Advanced LIGO Subsystem Descriptions

NSF Review of Advanced LIGO Project
5 June 2007

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LIGO-G070372-00-M

advancedligo

agenda

- Pre-Stabilized Laser (PSL)
- Input Optics (IO)
- Core Optics Components (COC)
- Auxiliary Optics System (AOS)
- Interferometer Sensing & Controls (ISC)
- Systems Engineering (SYS)
- Data Acquisition, Diagnostics, Networking & Supervisory Control (DAQ)
- Data Computing System (DCS)
- Seismic Isolation (SEI)
- Suspensions (SUS)
- Facility Modifications & Preparation (FMP)
- Installation & System Test (INS)

Pre-stabilized laser (PSL)

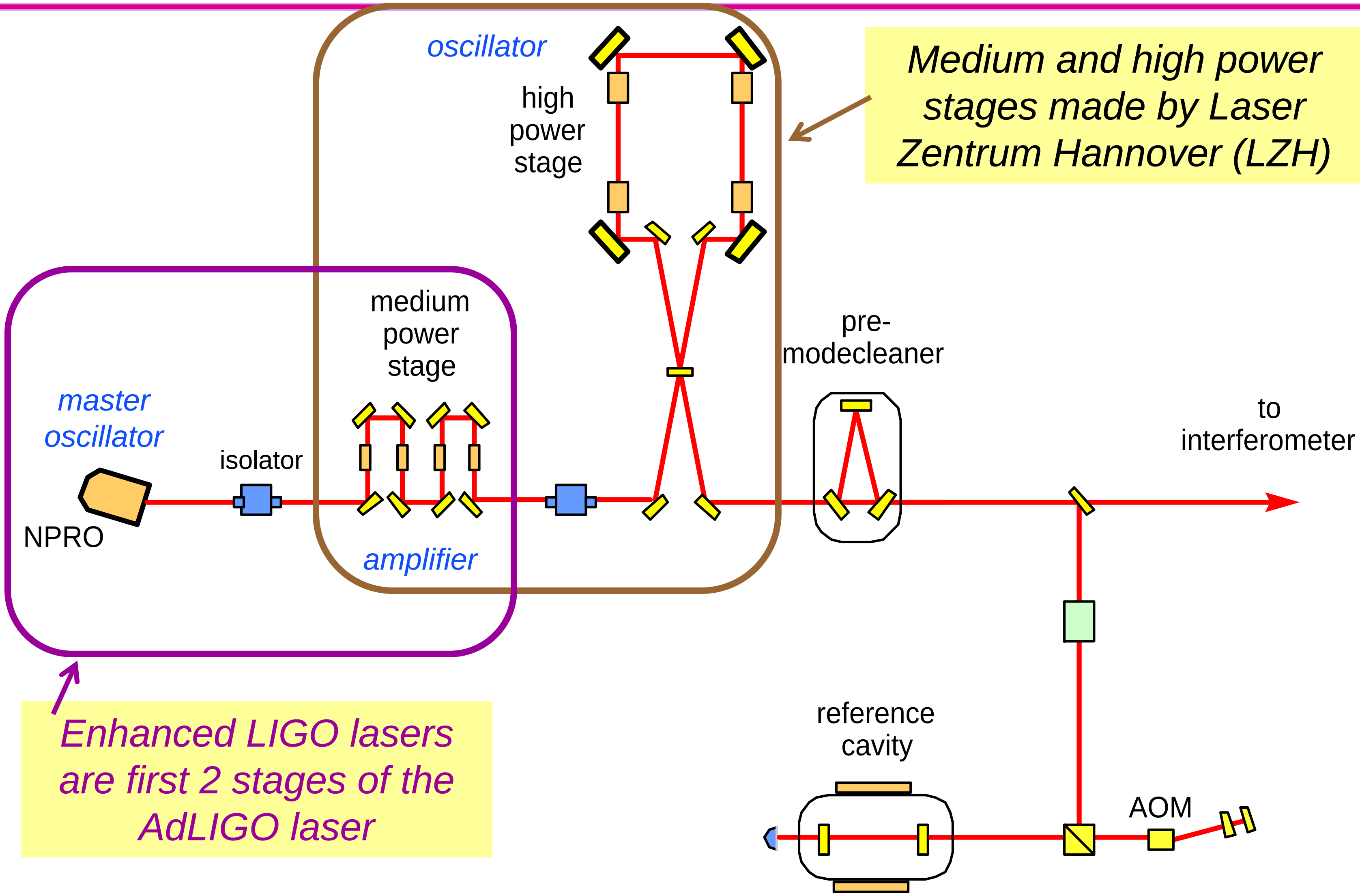
- **High power laser: 180 Watts**
- **Laser frequency pre-stabilization & frequency actuation**
- **Pre-mode cleaner for spatial clean-up and high-frequency filtering**
- **Diagnostic tools**

Supplied by Max Planck Inst. / AEI

- **Laser power stabilization**
- **Laser safety measures**
- **Facility infrastructure**
  - Laser and laser diode enclosures
  - Instrument racks, crates, power supplies
  - Supervisory controls & DAQ interfacing

Supplied by LIGO Lab

Pre-stabilized laser



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PSL: program status, progress & changes since 2006

- **AEI funding is approved, contract between AEI & LZH in place**
- **Fully staffed: 7 people @ LZH, 4 @ AEI**
- **LZH labs renovated**
  - » Clean, temperature stable environment for laser assembly
- **First NPROs for the observatories arrived**
  - » Innolight Mephisto: undergoing characterization
- **First Enhanced LIGO prototype laser (35 W) to be delivered to LIGO in summer 2007**
  - » First observatory laser near end of year
- **MOU between AEI and LIGO Lab is in preparation**
- **Front-end (medium power stage) changed from oscillator to amplifier**

PSL: changes & progress since 2006

- **Overall development plan:**

Laboratory prototype → **Functional prototype** → **Engineering prototype**

demonstrate concepts | **Now** | demonstrate specs | fit / form / function

Complete integration tests & begin production: Sep 2009

- **Laboratory prototype: design improvements & characterization**
  - » Front-end changed to amplifier
  - » Resonator design optimized
  - » Critical components identified and upgraded
  - » Improved beam quality
  - » Improved injection locking
  - » Noise performance characterized
  - » Current state: 150 W output power, 85% in TEM00 mode, operates 8-10 hrs continuously every day
- **Functional prototype: being built now**
  - » Improved laser head design
  - » Improved pumping design (higher efficiency)
  - » Two new heads tested in a standing wave resonator: 90 W TEM00

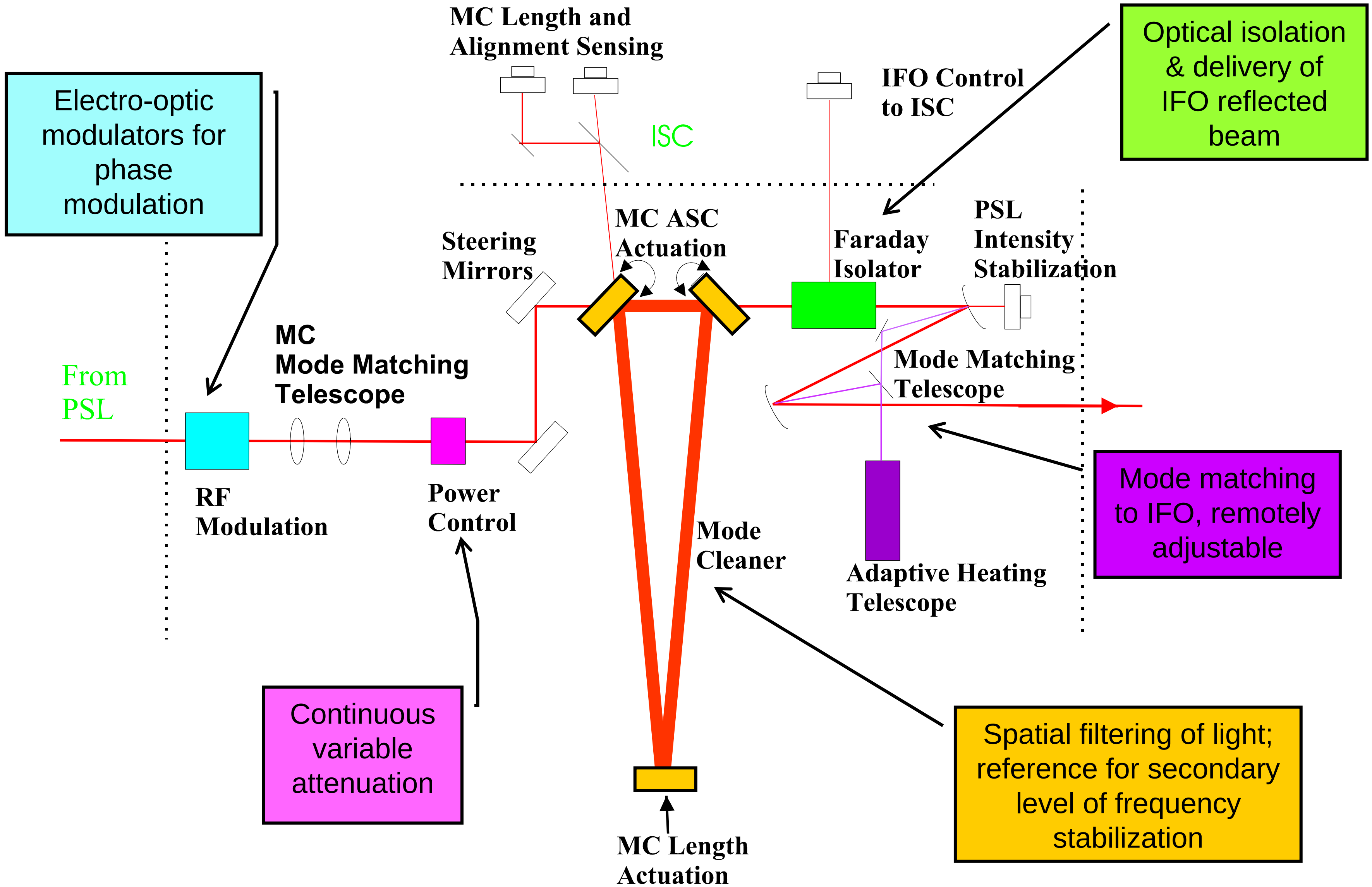
PSL: recommendations from 2006 review

- *The Panel encourages the German team to continue their effort and suggest that they share problems of added noise in photodiodes with researchers at NIST that face similar issues.*
  - power stabilization effort continued, stabilization of 35W laser
  - photodiode characterization and tests ongoing
  - contact between B. Willke and L. Hollberg at ASSP conference on photodiode research
  - contact initiated by T. Carruthers between AEI and NRL on high power photodiodes
- *The Panel suggests the AEI/LIGO Laboratory monthly meetings be formalized with formal meeting minutes.*
  - bi-weekly telecon meetings with minutes on the PSL Wiki

PSL: near term plans and project readiness

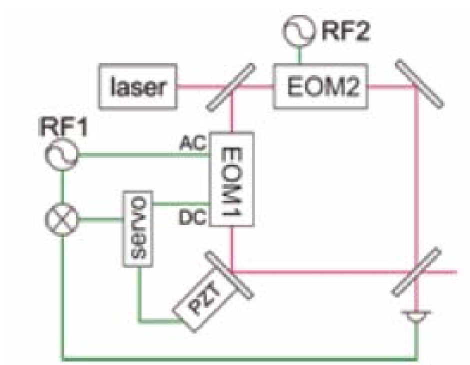
- **Diagnostic breadboards**
  - » 3 being built to allow reliable, reproducible and comparable tests of laser parameters at AEI, LZH & LIGO
- **Pre-mode cleaner development**
  - » First version designed, parts on order
  - » Design (finesse = 50) based on thermal loading experiments at Stanford
  - » Options for next version: sealed housing (vacuum); longer cavity for increased RF filtering
- **Preliminary design complete: Dec 2007**
- **Final design complete: Sep 2009**

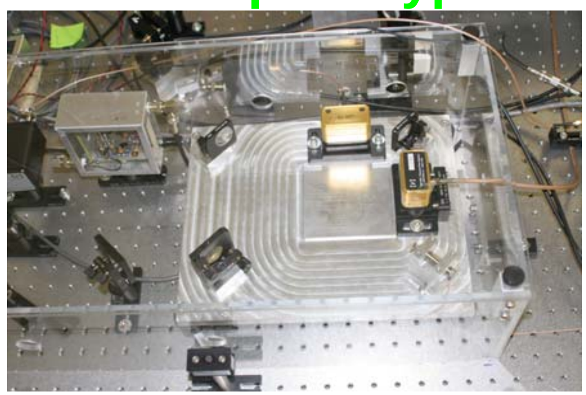
Input Optics



IO: program status, progress & changes since 2006

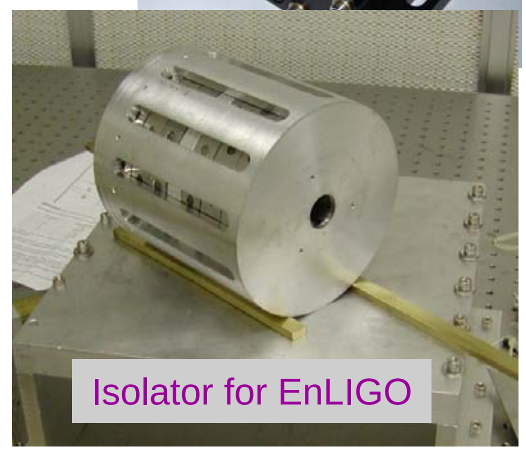
- **Preliminary Design Review in progress**
- **Faraday isolators & RTP modulators being prepared for Enhanced LIGO**
  - » Initial vacuum testing of Faraday shows a drop in isolation to 25 dB at high power
- **Mach-Zehnder architecture prototyped**





  - » Complex modulation (AM/PM) also being investigated
- **Mode cleaner optical design complete**
  - » Thermal modeling performed
  - » Finesse reduced to 500 (from 1500-2000)

Modulator for EnLIGO



Isolator for EnLIGO

IO: program status, progress & changes since 2006

- **Input mode matching telescope**
  - Designs and layouts have been made for both options of recycling cavity design (IO group is part of the team evaluating the RC design)
  - Controllable mode matching: concept changed from CO2 beam directed on a MMT mirror, to a segmented ring heater on the negative-dn/dT element in the Faraday isolator
- **Input optics light baffling**
  - Light baffling, beam dumps, and wire protection now part of IO scope (moved from AOS)
- **Active beam jitter suppression dropped from design**
  - Not needed: PSL beam stability plus MC filtering good enough

IO: recommendations from 2006 review

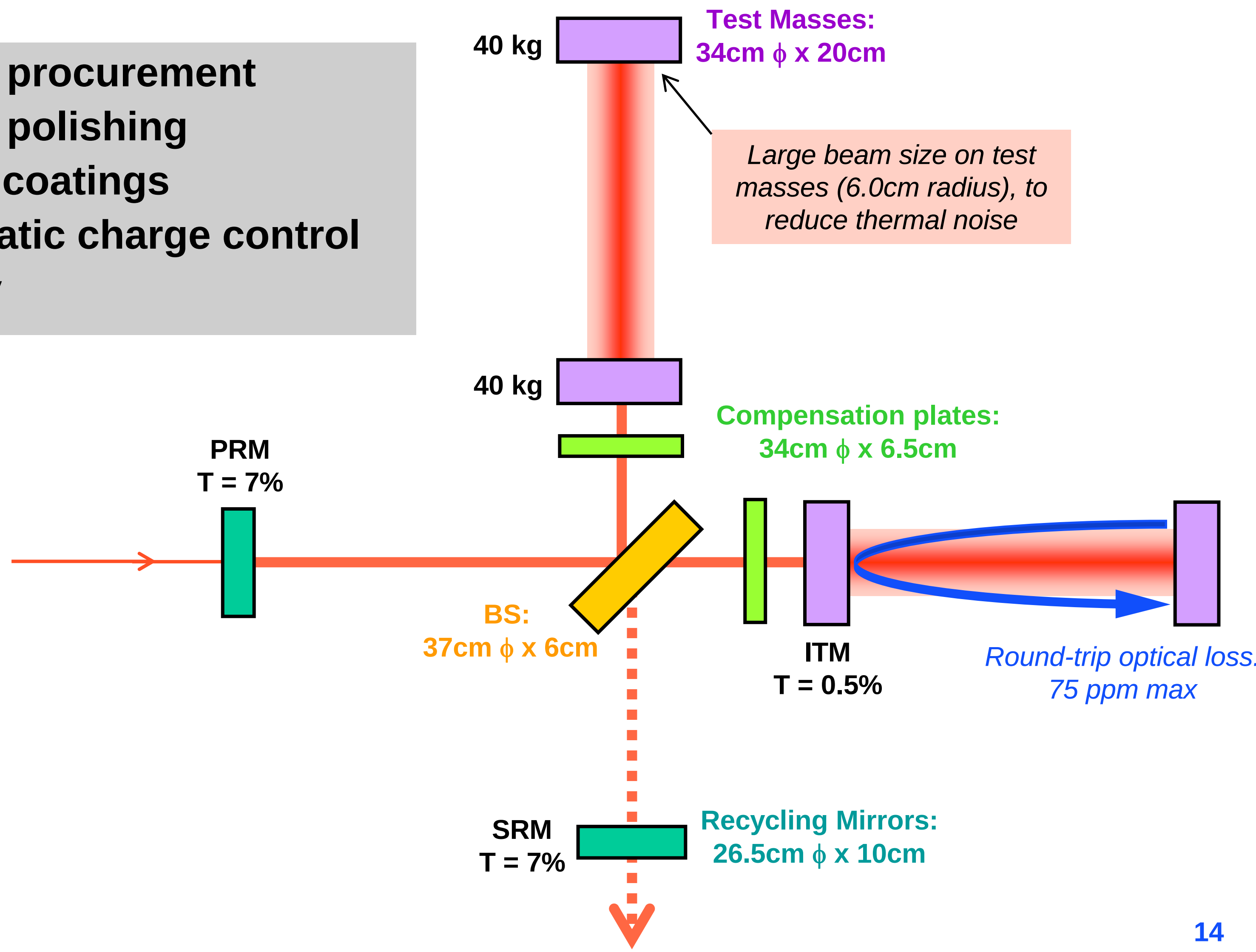
- *Power control: continue to improve use of TFP's due to simplicity, consider calcite, if necessary, and ensure proper safety considerations in the design and use of the beam dumps*
  - » A TFP is used in the design of the power control; adequate extinction for P control
  - » Two types of beam dumps are under consideration: a commercial, water-cooled dump; a UF-design where the beam is absorbed in a water-ink filled glass cylinder
- *MC: perform thermal modeling, modify control loops to handle the larger mass associated with larger optics, perform 'lifetime' (MTBF) measurements of the mode cleaner optics, and perform scattered light characterization/calculation*
  - » Thermal modeling has been performed, and distortions are acceptable
  - » A long term in-vacuum exposure and damage testing experiment has been set up and is awaiting test mirrors. Scattering on superpolished mirrors is being investigated.
- *Faraday: consider improvement of thermal compensation at highest power, for a given performance of the adaptive mode expanding telescope. Consider the use of calcite polarizers for improved isolation.*
  - » A calcite polarizer is used for isolation
  - » A controllable lens element is now part of the design

IO: near-term plans and project readiness

- **Complete preliminary design review (June 2007)**
- **EO modulation**
  - Finish investigation of complex modulation & decide whether to switch from baseline Mach-Zehnder (Sept 2007)
- **Mode cleaner**
  - Start long term damage of mirror coatings (Sept 2007)
- **Faraday**
  - Continue investigation of in-vacuum performance degradation & work on fixes (better heat-sinking of the crystal)
- **Mode matching**
  - Prototype and characterize segmented ring heater
- **IO Final Design Review, Aug 2008**
  - Long lead optics procurement begins early 2008

Core Optics Components

- Substrate procurement
- Substrate polishing
- Dielectric coatings
- Electro-static charge control
- Metrology



COC:
development status, progress & changes since 2006

- **Substrates**
  - Fused silica for many optics is 'standard': no development needed
  - An ultra-low-OH (low absorption) fused silica from Heraeus would be desirable for ITMs, BS, CPs: a large sample has been ordered for testing
- **Polishing**
  - Optical simulations of an arm cavity led to Pathfinder test mass polishing specification
  - Pathfinder project is in progress with 2 vendors (CSIRO & QED Technologies); results due in August
  - Will pursue contracting with a 3rd pathfinder polisher
- **Dielectric coatings**
  - Working with two coating vendors: CSIRO and LMA-Lyon
  - Developed a silica/titania-doped tantala coating: ~3x lower mechanical loss than initial LIGO (small samples)
  - LASTI test mass just coated by LMA with this recipe; metrology at Caltech imminent
  - Silica/silica-doped titania: better than initial LIGO, not as good as above
  - Absorption OK, point defect scatter unknown

COC: development status, progress & changes since 2006

- **Dielectric coatings, cont'd**
  - » Better understanding of coating thermo-optic noise: coherent effect of thermoelastic (dL/dT) & thermorefractive (dn/dT) terms
    - – Direct measurements of dn/dT being carried out by Gretarsson
  - » Modeling of coating layer thickness optimization
    - – By moving away from ¼-wave layer thickness, thermal noise can be reduced by ~10% in amplitude
    - – Such a coating design will be produced by LMA and tested in the Thermal Noise Interferometer at CIT
- **Electro-static charge research has ramped up**
  - » LSC working group on Charging formed
  - » Trinity and Moscow Stage groups measuring charge decay times on fused silica
  - » Pursuing a UV mitigation scheme
    - – Under development at Stanford; building on LISA, GPB and GEO experience
- **Better understanding of optical loss in initial LIGO optics**
  - » Informs what needs to be improved for Advanced LIGO
  - » Point defect scatter
    - – ~10ppm of point scatter loss in installed test masses
    - – More point scatter in large mirrors than small
  - » Microroughness of CSIRO-polished mirrors not as good as formerly believed
- **Cleanliness & handling**
  - » Exploring use of 'First Contact', a protective polymer for optics

COC: recommendations from 2006

- *Coating development is the only element that could delay the test mass delivery and should be followed closely.*
- *The thermal noise in coatings remains a potential limitation to the mid-band sensitivity. The Panel strongly recommends that LIGO maintain (and possibly increase) the current level of research towards the development of mechanically low-loss, high-finesse optical coatings whose contribution to the thermal noise budget of the detectors will be negligible.*
  - We have a coating recipe and vendor that is expected to produce acceptable coatings (just-delivered LASTI test mass is the first large optic test of this); ***however, improvements are desirable, coating thermal noise is the dominant noise term in the 50-100 Hz band …***
  - Optimized layer thickness design: ~10% noise reduction
  - Three-component alloy (silica-titania-tantala) may be worth pursuing
  - Different bombardment ions (other than Ar) may be worth pursuing
  - We plan on having a dialogue with REO regarding their interest in working with us

COC: recommendations from 2006

- *The understanding and, if necessary, elimination of the impact of electrostatic charging on Advanced LIGO performance should be prioritized.*
  - The issue has high priority within LIGO/LSC
  - LSC working group formed: charging workshop organized for July 2007 at MIT; will include LISA people
  - UV mitigation scheme being pursued; Stanford measuring effect of UV on coatings
  - Two charge decay experiments over the last year
  - Charging research plan drafted (LIGO-T070118)
  - Learning from initial LIGO, Advanced LIGO avoids contact of test masses with dissimilar materials (ie, use fused silica earthquake stops)

COC: near term plans and project readiness

- **Substrates**
  - » Evaluate ultra-low OH material for homogeneity (Sept 07)
- **Polishing**
  - » Evaluate results of pathfinder polishing (August 07)
  - » Use to establish final polishing specification (Nov 07)
- **Coatings**
  - » Characterize the LASTI test mass just coated
  - » Continue investigation of scatter in initial LIGO; work with vendors to ensure low scatter coatings
  - » Quantify coating stress effects on beam splitter: compensating for coating deformation
  - » Continue R&D for low mechanical loss and absorption: will coat Test Masses with best possible coating in September 2009
- **Project readiness**
  - » Ready now to: order glass; polish & coat recycling cavity optics; measure scatter on large optics; clean and handle optics
  - » Will be ready in time to: polish & coat arm cavity optics; store large optics; perform surface metrology of large optics

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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

AOS:
development status, progress & changes since 2006

- **Thermal Compensation System**
  - » Requirements & Conceptual Design completed (Aug 06)
  - » Ring heaters removed from the compensation plates
    - – all test masses have ring heaters, CPs only CO2 beams
  - » Hartmann sensors selected for wavefront measurement
  - » Compensation plate dimensions finalized
  - » New plan for testing thermal compensation in LASTI was developed
  - » Ring heater prototype being built
  - » New post-doc (summer ’07), brings expertise with Hartmann sensors
- **Scattered light control**
  - » Requirements & Conceptual Design review in progress
  - » Determined that most components need modest vibration isolation (ie, suspension)
    - – Output Faraday Isolator
    - – Cryopump baffle
    - – Arm cavity baffles, cavity beam dumps & ITM elliptical baffles (suspend from BSC SEI platform)
  - » Stray light control in IO chambers assigned to IO

AOS:
development status, progress & changes since 2006

- **AOS responsible for cameras (scope transferred from ISC)**
- **Other components are also in the requirements/conceptual design review phase:**
  - » Photon calibrator
  - » Optical levers
  - » Beam reducing telescopes
  - » Viewports

AOS: recommendations from 2006

- *The Panel encourages continuing the effort to improve TCS including a sensing method since it seems to be an effective way to control overall mode quality in the system. It provides a way to mitigate the parametric instability, the impact of which on the overall system is still not known.*
  - » Hartmann sensor (developed at Adelaide) has been selected. Thermal control of parametric instability is under theoretical investigation, and experimental investigation at Gingin.
- *The Panel encourages the design of the compensation plates.*
  - » A design has been established, and a prototype for LASTI testing is being produced.
- *The Panel encourages continuing the effort to qualify a second vendor for the parabolic mirrors.*
  - » We have qualified a second vendor, Tydex, J.S. Co. of Saint Petersburg, Russia. Given their high quality and low price they are now our primary vendor.

AOS: near term plans and project readiness

- **Initial Alignment System**
  - » Similar to initial LIGO, no additional testing needed
- **Thermal Compensation System**
  - » Continued optical modeling of thermal distortions (FFT simulation)
  - » Evaluate benefits of high-emissivity coatings for the barrels of the CPs and ITMs
  - » Ring heater fit check and thermal load test on LASTI quad noise prototype, starting 2007
  - » Full sensor-compensator test planned for LASTI in 2008-9
- **Stray light control**
  - » Setting up a scattering testbed to characterize materials
  - » Prototypes planned for suspended components (Faraday, arm cavity baffle, etc.)

Interferometer Sensing & Control (ISC)

- **Design of the 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**
- **Seismic platform interferometer, if implemented**
  - System to stabilize low-frequency fluctuations of the long arms by 1-2 orders of magnitude: aid to lock acquisition

ISC: development status, progress & changes since 2006

- **Requirements & conceptual design review to occur this summer**
- **DC readout design is well-advanced: major component of Enhanced LIGO**
  - » Output mode cleaner & photodetector being prototyped at Caltech (all components on order): the major ISC activity over the past year
  - » OMC suspension prototype built, being tested at Caltech
  - » Tip-tilt mirror development for OMC alignment: prototype built at Australia National University
- **Length sensing and control**
  - » New modulation scheme adopted: lower modulation frequency & more flexible interferometer tuning
  - » Noise modeling of global control in progress
  - » New frequency domain tool adopted for length sensing & control modeling: incorporates radiation pressure effects
- **Alignment sensing and control**
  - » Wavefront-sensor alignment signal calculations have been performed
  - » New InGaAs quadrant photodiodes identified and tested

ISC:
development status, progress & changes since 2006

- **Digital controls**
  - Custom converters have been prototyped at LHO
    - ADCs are 30-100x quieter than initial LIGO
    - DACs are 2-3x quieter than initial LIGO
  - Commercial solutions are being tested in R&D for suspensions, seismic isolation, …
- **Lock acquisition**
  - Simulations of a single arm cavity acquisition have been made
  - Locking test of a quad+triple suspension cavity in progress at LASTI
- **Seismic platform interferometer**
  - Australia National University (ANU) has taken on responsibility for this, starting with a feasibility study, to be reviewed in fall 2007
- **More people involved within the last year**
  - ANU group (Slagmolen, McClelland): responsibility for tip-tilt stages and SPI study
  - Frolov at LLO: alignment calculations
  - Waldman, Ballmer, Adhikari, Mandic at Caltech: output mode cleaner, global controls modeling, modulation scheme design, OMC suspension
  - New hires at MIT, Evans, Barsotti: lock acquisition (LIGO & Virgo experience), modeling tool development

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ISC: recommendations from 2006

- *The Panel recommends that the project investigate the possibility of exercising ISC hardware with simulations of the relevant actuator transfer functions (and also the converse to exercise the actuator hardware with simulation of ISC hardware).*
  - » This may be worthwhile later as the design progresses.
- *The testing plan for ISC hardware components and subsystems needs clarification. The Panel applauds the team's idea of outsourcing tests of components and subsystems to LSC members, to allow other institutions ownership in more of the LIGO hardware.*
  - » We are also working with commercial testing outfits, with mixed success. We'll continue to look for testing by LSC member institutions & Lab grad students.

ISC: recommendations from 2006

- *The cost basis for software requirements could be improved. Staffing and thus costing estimates for computing needs are immature. For example, the control and supervisory software is unlikely to need simulation. The separation of programming activities into three parts, one for each interferometer, appears artificial.*
  - » The software cost estimates were based on initial LIGO experience. A review of the SW costs did not lead to any changes. The separation by interferometer was indeed artificial.
- *The panel recommends an execution plan for the seismic platform interferometer (SPI), including scheduling of a CDR. The benefits from an SPI, and thus the requirements on it, need a firm basis from simulations of the system and/or from prototyping.*
  - » ANU has taken on responsibility to do a feasibility study, which will be reviewed in fall 2007. At that time we will decide if there is a design worth pursuing.

ISC: near term plans and project readiness

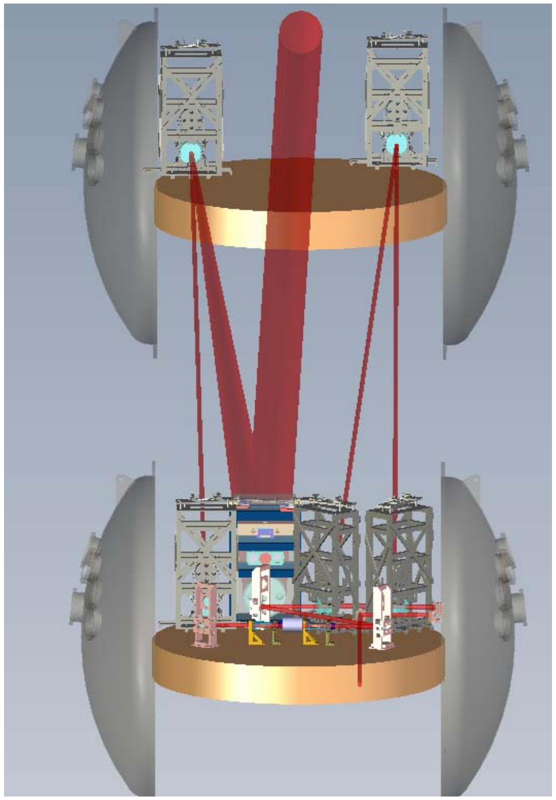
- **Complete requirements & conceptual design review, summer 2007**
  - » Preliminary design: Mar 2008
  - » Final design: Mar 2009
- **Complete output mode cleaner & DC readout**
  - » Install in Enhanced LIGO in Dec 2007
  - » EnLIGO commissioning will inform any design changes for the Adv LIGO units
- **Review custom converter development in summer 2007**
- **Prototype RF detector design (Caltech)**
  - » A new preamp circuit topology has been chosen, better for readout of multiple frequencies
- **Begin RF demodulator design & prototyping (LHO)**
- **Project fabrication schedule to start relatively late**
  - » Mar 2009, lasting until June 2011

Systems Engineering (SYS)

- **Systems Engineering is Level-Of-Effort in the Construction Phase**
- **Maintain Interface Control Documentation (ICD)**
- **Modeling/Simulation**
  - » Perform System & Performance Trade Studies if/as issues arise
  - » End-to-End Simulation
- **Maintain technical configuration management**
  - » optical layout
  - » physical integrated layout drawings
  - » optical table mass budgets
- **Define integrated test plans & procedures**
- **Review/approve**
  - » Significant Technical Revisions (through the TRB)
  - » Subsystem acceptance test plans & test reports
  - » EMI/EMC & grounding implementation
  - » Vacuum Qualification of Materials
- **Systems Engineering does not include Fabrication, Installation or Integrated testing.**

SYS
development status, changes & progress since 2006

- **Currently in the Preliminary Design Phase**
- **Finalized Core Optic sizes**
- **Evaluated, and rejected, the SAS alternative to the baseline seismic isolation system**
- **Design studies in process:**
  - » Revision/refinement of the Optical Layout
    - – Trade between vertical and horizontal wedge angles
  - » Recycling cavity geometry: Stable vs Marginally Stable trade study
  - » Parametric instabilities
  - » Seismic Platform Interferometer inclusion
    - – Feasibility Study undertaken by ANU – review Sep 2007
  - » Update to Beam Tube Scattering Analysis
  - » Working on interface control definition
  - » Vacuum equipment layout design nearly complete
    - – Includes septum plate for isolation of HAM 6 chamber for Enhanced LIGO

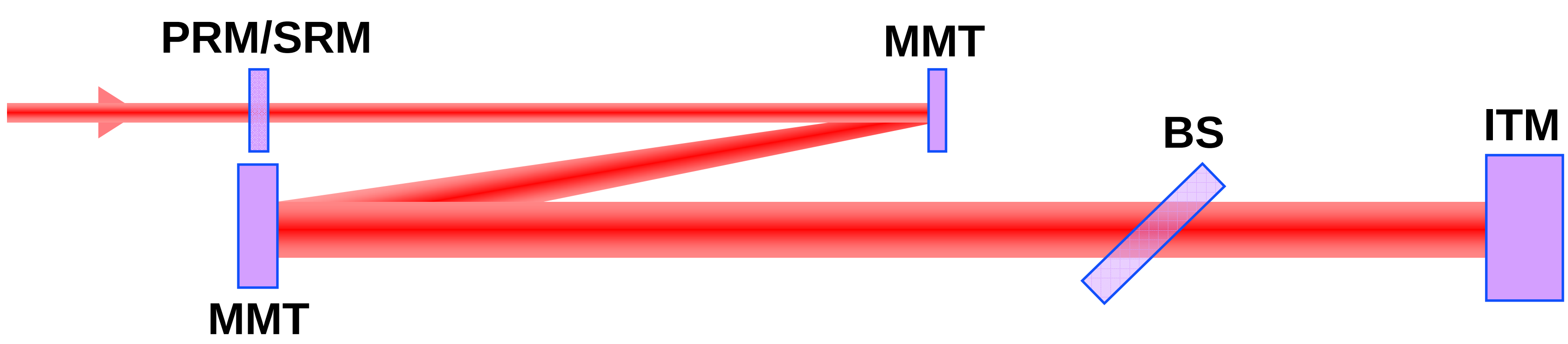


•3D, Integrated Opto-mechanical layout captured in SolidWorks CAD

•Optical layout defined with Zemax

Recycling cavity geometry

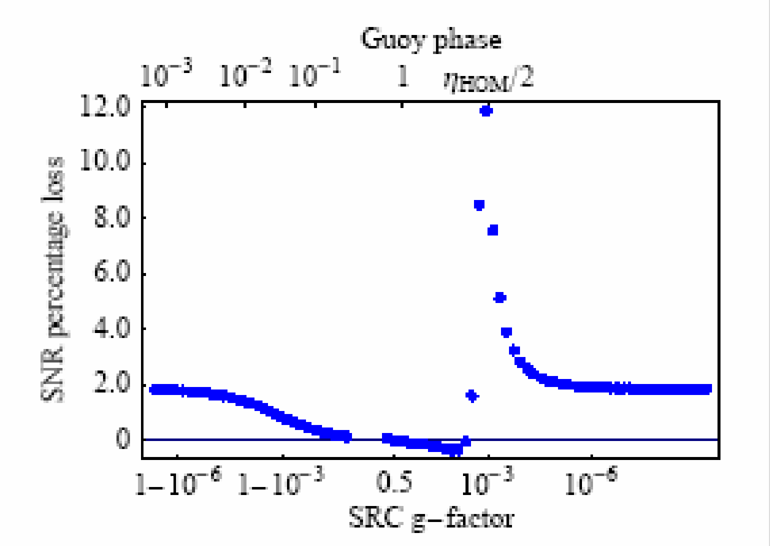
- **Current design:**
  - » Gouy phase shift in the recycling cavities (RC) is very small
  - » RCs are at the edge of stability, and thus rather degenerate (as in initial LIGO)
  - » Appears to require very tight tolerances on the radius-of-curvature matching of the ITMs and the recycling mirrors (power and signal)
- **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



Recycling cavity geometry: status & plans

- **Analytical tools developed to**
  - » Calculate telescope-mirror curvatures needed for specific Gouy phases
  - » Calculate wavefront-sensor alignment signals
- **Plans:**
  - » Investigate using FFT simulation
  - » Make detailed performance comparison
  - » Make a detailed cost comparison: rough estimate shows small cost impact with the stable geometry
    - – More triple-suspension optics, but offset by simpler optics for pick-off beams and the output beam
  - » Choose the geometry by the time of the SYS PDR

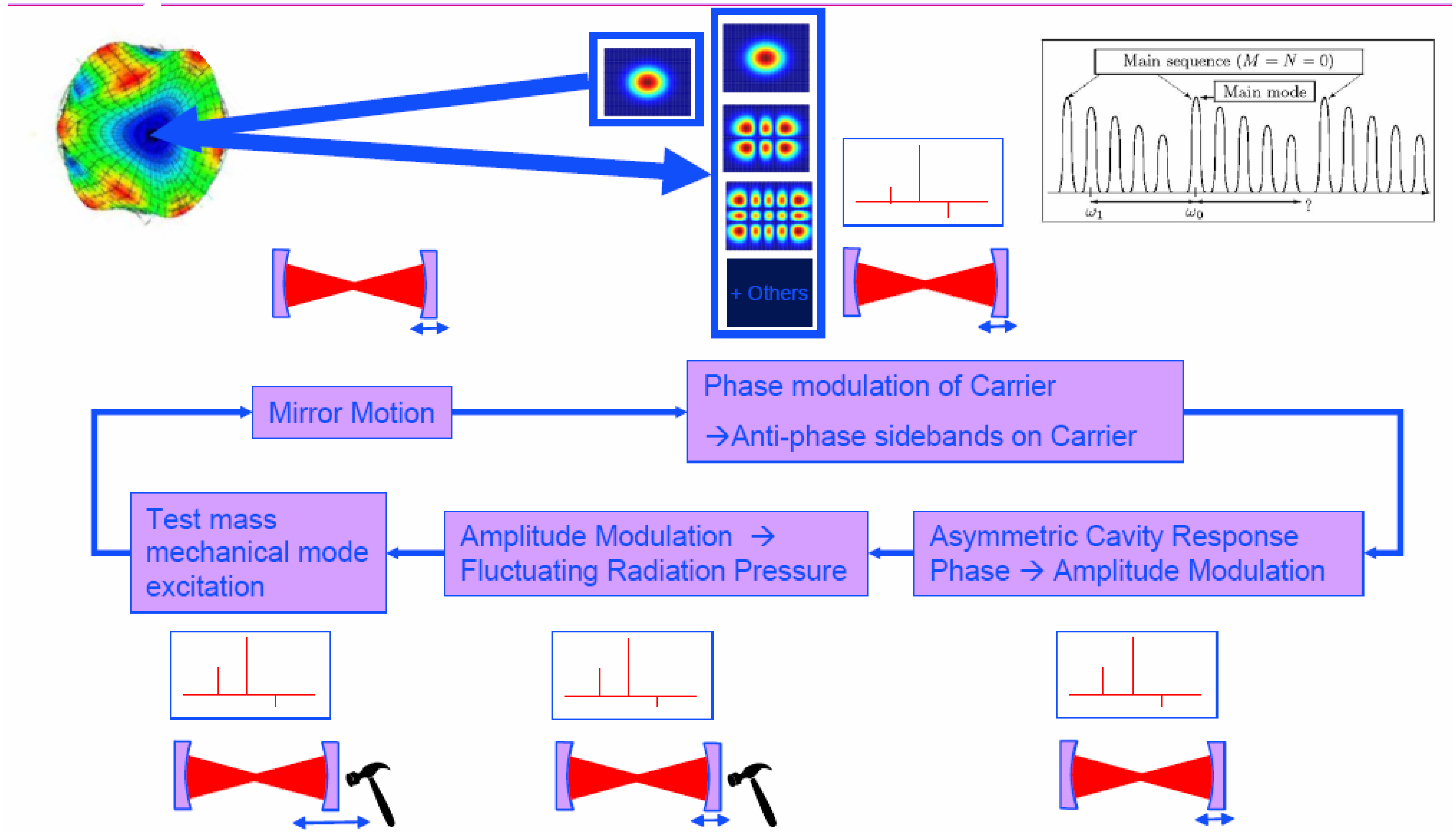
Modal model results indicate a Gouy phase choice of ~0.7 rad, to reduce sensitivity to ITM-SRM ROC mismatch:



These results will soon be checked & extended using the FFT simulation.

Parametric Instabilities

- **Combination of high stored optical power and low mechanical loss may cause an instability:**



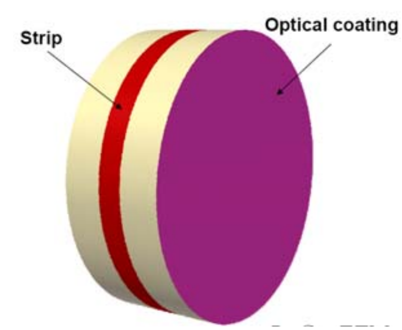
Parametric Instabilities: 2006 status

- **First recognized by Braginsky & group in 2001**
- **First detailed analysis for a Advanced LIGO arm cavity by Univ of Western Australia group (2004-2005)**
  - » Of order 10 modes calculated to have parametric gain > 1
  - » Power recycling included analytically, but assuming matched arms
    - – Enhancement of optical gain possible, ~10x
    - – But, not expected to exist for small differences between the arms
  - » Simplified optical model
- **Mitigation options identified**
  - » Mechanical Q reduction; thermal tuning of modes; active feedback suppression
- **2006: *The Panel recommends …***

that LIGO continue their pursuit of a better theoretical understanding and modeling of the various instabilities that will arise at the higher power operation of AL toward developing solutions that will mitigate or eliminate the instabilities. To the degree possible, the Panel recommends that laboratory tests be carried out which mimic the high power operation of AL, which will be immensely helpful in the real-world indentification, understanding and mitigation of any instabilities. Care must be taken to avoid degradation of the strain sensitivity by the application of the mitigation procedure.

Parametric instabilities: progress since 2006

- **Analytical investigations of effects of power and signal recycling (Kells, Vyatchanin, Ottaway)**
  - » Recycling can enhance the parametric gain (~10x), but this enhancement is over a ~10x narrower frequency range
  - » Enhancement only for low order optical modes (< 4^{th} order)
  - » May be an advantage if there are only a few modes to avoid
- **Detailed survey of an AdLIGO arm cavity with a realistic optical model (FFT simulation: Bantilan, Kells)**
  - » Parametric gain calculated for all acoustic modes up to 90 kHz (9000 modes): 6 modes with R>1
  - » All R>1 points caused by resonant behavior of a single higher-order mode
  - » Only optical modes or order 6 or smaller are significant
- **More calculations of Q-reduction via ring damper**
  - » Optimization of strip geometry: factor of ~20 average Q reduction, with a 2% increase in thermal noise
  - » Calculations for sapphire, to be redone for fused silica
  - » Gold coating being investigated as a damping material
- **Analysis of 'tranquilizer cavity' proposed by Braginsky (UWA)**
  - » Looks impractical for Advanced LIGO



Parametric instabilities: plans

- **Mechanical quality factor tests of a gold coated sample**
- **Active damping feasibility**
  - » Plan to make a test at LASTI, using test mass electro-static drive to damp higher order acoustic modes
- **Experimental plans at the Australian Gingin facility**
  - » 80m long cavity, high power
  - » Look for 3-mode interactions: excite acoustic modes; look for higher order optical mode excitations & effect on acoustic mode Q

Post Amaldi 7 conference workshop on

Stabilisation of Parametric Instabilities in Advanced Gravitational Wave Detectors

Perth, 16-18, July 2007

The ACIGA UWA group proposes to hold an Amaldi conference satellite workshop in the week after the Amaldi conference at the site of ACIGA's Gingin High Optical Power Facility, from 16 to 18 July 2007 on the above topic. The goal of the workshop is

a) to reach a consensus on the magnitude of the PI problem
b) to determine the level of risk PI poses to advanced detectors
c) to understand limitations in the theory and modelling of PI,
d) to assess methods for controlling PI and
e) to identify priorities for the next phase of research and
f) propose possible implementation strategies.

SYS: recommendations from NSF 2006 Review

- *Develop specifics for strengthening quality assurance activities within the next 12 months and before construction start. This may involve adding skilled staff.*
  - » Have appointed Vern Sandberg as the Manager for Planning & Overseeing QA by Test
  - » Have begun process to advertise for QA hire

SYS: near term plans and project readiness

- **Complete the Preliminary Design, Oct 2007**
  - Milestone for SYS Readiness for the Advanced LIGO project
- **Final Design Review, Nov 2008**
  - Update overall system description and arbitrate interfaces as the subsystems complete their designs
  - Decision on CDS Infrastructure/Networking/Topology
  - Decision on CDS cooling
  - Revise/update Interface Control Documents
  - Incremental updates to the final design as subsystems complete development

Data Acquisition, Diagnostics, Networking & Supervisory Control (DAQ) Subsystem

- **Data Acquisition System Infrastructure**
  - » receive, digitize, format, broadcast, store and serve on-site near-term data
  - » "FrameBuilder"
- **Networking infrastructure**
  - » Real time system networking and control room (supervisory) networking
- **Interferometer Supervisory Controls**
  - » EPICS-based control of top-level functions (alarms, watchdogs, system health & status, etc.)
  - » Control Room Equipment
- **Physics and Environment Monitoring**
  - » Just field cabling, no new instrumentation
- **Timing System**
  - » GPS derived timing system for synchronizing all real-time systems and data acquisition
  - » Atomic clock system for independent timing system diagnostics
- **Mass Storage Systems**
  - » Provide quick look-back data for commissioning & control room diagnostic functions
- **Diagnostics Monitoring and Test Tools**
  - » Computers & software to perform real time and look-back diagnostics
- **Control & Data System Test Stand for each Observatory**
  - » Enables offline component and software testing

DAQ
development status, changes & progress since 2006

- **Requirements and Conceptual Design review completed**
  - Support for prototypes, test stands and Enhanced LIGO requires design and implementation to proceed in parallel
  - Conceptual design based on present technology, which will evolve prior to first Adv. LIGO install
- **Prototype systems installed & operational**
  - At the LIGO Advanced Systems Test Interferometer (LASTI) at MIT
    - FrameBuilder
    - Real Time Network and Switching
    - Quadruple and Triple Controls Prototype Suspension systems
    - Hydraulic External Pre-Isolator (HEPI) Controls (3 chambers)
    - Seismic Attenuation System (SAS)
    - Squeezing Experiment
  - At the Interferometer Sensing & Controls Testbed (40m lab) at Caltech
    - Output Mode Cleaner (OMC) prototype
    - Alignment Sensing System
    - Enhanced LIGO configuration FrameBuilder
    - Advanced modulation scheme test system
  - Others:
    - Pre-Stabilized Laser (PSL) Diagnostic Bread Board (DBB) at Hannover, Germany
    - OMC Tip/Tilt Mirror Suspension Test System at the Australian National University
    - Internal Seismic Isolation (ISI) Control System at Stanford (in progress)
- **Automatic real time code generation from Matlab files is operational**
- **Ported Control and Data System tools to Linux**

DAQ
development status, changes & progress since 2006

- **No scope or significant technical changes since the NSF May 2006 review**
- **Standardized electronics enclosures**
  - » in house design, commercially manufactured, can be EMI tight
  - » Standardized DC power connections & DC power conditioning
- **DC Power Distribution design underway**
  - » Remote bulk power supplies
  - » 48VDC power distribution
  - » At rack power regulation and conditioning to desired voltages

DAQ: recommendations from 2006 review

- *Test Infiniband for use as real time network.*
  - » Plan to test infiniband in Sep-Dec 2007 on a Caltech test stand first and then at the LASTI facility
- *Refine data storage requirements and use Moore's law in cost estimate.*
  - » Requirements are currently being reviewed (Requirements & Conceptual Design Review) – have increased full data storage for rapid look-back from 4 days to 2 weeks
  - » Applied Moore's law in the cost estimate for data storage
- *Apply Moore's law to computer cost estimates.*
  - » Applied Moore's law in the cost estimate for DAQ system computers
  - » Compute requirements have increased by a factor of ~4.5
    - – Need to improve performance of present DMT code
    - – Desire to run additional analysis code for commissioning support
    - – As a consequence of the larger data rate for Adv. LIGO

DAQ: near-term plans and project readiness

- **Development Plans**
  - Complete Conceptual Design Review (May 2007)
  - Resolving data acquisition system & network stability issues at LASTI (corresponding to high demand from multiple projects)
  - Diagnostics Test Tool (DTT) augmentation and Matlab link
  - New timing system is installed in LASTI & 40m Lab
    - Final revision in progress – final review at end of 2007
  - DAQ Preliminary Design Review, Dec 2007
    - Choose distributed or centralized data acquisition
  - DAQ Final Design Review, Dec 2008
- **Fabrication**
  - DAQ is not schedule critical
  - Most hardware elements are commercial, short lead items
  - Fabrication not planned to start until 2009
  - Test stands built early to support acceptance testing of subsystem components
  - Mass storage and computer systems purchased as late as possible to avoid early obsolescence
  - Recent hiring (for pan-subsystem electronics & software, not just DAQ):
    - Hired 3 electronics technicians
    - Searching for 2 electronics engineers and a real time programmer

Data Computing System (DCS)

- **Provide LIGO Laboratory Tier 0, 1, 2 components & capacities as part of the LIGO Data Grid distributed computing facility**
- **Provide the computing capabilities & capacities required for production analysis of LIGO data**
  - Direct access to LIGO data sets by collaboration
  - Data distribution to rest of the data grid
  - Data analysis
    - Pipeline production
    - Algorithm development/testing/validation
    - Monte Carlo simulations
    - Reorganization of data as required to support analysis
    - Provide the computing capabilities & capacities required for production analysis of LIGO data
- **Laboratory to provide 50% of capacity**
  - Present situation adopted as model for the future
  - Remainder of compute need from GEO/Tier-2 outside the LIGO Lab

DCS
program status, changes and progress since 2006

- **Performed new bottom up estimate of DCS computational requirements scaled from actual S5 analysis and Moore's Law**
- **Adopted computing scope to support one-half of total community need**
- **Cost estimate reviewed & revised (per NSF May 2006 review recommendations & re-assessment of requirements)**
- **Reduced DCS total cost including contingency by $2.76M based on recommendations from the review panel & a new cost estimate:**
  - Reduced number of cluster nodes (from 1456 to 1188)
  - Fixed basis of estimate mistake and reduced size of networking equipment
  - Reduced the size of Workgroup servers for Data Management, Database, Post-processing
  - Added Archive disk backup system for 3yr
- **Data archival system now provides multiple, geographically separated copies of primary and secondary data sets**

DCS: recommendations from 2006 review

- *Complete the computing plan document, taking into account all current data on computing requirements, and maintain the document to track the evolution of algorithm performance and computing needs.*
  - » Agreed. The existing Computing Plan will be updated. A survey has been performed and used to help re-scope and re-cost the DCS subsystem.
- *Fix a firm upper limit on the uncharacterized computing requirements for the project. Significant future changes in computing requirements should trigger a change control mechanism. Hiding contingency within the computing budget should be avoided.*
  - » We have re-evaluated the project requirements and removed any hidden contingency.
  - » A new bottom up analysis of computational needs based on S5 experience has been completed.
  - » Significant changes from this baseline will trigger a Change Control Board (CCB) action.

DCS: recommendations from 2006 review

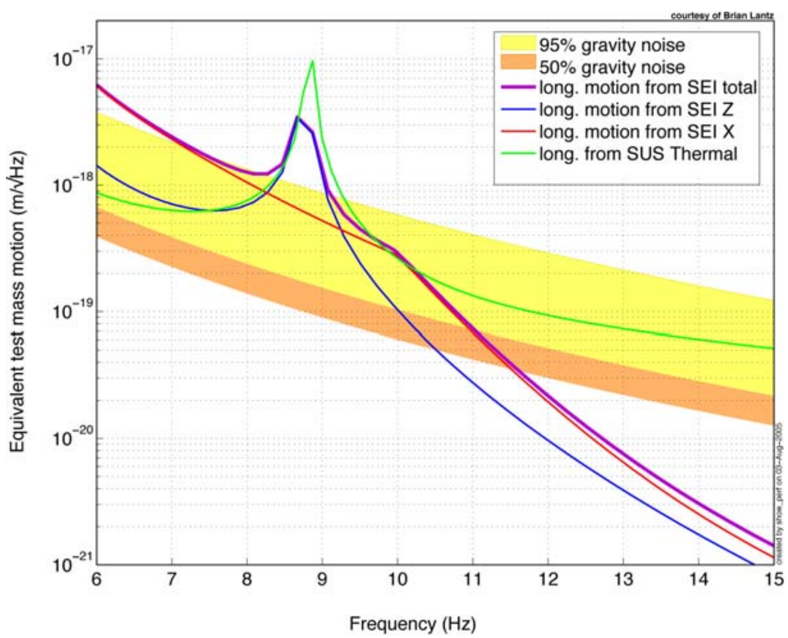
- *Generate a new cost estimate based upon the new computing requirements, and Moore's law. Management should track that the cost of this system will change significantly with the purchase date.*
- *Cost estimates for networking should be reduced under the assumption that 10G ethernet will cost then what 1G ethernet costs today.*
- *Cost estimates and capacity requirements for the Gateway Servers and Dataservers should be motivated by specific performance data.*
  - Cost estimates have been revised in accordance with the new computing requirements.
  - Timing of the acquisitions was re-evaluated.
  - Moore's law was applied in the cost estimate.
  - A decision was made to supply 50% of the estimated computing power with an understanding that the community will supply the remainder ; This is roughly consistent with the situation today
  - Networking needs were evaluated and re-costed
  - The reduction in the bottom line cost estimate is comparable to the committee's estimate

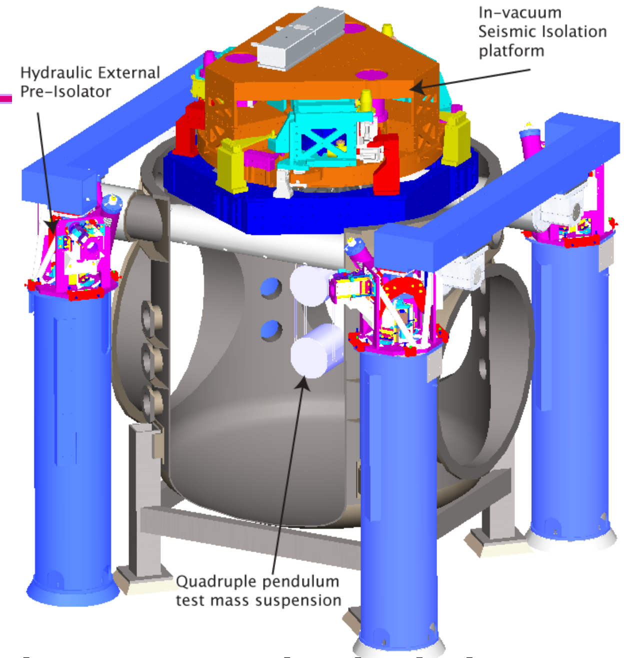
DCS: near term plans and project readiness

- Working on the Computing Plan
- The DCS implementation for Advanced LIGO is expected to be straightforward
- Increase in data rates, capacity over existing infrastructure seems well within projected technology evolution
- Will employ a just-in-time approach, deferring major procurements until Advanced LIGO science operations are "within sight"
- Build-to-cost reduces risks
- Will track the potential need for facilities upgrades as Advanced LIGO construction proceeds

Seismic Isolation Subsystem (SEI)

- **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**



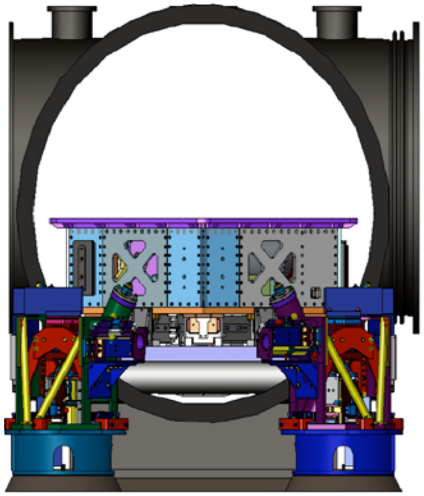


- **Choose an active isolation approach:**
  - » 3 stages of 6 degree-of-freedom each
  - » Hydraulic External Pre-Isolation (HEPI)
  - » Two Active Stages of Internal Seismic Isolation
- **Increase number of passive isolation stages in suspensions**
  - » From single suspensions in initial LIGO to quadruple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

SEI
development status, changes and progress since 2006

- **Hydraulic External Pre-Isolator (HEPI):**
  - » Deployed successfully at LLO, costs & performance understood
  - » Study underway to determine ideal configuration for LHO
- **Internal Seismic Isolation (ISI):**
  - » Results from Technology Demonstrator at ETF/Stanford:
    - 12-DOF controllers
    - Measured instrument noise floors at required level
    - Active isolation factor at required level
    - Accommodation of reactive load (prototype SUS cage)
  - » Understand costs and performance reasonably well
- **ISI for the BSC chamber:**
  - » Completed in-air testing and is proceeding to Ultra-High Vacuum clean assembly
- **ISI for the HAM chamber:**
  - » Completed design & detailed
  - » Started fabrication of 2 units for Enhanced LIGO
  - » Designed, built, tested, evaluated, reviewed and rejected a prototype HAM Seismic Attenuation System (SAS) as a possible alternative to ISI

BSC-ISI Assembly at LASTI



HAM-ISI CAD Model

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SEI: recommendations from 2006

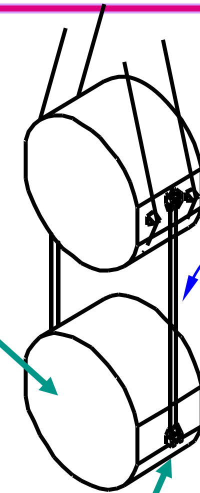
- *A cost saving analysis of the upfront effort vs. possible down time should be performed for the unit components that can be qualified before assembly.*
  - » We have designed and built two hardware emulation units for qualification testing of active SEI components.
    - – We can run pre-installation tests on sensors (L4C, GS-13 and STS-2) with the pod controller.
    - – Likewise the computer-ADC-analog filter-cable set can be tested with the pod emulator before installation.
  - » Similar testing will be performed on the electromagnetic actuators before assembly.
  - » These testing units, and procedures for their use, will be used on the SEI prototypes.
  - » We view these measures as risk reduction and are not counting on a cost savings resulting from decreased down time during subsystem and integrated system-level testing.

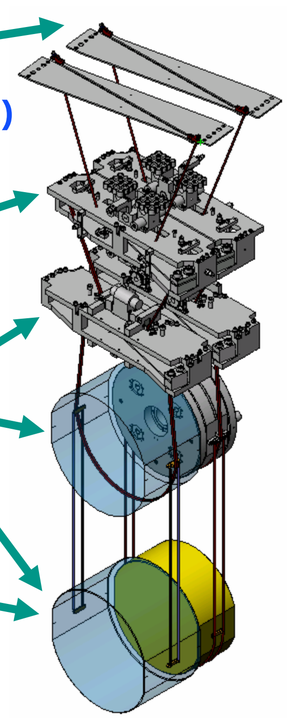
SEI: near term plans and project readiness

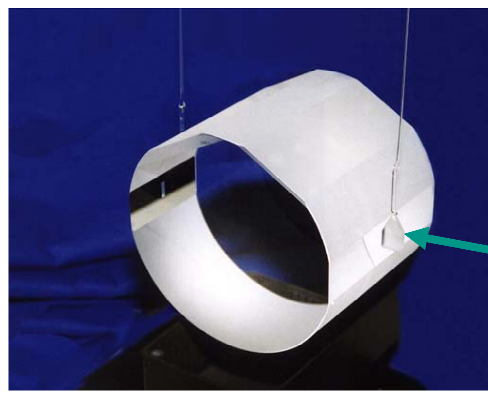
- **ISI for the BSC Chamber**
  - Clean re-assembly & installation into the BSC Chamber at LASTI in July 2007
  - Stand-alone controls testing and then integrated with the quadruple pendulum suspension system Fall 2007
- **ISI for the HAM Chamber**
  - Fabricate 2 units for Enhanced LIGO
  - Install one at each Observatory in Dec 2007
- **Preliminary Design Review**
  - BSC-SEI, Dec 2007
  - HAM-SEI, Feb 2008
- **Final Design Review**
  - BSC-SEI, Oct 2008
  - HAM-SEI, Apr 2009
- **Lessons learned from the prototypes will be incorporated into small or modest final design changes**
- **Development schedule completion is consistent with the Advanced LIGO Project schedule**

Suspension Subsystem (SUS)

- **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



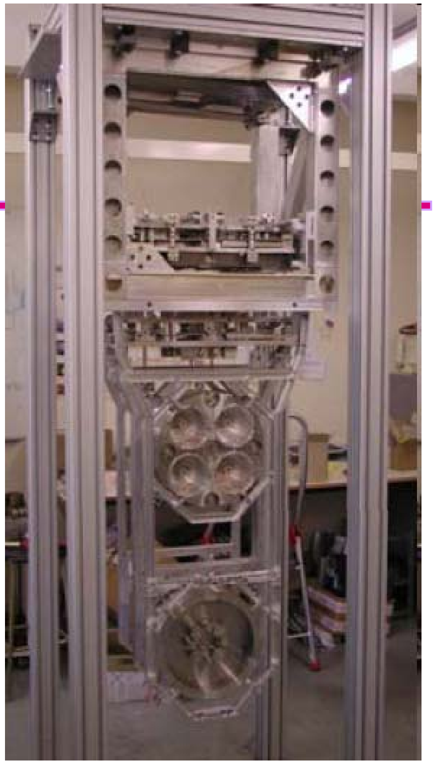




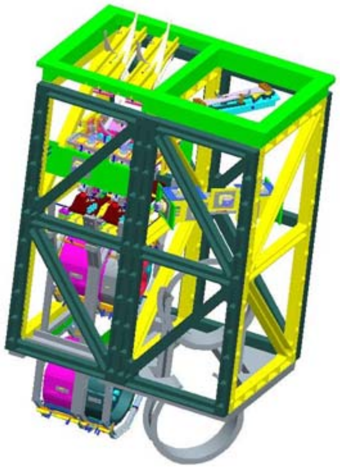
- **Choose quadruple pendulum suspensions for the main optics and triple pendulum suspensions for less critical cavity optics**
- **Create quasi-monolithic pendulums using fused silica ribbons to suspend 40 kg test mass**

SUS development status

- **BSC Chamber Suspensions (UK Scope)**
  - » End Test Mass (ETM)/Input Test Mass (ITM) quadruple pendulum:
    - – Prototype reviews
      - Electronics (July 2005)
      - Ribbons, Fibres, Bonding (October 2005)
      - Quadruple pendulum system (July 2006)
      - all significant design risks retired, based on controls prototype installed & tested at LASTI
      - approval for fabrication of the "noise" prototype
    - – Preliminary Design Review, Oct 2007
      - After LASTI "noise" prototype assembly & installation
    - – Final Design Review, Mar 2008
      - Follows full testing of ETM/ITM noise prototype at LASTI
        - » Integrates fused silica fibres & R&D for bonding & welding process
        - » Includes coupled dynamics investigations with stiffer structural fram
  - » Folding Mirror (FM) and Beamsplitter (BS) triple pendulua:
    - – Working on preliminary design
    - – Final Design Review, Dec 2007



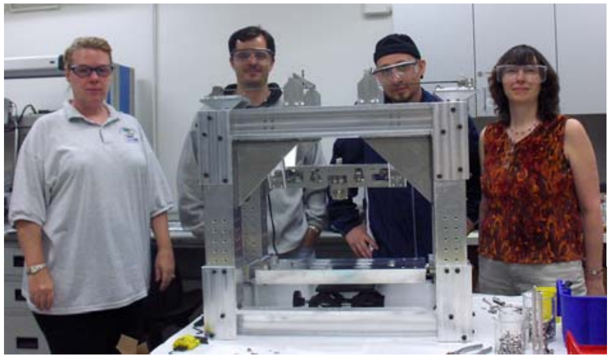
ETM/ITM Quadruple Pendulum Noise Prototype Assembly at RAL



FM/ITM Quadruple/Triple Pendulum Assembly

SUS development status

- **Input Mode Cleaner (IMC) triple pendulum**
  - » Prototype review, June 2006
  - » Preliminary Design Review, June 2007
  - » Final Design Review, Oct 2008
    - – After LASTI testing of final prototype
- **Output mode cleaner (OMC) double pendulum**
  - » Requirements and Conceptual Design Review, Dec 2006
  - » Preliminary Design Review, June 2007
    - – Informed by bench testing on Enhanced LIGO unit (prototype)
  - » Final Design Review, Dec 2008
    - – To be Informed by Enhanced LIGO commissioning
- **Recycling Mirror (RM) triple pendulum suspension**
  - » Basic design completed, detailing for prototype now
  - » Preliminary Design Review, April 2008
    - – To be informed by LASTI prototype testing
  - » Final Design Review, Jan 2009
- **Auxiliary Suspensions (single pendulum)**
  - » Preliminary Design Review, Oct 2008
  - » Final Design Review, Jan 2009



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SUS: changes and progress since 2006

- **Possible change from silica ribbon to wire suspension for the beamsplitter**
  - Simplifies design and production
  - Possible if the beamsplitter wedge is horizontal rather than vertical (Systems decision in June 2007)
- **Acceleration of OMC design and production to support Enhanced LIGO**
  - Bench testing prototype now
- **LASTI program replan**
  - Prototyping of recycling mirror triple (large mass compared to IMC) now included
  - Violin mode damping tests added
- **Thermal compensation changes to baseline**
  - Has affected detailed design of support structure
- **Electrostatic drive on compensator plate**

SUS: recommendations from 2006

- *Violin mode damping*
  - Active damping of the violin-modes is required
  - Sensors to detect ribbon motion (by stress-induced birefringence) are under development with UK funding
    - Proof of concept under test now
    - UHV compatible prototype Sep 2007
    - Set of 4 sensors installed on LASTI quadruple pendulum Spring 2008
- *Charging –see comments under COC*
- *Manpower issues*
  - Norna Robertson has joined LIGO as suspensions lead (from U of Glasgow & Stanford)
  - Plan to train observatory personnel at LASTI on noise prototype
  - Estimates of assembly time of quads and triples carried out based on experience with prototypes – good agreement with estimates used in budget
  - Mechanical engineers – plan to hire 3 MEs at LLO. In interim we have hired 2 contract MEs at Caltech to support design and prototyping
  - Funding for two site assembly leads added to project
- *Test plans in prototyping phase*
  - Revised LASTI test plan put together and reviewed
  - Quad noise prototype near term test plan under development, draft already done
  - Test plans for other suspension prototypes: IMC and OMC plans complete (IMC tested already, OMC underway)

SUS: near term plans and project readiness

- **BSC Suspensions (UK scope)**
  - Test the ETM/ITM quadruple suspension at LASTI/MIT
  - Train staff on quad assembly including ribbon fabrication and welding
  - Complete the Final Design Review, based on LASTI test results
  - Review production readiness and start production
- **HAM Suspensions (US scope)**
  - Finalize earthquake stop design (informed by UK and Enhanced LIGO designs)
  - OMC
    - Install OMC suspensions in Enhanced LIGO
    - Complete design updates (final design) based on Enhanced LIGO commissioning
  - RM
    - Build the RM suspension prototype and test at LASTI
  - Complete designs for IMC (final design update) and Auxiliary suspensions

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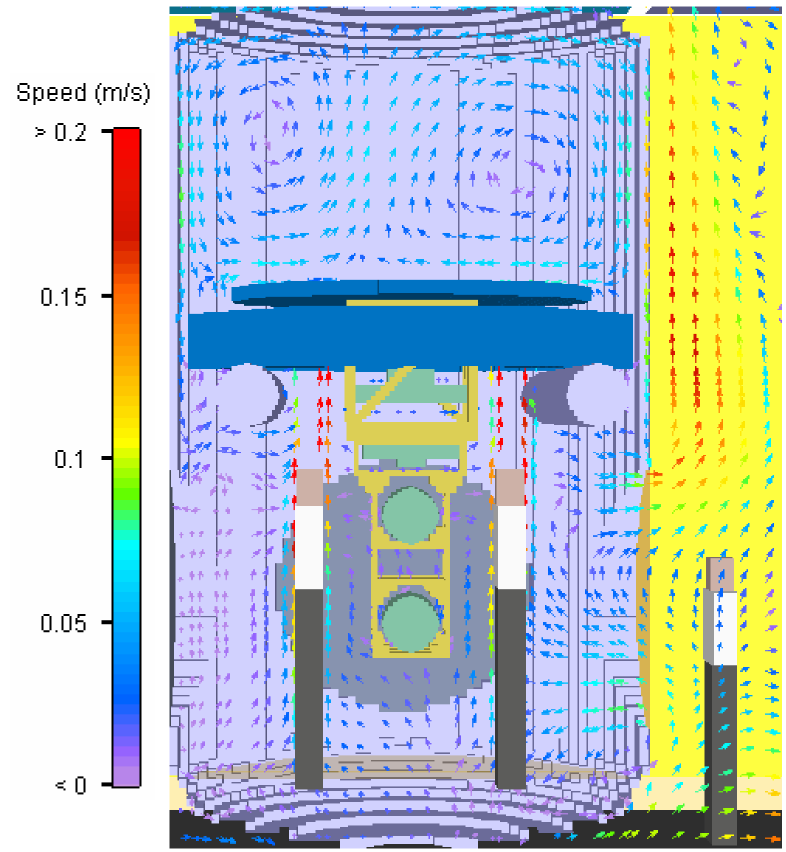
Facility Modifications & Preparation (FMP)

- **Design & Build Vacuum System Modifications**
  - » Convert 2 km at Hanford Observatory to 4 km
  - » Move HAM Chambers for Input Optics (IO) and Interferometer Sensing & Control (ISC) use
  - » Does not include installation (INS WBS scope)
- **Prepare the facilities (buildings, laboratories):**
  - » Clean/modify spaces for use as clean assembly areas
  - » Refurbish large, portable, soft-walled, clean rooms
  - » Procure additional large, portable, soft-walled, clean rooms
  - » Procure additional vacuum bake ovens
  - » Prepare clean & conditioned spaces for storage
  - » Does not include assembly (subsystem WBS scope)
  - » Prepare an inventory control system and include staff to maintain inventory
- **Prepare for assembly and installation tasks:**
  - » Purchase additional material handling equipment, installation fixtures, optics lab supplies, clean room supplies, etc.
  - » Purchase supplies for wrapping, palletizing, storing assembled components
  - » Stage completed assemblies
  - » Plan the installation task (INS WBS only executes plan)
  - » Does not include installation (INS WBS scope) or system/subsystem test/acceptance (PM/systems WBS scope)
  - » Need to identify Government Equipment to be Scraped or ‘Surplused’ for approval

Ultra-High Vacuum (UHV) Preparation & Cleanliness

- **Particulate Cleanliness Requirements are more stringent than for initial LIGO**
  - » Particulate cleaning: Ionized, particulate free airflow over benches are planned
  - » Basic Paradigm: The optical surfaces are only exposed when absolutely necessary
  - » Performing R&D on a protective film product (First Contact™)
  - » LIGO Lab spaces plus Class 100, soft-walled clean rooms erected within are adequate
  - » Plan to add laminar air shower into the Test Mass (BSC) Chambers

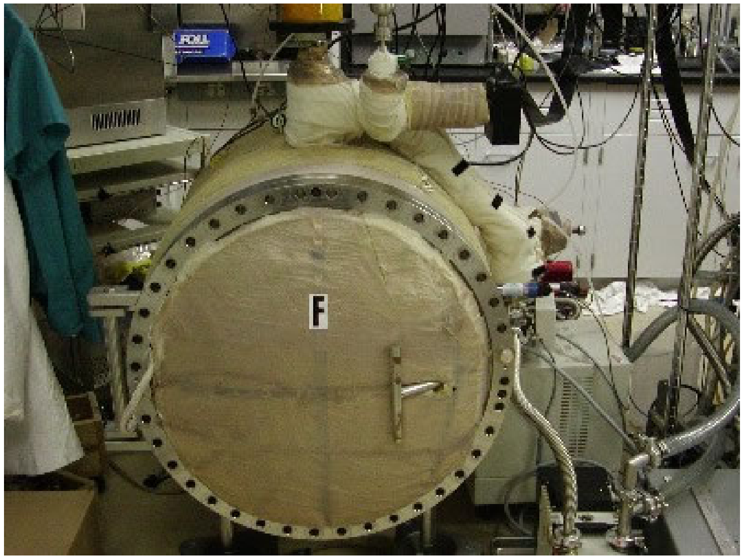


Computational Fluid Dynamics Simulation: Natural convection caused by the workers dominates the airflow patterns without an in-chamber laminar air shower

Ultra-High Vacuum (UHV) Preparation & Cleanliness

- **Low-Volatile Residue (out-gassing) Cleanliness Requirements are the same as for initial LIGO**
  - » Same clean and bake (air or vacuum) procedures/protocols as used for Initial LIGO
  - » Added Vacuum Bake Oven Capacity needed to support assembly schedule

Large Air Bake Oven developed for Seismic Isolation Part Cleaning



Vacuum Bake Oven at Caltech

FMP development status, changes and progress since 2006

- **Subsystem assembly space & facility requirements**
  - » Initial estimates received
  - » need to definitize & update as prototypes are built – leads to written Assembly Plan with coordination of common space use
- **Vacuum Modifications**
  - » Review & refine conceptual design once optical layout has passed Preliminary Design Review (ADL Systems)
- **Cleanliness Requirements**
  - » Particulate cleanliness requirements need to be firmed up, especially with regard to in-situ environment
  - » Driven by low optic scattering requirements – on-going studies by COC subsystem
  - » Concept for improved air flow/cleanliness in the chambers in development
- **Early start on staging building modifications**
  - » drawings and cost estimate for HEPA filtered air etc.. $50,000 (within budget)
- **Lab areas being cleaned up now**
  - » new ceiling tiles
  - » repair of HVAC system underway
- **Hired consultant to look at improving clean room usage in LVEA**
  - » Additional clean room estimates good
  - » Possible need to replace LVEA HEPA filters (within contingency)

FMP: recommendations from 2006

- *Ensure field management staff at both sites is in place and up to speed prior to project start in FY08.*
  - The FMP leader, John Worden (at LHO), is working with his counterpart at LLO, Allen Sibley, to plan the FMP effort.
  - Full scale mechanical testing of Adv. LIGO prototypes at LASTI makes use of Observatory staff members
  - Enhanced LIGO is an excellent in situ training opportunity for Observatory staff.
- *Implement an inventory management system.*
  - Concept and cost estimate for inventory control system $35K plus tech hours at two sites $474K
- *The estimate for the stainless steel vacuum tubes needed is much less than current market prices. It was derived by escalating old numbers with a nominal escalation rate which is much lower than the specific market experience for these commodities.*
  - Incorporated 2006 budgetary estimate from PSI for Vacuum Equipment; added $2,356K
  - Updated Stainless Steel pricing for 2007 and for a design change in the End station spool; added $260,000 (within contingency).

FMP: near term plans and project readiness

- **Will install large air bake oven (used for HAM-SAS) at LLO for use with the HAM-ISI units for Enhanced LIGO**
- **Will develop & document a plan for vacuum preparation & baking, assembly and storage usage to help with installation planning**

Installation (INS) WBS Functions

INS is the project phase between subsystem assembly & project completion

Includes:

- **Removal**
  - » Removal of existing detector equipment
  - » Disposition or storage of equipment
  - » Particulate clean up of vacuum chambers
- **Installation**
  - » Installation of Vacuum Equipment
  - » Installation of all Detector Equipment
    - – External to vacuum system
    - – Internal to vacuum system
- **Testing**
  - » In-situ Unit/subsystem Testing
  - » Integrated System-Level Testing

Does not include:

- **Installation Planning (FMP scope)**
- **Installation Staging (FMP scope)**
- **Assembly (subsystem scope)**
- **Unit Acceptance testing (subsystem scope)**
- **Installation Fixtures (subsystem & FMP scope)**
- **Data & Computing System (DCS) installation & test**

Basic Strategy

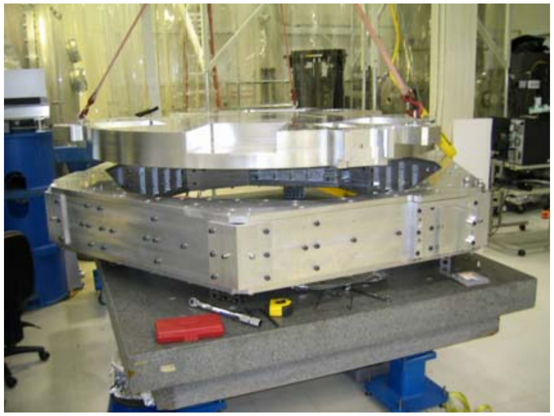
- LIGO manages all INS activities
  - **No subcontracted effort**
  - **Skilled trade labor all directed by LIGO staff**
- Prior to INS start:
  - **Integrated Testing & Training at LASTI Lab (@MIT), 40m Lab (@Caltech) & Enhanced LIGO (@LLO & LHO)**
  - **Assembly and acceptance testing principally at the Observatories; some at MIT & Caltech**
    - **Not planning to specialize assembly at one observatory or the other – all assembly is done at each observatory (with the exception of HEPI)**
    - **Each observatory staff gains familiarity with the equipment that they will debug and maintain**
- Readiness Review
- After INS Start:
  - **Simultaneous installation at both observatories (optimum staff utilization)**
  - **Time phased installation of subsystems (leveling load on experts)**
    - **Sufficient to transfer/re-direct expertise to support 2nd observatory installation**
    - **Some time to rework or work-around in response to problems**
  - **Installation & Integrated Testing are parallel activities**
    - **emphasis on early discovery of problems at integrated systems level**
    - **emphasis on installation of in-vacuum components ASAP**

INS Procedure Development & Training at the MIT LASTI Facility

- **Large Full-Scale Prototype Assemblies are Installed & Tested in the LASTI Facility Chambers**

Mode Cleaner, Triple Suspension Installation in a HAM Chamber at LASTI

Quadruple Suspension Installation on Temporary Optics Table at LASTI



Internal Seismic Isolation (ISI) Assembly at LASTI (to be installed in BSC Chamber in 2007)

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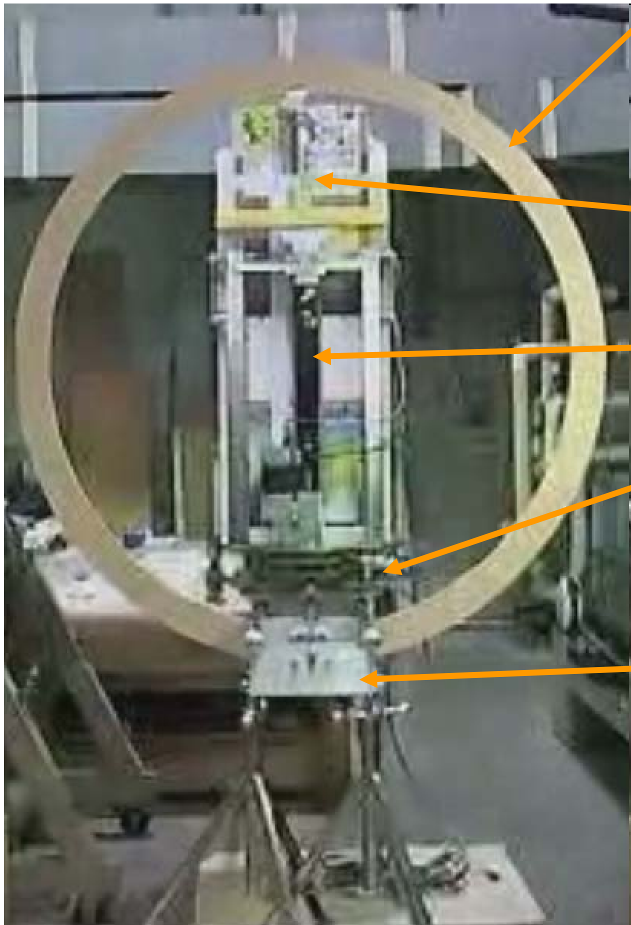
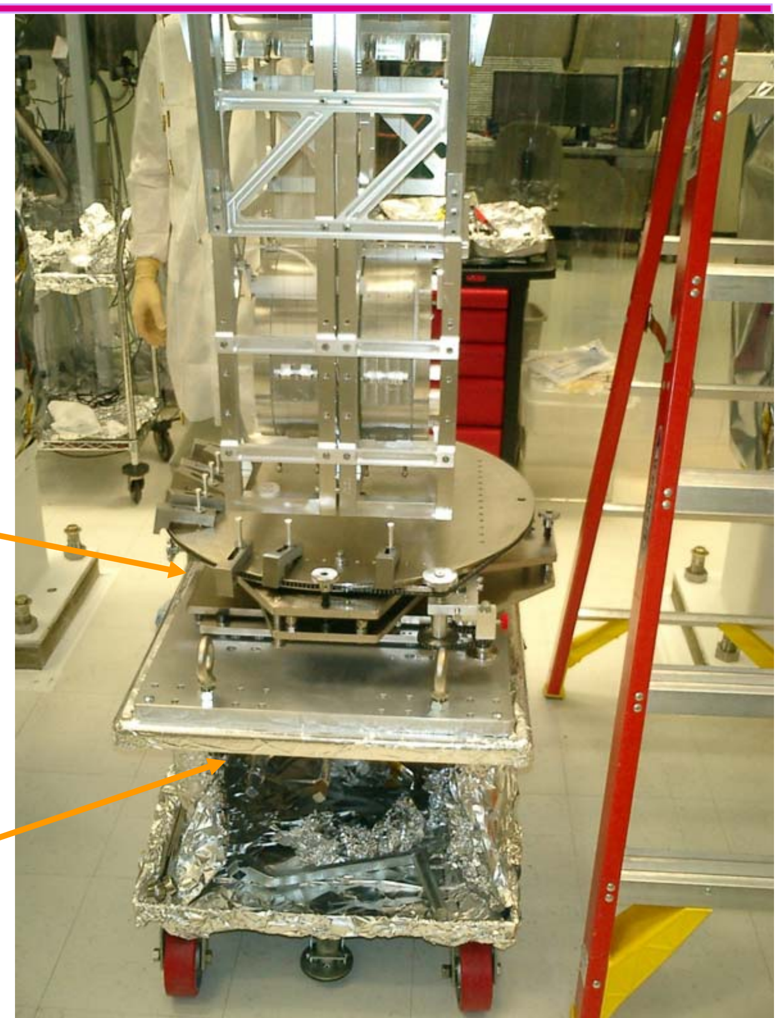
Installation Tooling Developed to Date

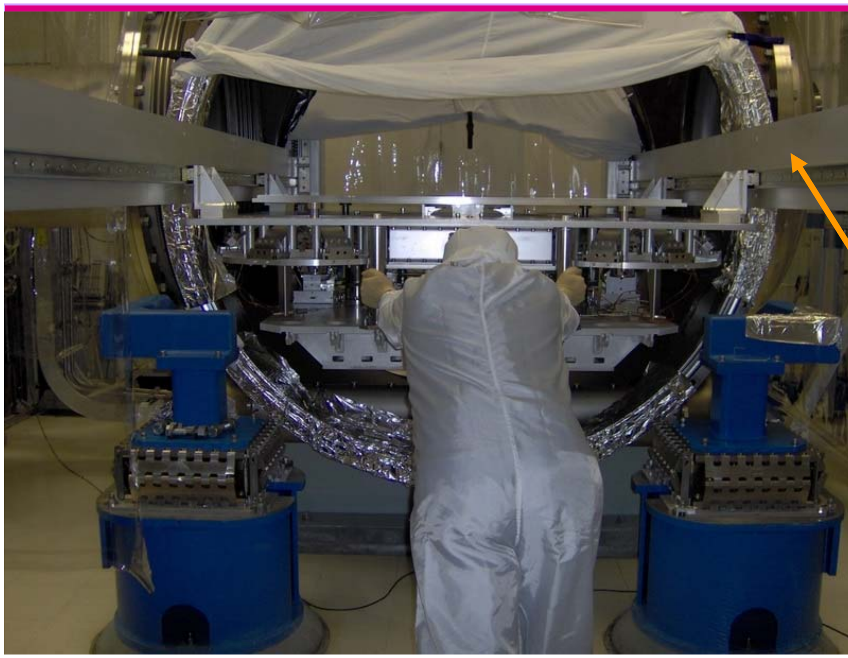


Demonstration of the Elevator and 5-axis Fixture on the Conveyor



Installation of the Quadruple Pendulum (controls prototype) with the 5-axis Fixture on the Lift Cart

Installation Tooling Developed To Date (continued)



RAIL

HAM Chamber Elevator Fixture

HAM Chamber Elevator Fixture Spanning the Chamber and Inserting a "payload" (the HAM-SAS prototype)

- HAM Chamber Elevator Fixture developed and used to install HAM-SAS – will be used for HAM-ISI
- The Articulated Arm fixture is nearing completion and will also be tested in the next few months

INS: recommendations from 2006

- *Work out the installation sequence independently of the presently scheduled shutdown plan. The shutdown sequence of the current facilities may be subject to change and the Advanced LIGO project staff needs to be ready to provide management with meaningful choices planned well ahead of time.*
  - Agreed. Detailed scheduling of the installation sequence will begin as staff is added at the project start.

Summary

- **Rate of progress is staffing limited**
  - » except coating R&D, but coatings are good enough to proceed and we have time to improve coatings
  - » Accelerating hiring in preparation for the project
- **R&D proceeding well**
  - » No significant technical issues
  - » matched to and keeping up with project schedule
- **Enhanced LIGO is an early test of many Advanced LIGO subsystems**
  - » Will retire a lot of technical/implementation risk
- **Ready to proceed with the project**