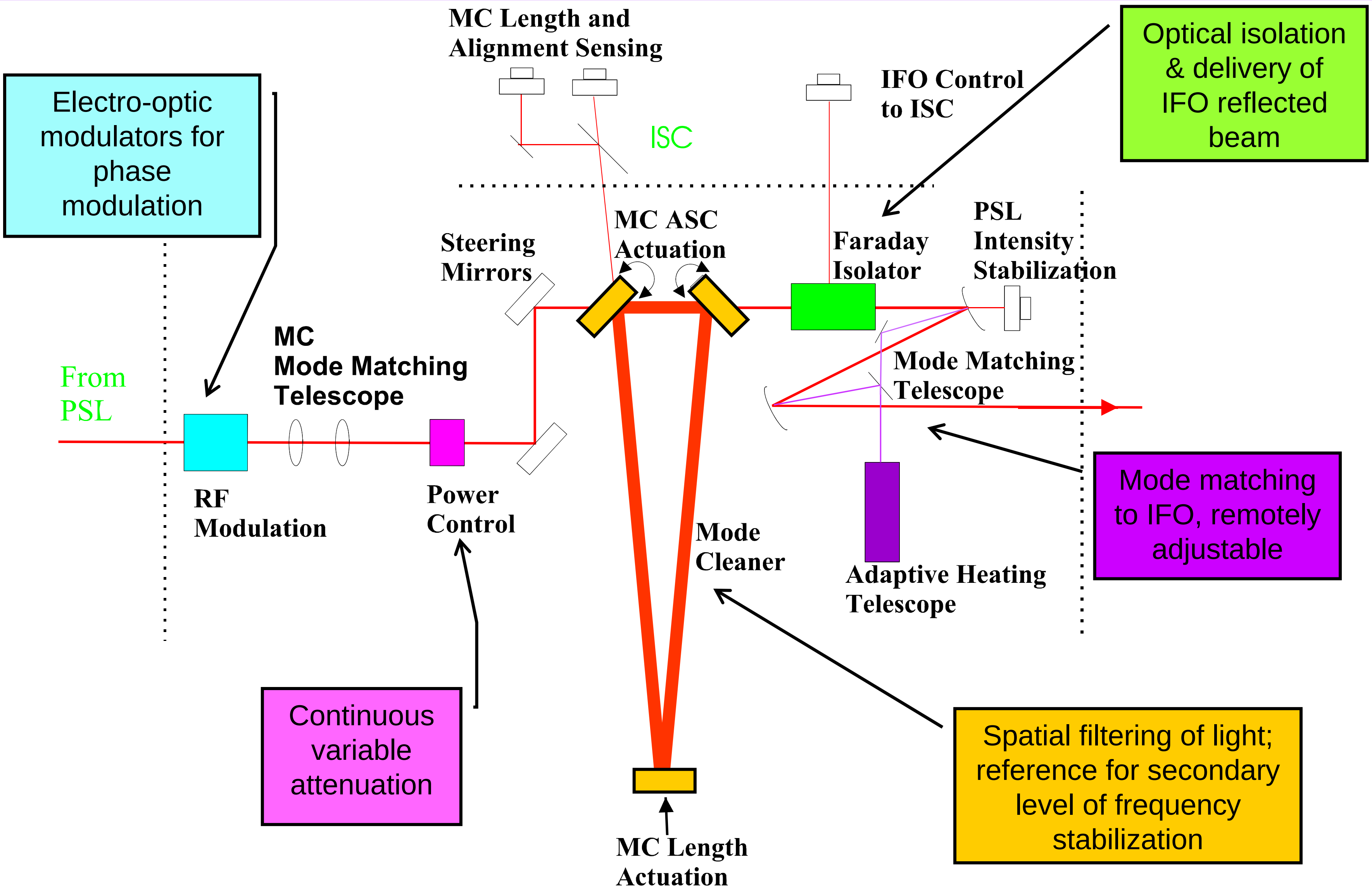
Input Optics



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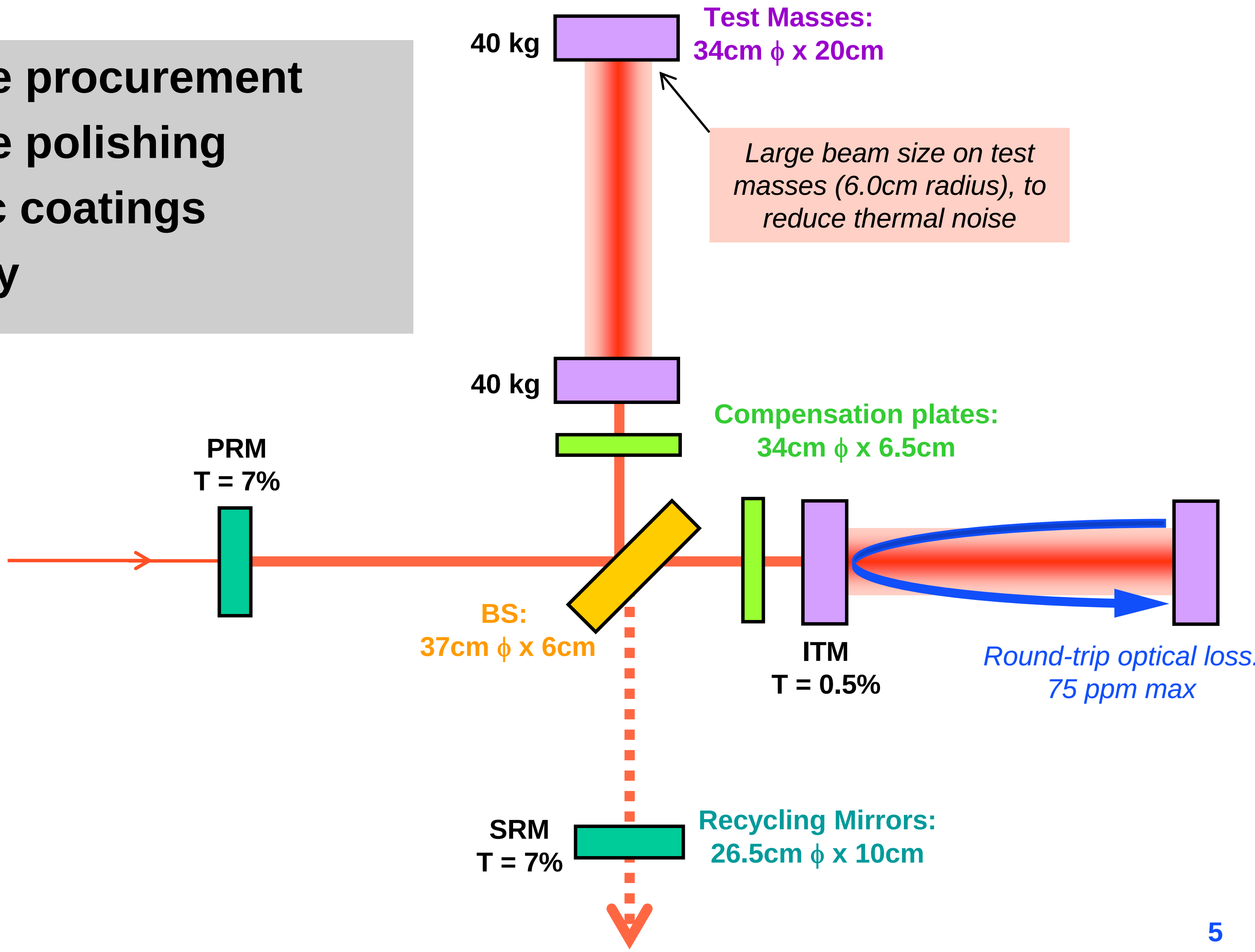
Core Optics Components

- Substrate procurement
- Substrate polishing
- Dielectric coatings
- Metrology



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Core Optics Components

- **Substrates**
  - Fused silica: Heraeus (for low absorption) or Corning
  - Specific grade and absorption depends on optics
  - ITMs and BS most critical (need low absorption and good homogeneity)
- **Polishing**
  - Low micro-roughness (< 1 angstrom-rms)
  - Low residual figure distortion (< 1 nm-rms over central 120mm diameter)
  - Accurate matching of radii-of-curvature
  - Surfaces for attachment of suspension fibers
- **Dielectric coatings**
  - Low absorption (0.5 ppm or smaller)
  - Low scatter
  - Low mechanical loss (< 2e-4)
- **In-house Metrology**
  - ROC, figure distortion, scattering, absorption

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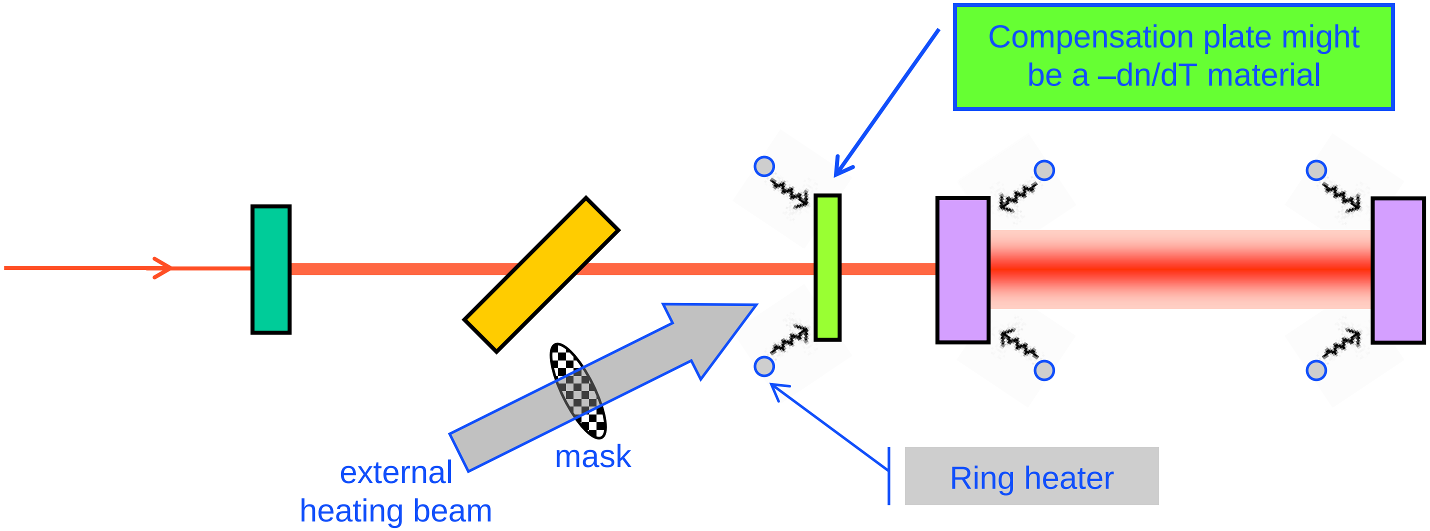
Auxiliary Optics Subsystem (AOS)

- **Initial Alignment System**
  - » Surveying support for proper installation of components
- **Photon calibrators**
  - » Calibration tool using photon pressure of a modulated laser beam
- **Viewports**
  - » For beams entering and exiting vacuum
- **Optical levers**
  - » Orientation monitors of each suspended optic, relative to the floor
- **In-vacuum stray light control**
  - » Baffles and beam dumps for diffuse scattering and ghost beams
- **Beam reducing telescopes**
  - » For pick-off beams and the output beam
- **Thermal compensation system**
  - » Senses thermal distortions of core optics and corrects by adding compensating heat

Thermal compensation system

Absorption and thermal lensing at high power operation

Optic	*Substrate*			*Surface*		
	Power	*absorbed power*	*Induced lens*	*Power*	*absorbed power*	*Induced lens*
ITM	**1 kW**	**120 mW**	**$(6.8\ \mathrm{km})^{-1}$**	**800 kW**	**400 mW**	**$(100\ \mathrm{km})^{-1}$**
ETM				**800 kW**	**400 mW**	**$(100\ \mathrm{km})^{-1}$**



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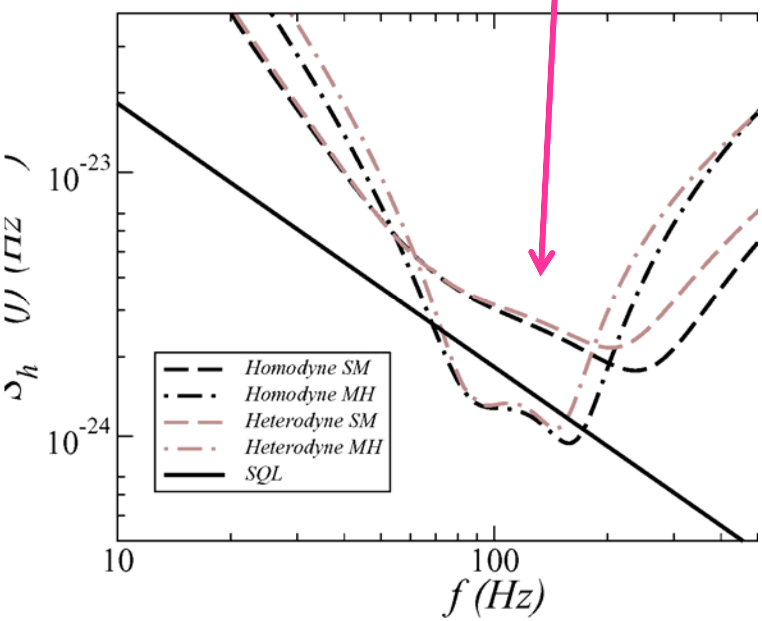
Interferometer Sensing & Control (ISC)

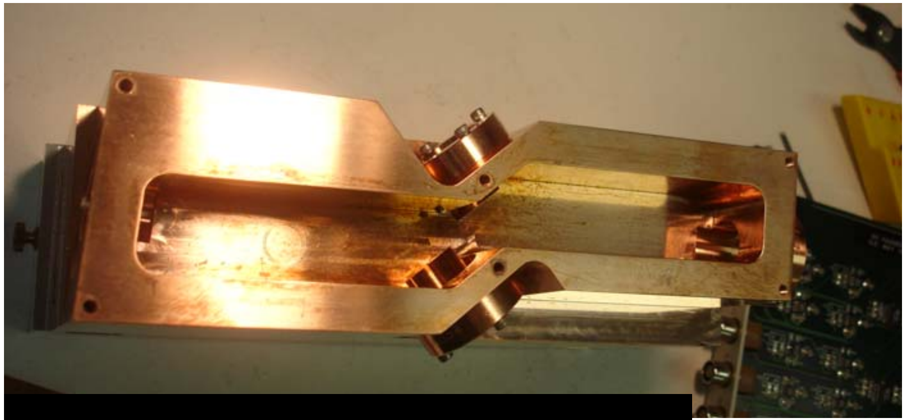
- **Specifies input beam modulation scheme to:**
  - » Sense the global interferometer lengths
  - » Sense the global interferometer mirror angles
- **Detection tables for all sensed beams**
  - » Opto-mechanical hardware, photodetectors
  - » All beams involved in critical control loops will be detected in-vacuum, on vibrationally isolated tables
- **Digital controls hardware and software for all length and alignment controls**
  - » Including data conversion
- **Lock acquisition of the interferometer**
- **Readout of the gravitational wave channel**

ISC: DC detection & output mode cleaner

- **DC (homodyne) detection: decided in favor of in 2003**
  - » Interferometer is offset from the dark fringe (1-10 pm), and the resulting DC carrier field is used as the local oscillator for detecting the GW signal
  - » Less sensitive to input beam noise than RF (heterodyne) detection
  - » Quantum noise sensitivity as good as or better than RF detection



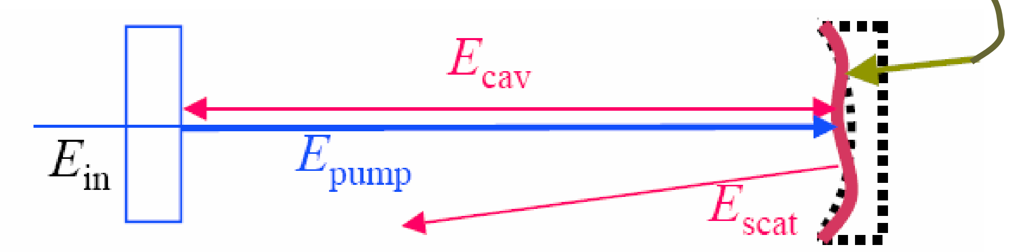
- **Output mode cleaner**
  - » Needed to reject higher-order mode light at the output
  - » Rejects RF sideband power for DC detection



Caltech 40m prototype

System design challenges: *potential instabilities at high power*

- **Unstable optical spring when the SRC is detuned**
  - » ISC length control system will provide wideband feedback (~200 Hz) to stabilize (unstable mode at 50-60 Hz for nominal tuning)
- **Angular instability due to radiation torque**
  - » Led to choice of negative g-parameters for cavities: 1 – L/R = -0.93
  - » Feedback stabilization provided by ISC alignment controls: challenge is to provide enough feedback to stabilize, without introducing noise
- **Parametric instabilities**
  - » Test mass mechanical modes can parametrically pump energy into higher-order cavity modes



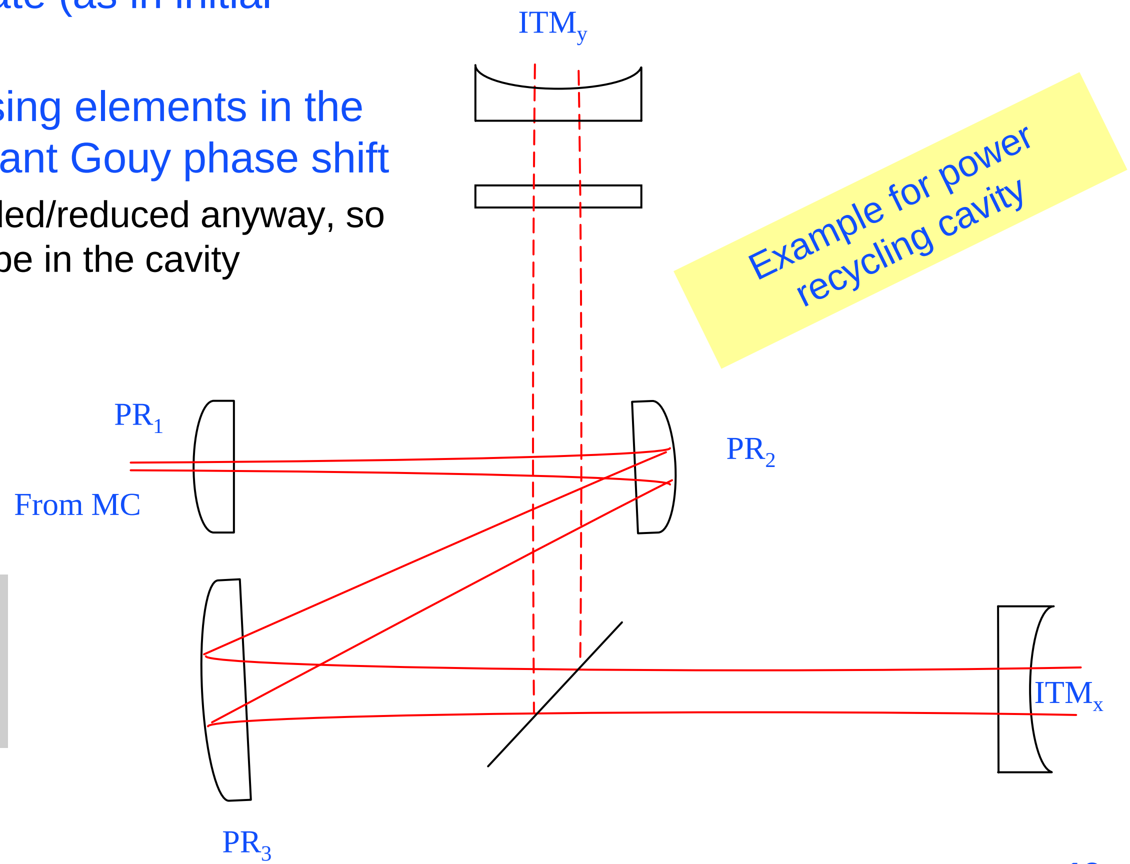
  - » Modeling of the phenomenon is being further refined (Braginsky, UWA, CIT)
  - » Currently ~10 modes predicted to be unstable at full power

Mitigation options:

- *reduce Q of mechanical modes by selective application of lossy material*
- *increase cavity mode loss by tuning coating aperture, and/or ITM transmission*
- *fine tune the cavity mode spectrum using the TCS actuation of ROCs, to avoid critical modes*

Open system design options

- **Configuration of recycling cavities**
  - » Current design: Gouy phase shift in the RCs is very small; RCs are at the edge of stability, and thus rather degenerate (as in initial LIGO)
  - » Alternative: include focusing elements in the RCs to achieve a significant Gouy phase shift
    - – beam has to be expanded/reduced anyway, so just include the telescope in the cavity



Stable configuration appears to have many advantages, and is being carefully studied

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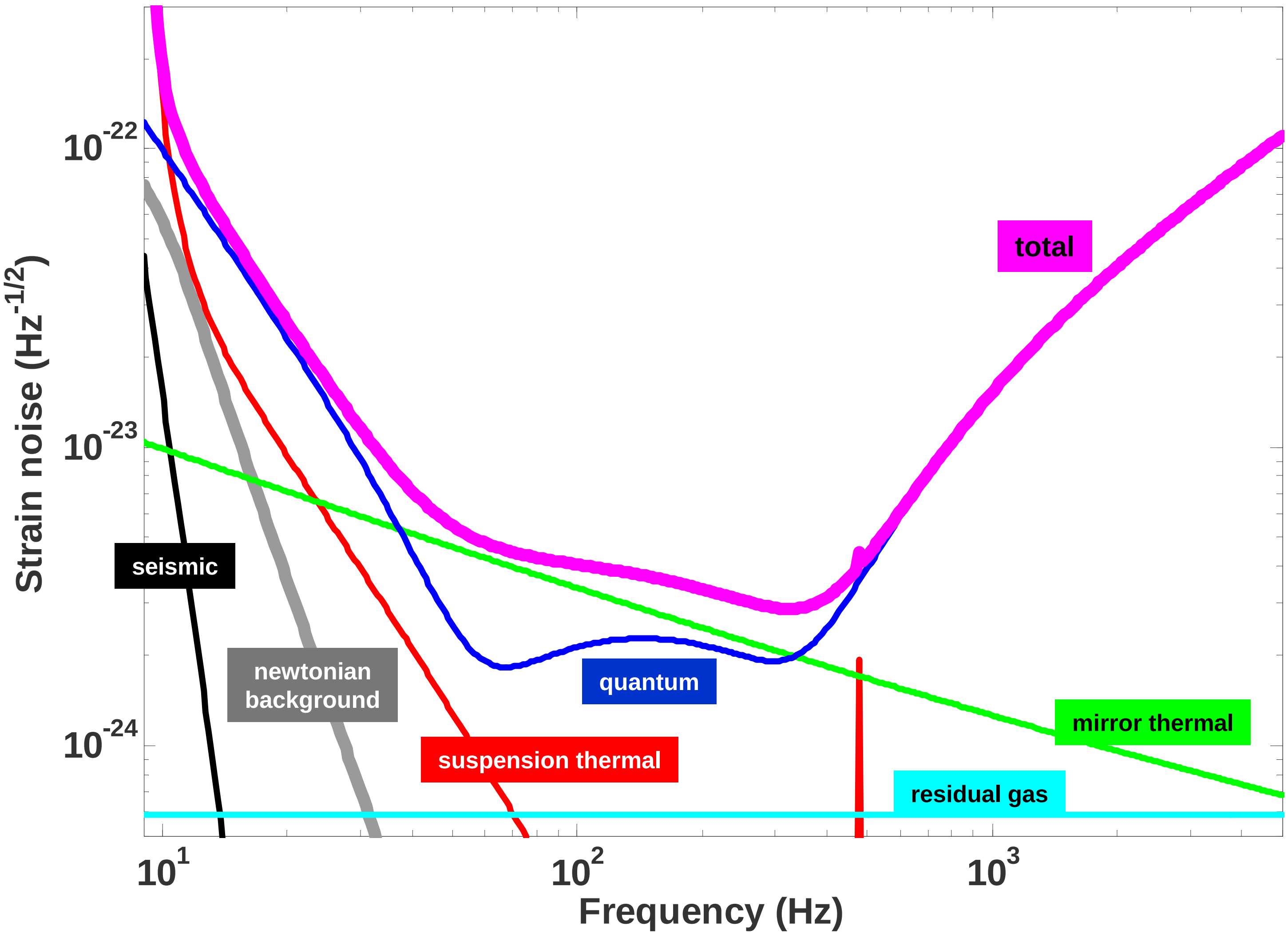
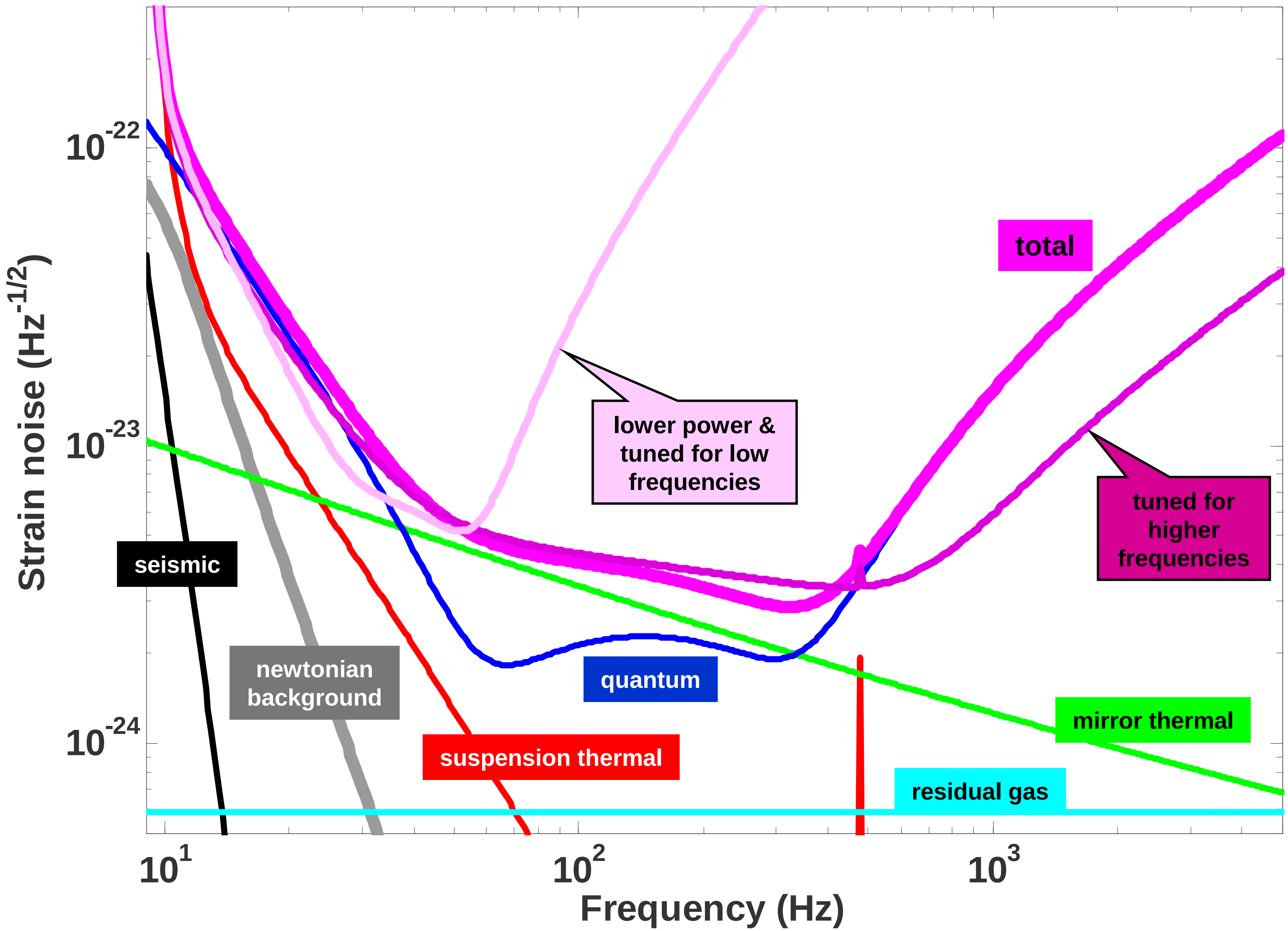
Design option: Seismic Platform Interferometer

- **Concept:**
  - » form a 'simple', relatively low-sensitivity interferometer between the ITM & ETM platforms
  - » Use it to stabilize the 4km arm lengths at low frequencies (below a few Hertz)
- **Motivation:**
  - » Arm length fluctuations are dominated by low frequency motions, f < 0.5 Hz; motion in this band (~100 nm-rms) not expected to be much lower than in initial LIGO (@LLO, w/ HEPI)
  - » Reducing this rms by another factor of 10-100x could:
    - – Make lock acquisition much simpler
    - – Enable lock acquisition during times of high micro-seism
    - – Possibly beneficial during interferometer operation as well
- **Status:**
  - » Schemes for implementing an SPI are being considered
  - » Falls in the domain of the ISC subsystem, if implemented

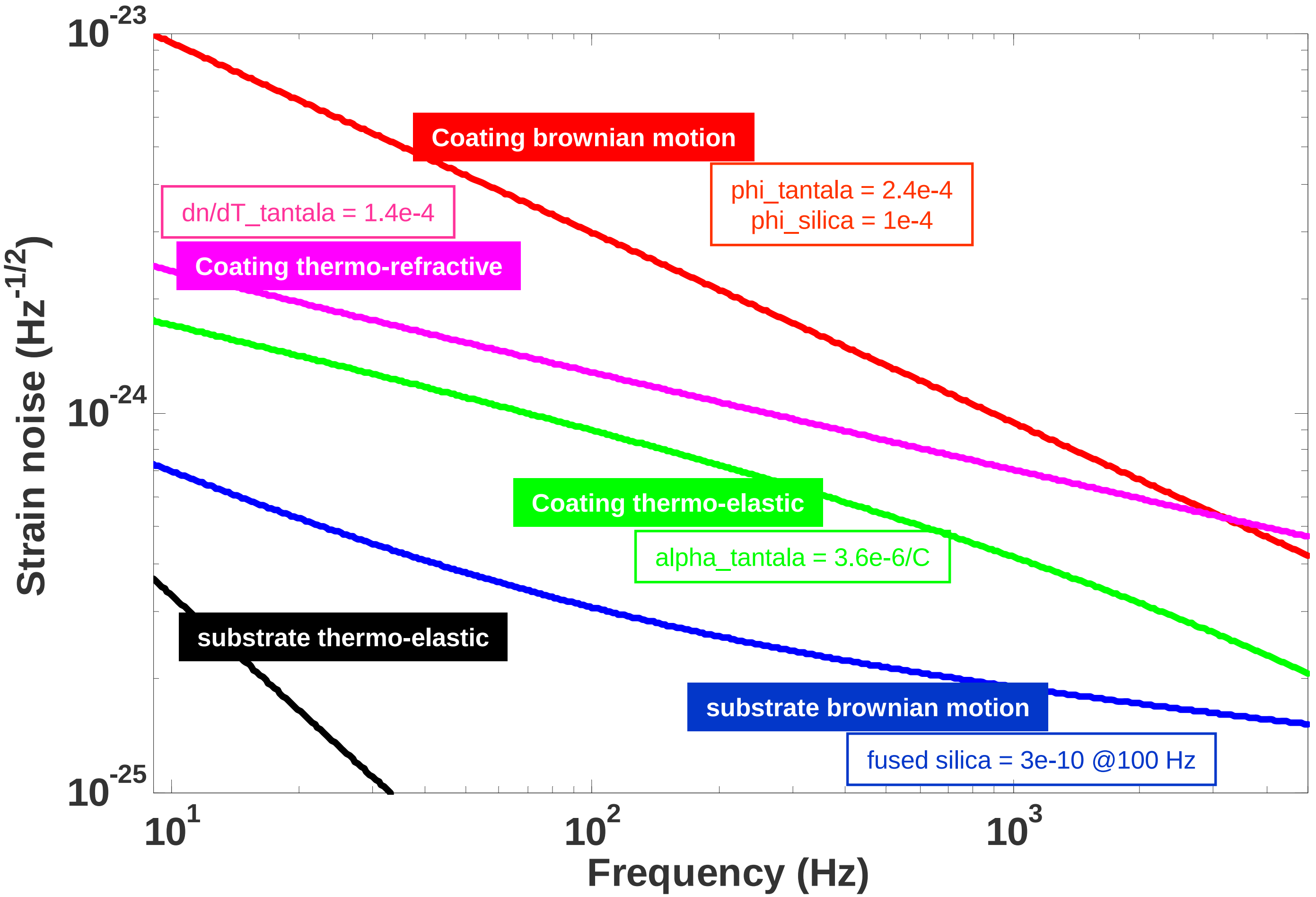
Interferometer performance estimate



Interferometer performance estimate



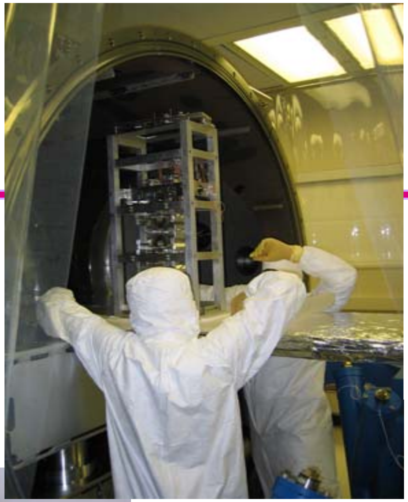
Mirror thermal noise contributors



System Testing

- **Two major LIGO prototype test facilities:**
  - » LIGO Advanced System Test Interferometer (LASTI) @MIT – full scale tests of :
    - – seismic isolation
    - – suspensions, laser
    - – mode cleaner
  - » 40m Interferometer @Caltech
    - – Sensing/controls tests of readout
    - – Lock acquisition
    - – Engineering model for data acquisition, software
- **Support from LSC testbeds**
  - » Gingin Facility @Gingin, Australia – high power cavity, for:
    - – Thermal compensation: sensors and actuators
    - – Parameteric instabilities
  - » 10m Interferometer @U of Glasgow – readout
  - » Engineering Test Facility (ETF) @Stanford – seismic isolation
  - » GEO600 @Hanover, Germany – much more than a prototype! (test of the quasi-monolithic fused silica suspension)
- **Initial & enhanced LIGO**
  - » Hydraulic External Pre-Isolator (HEPI)
  - » Thermal Compensation System
  - » High power modulators & isolators
  - » Output mode cleaner & DC readout

LASTI (Triple Suspension in a HAM Chamber)



Gingin Facility

40 M Lab