Advanced LIGO Technical Description
Part II

NSF Review of the Advanced LIGO Project
25 - 27 April 2011

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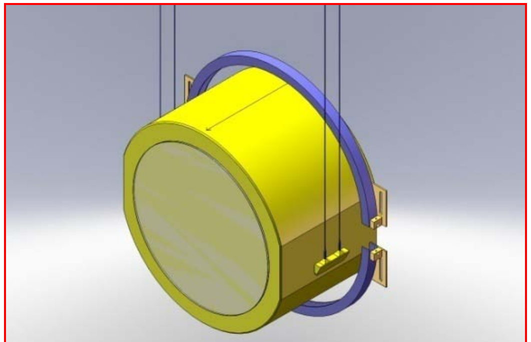
Agenda

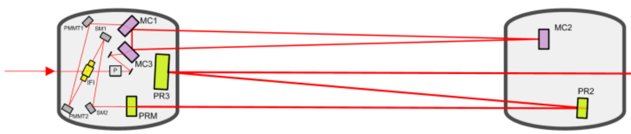
- Systems Engineering (SYS) I: Interferometer design
- Pre-stabilized Laser (PSL)
- Input Optics (IO)
- Core Optics Components (COC)
- Interferometer Sensing & Control (ISC)
- Systems Engineering (SYS) II: High Power & gas damping
- **Auxiliary Optics Subsystem (AOS)**
  - Thermal Compensation System (TCS)
  - Optical Levers (OptLev)
  - Photon Calibration (Pcal)
  - Stray Light Control (SLC)
  - Initial Alignment System (IAS)
  - Transmission Monitor System (TMS)
- **Seismic Isolation (SEI)**
- **Suspensions (SUS)**
- **Data Acquisition, Diagnostics, Networking & Supervisory Control (DAQ)**
- **Data Computing System (DCS)**
- **Facility Modifications & Preparation (FMP)**
- **Systems Engineering (SYS) III: layout, interfaces, etc**
- **Summary**

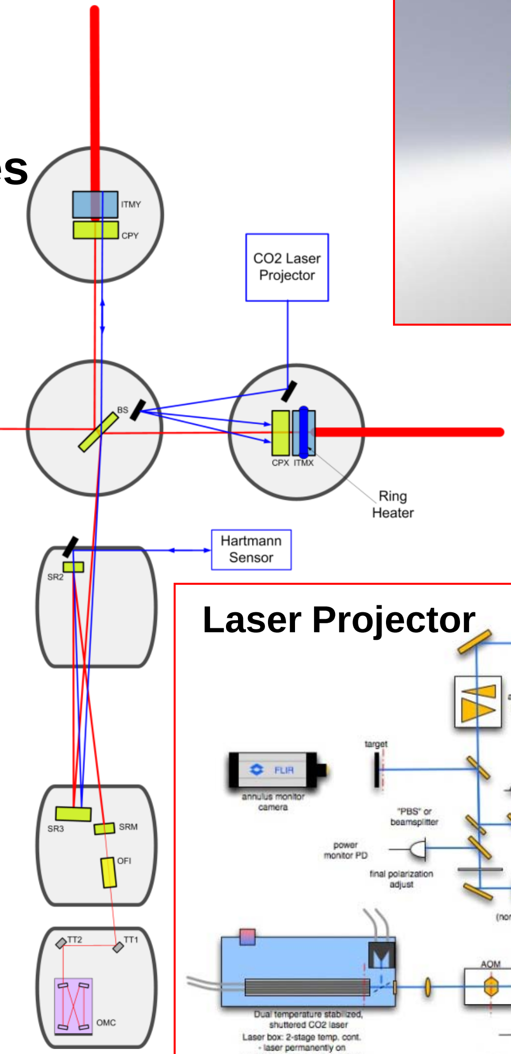
Thermal Compensation System (TCS)

- **Measure & Control thermal lens in the Input Test**
  - » Maintain thermal aberrations to within λ/50
- **Control the Radius Of Curvature (ROC) in the Input & End Test Masses**
  - » Provide 35 km ROC range

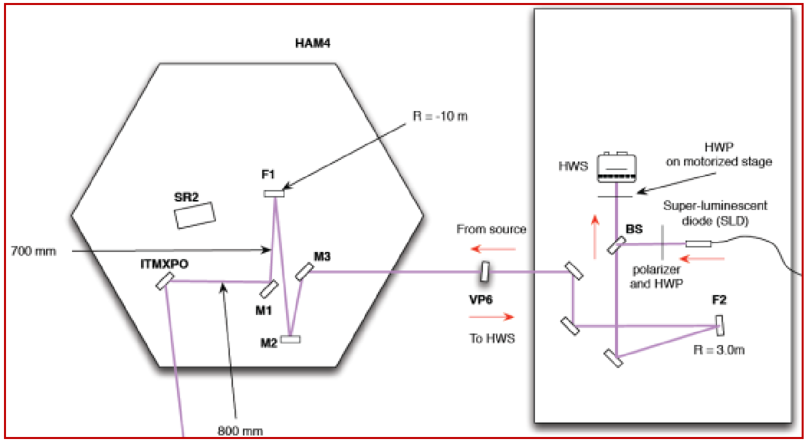


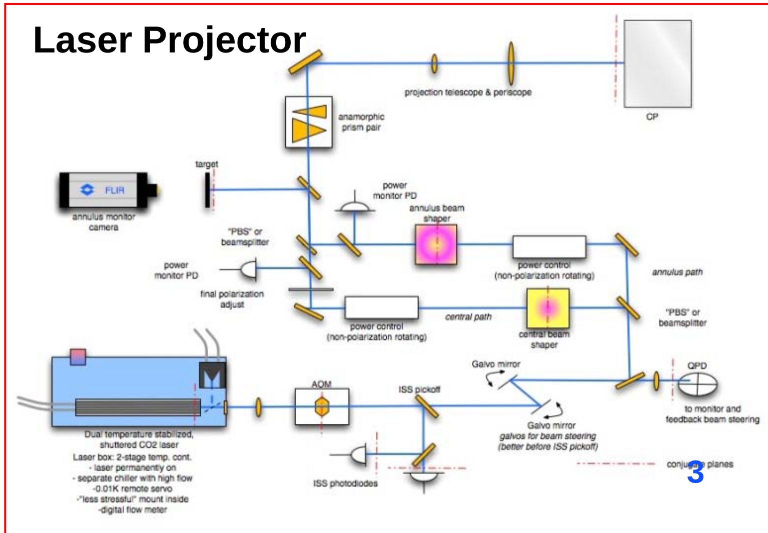
Ring Heater





Hartmann Wavefront Sensor



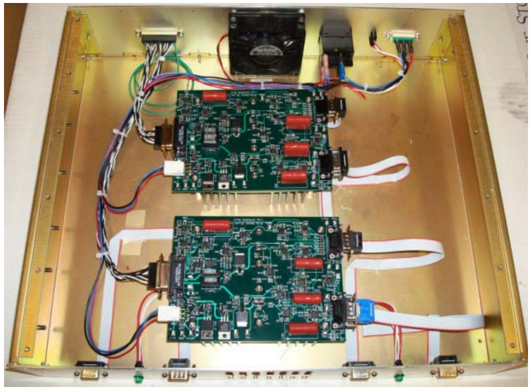


Thermal Compensation System (TCS) -- Status

- **Ring Heater**
  - » Completed Final Design Review (Dec 2010)
    - – with caveat that uniformity must be tested & shown acceptable
  - » First Article units fabricated
    - – In-vacuum test results due soon
  - » Fit checks completed on Quadruple Suspension
  - » Currently testing heating uniformity (UFL)
- **Hartmann Wavefront Sensor**
  - » Cameras ordered (U. of Adelaide, FDR Aug 2010)
  - » Probe beam wavelengths chosen
  - » Layout is mature
  - » Software being prototyped (beta released)
  - » FDR Oct 2011
  - » Diagnostic system – does not drive schedule

Ring Heater on Quad SUS

Ring Heater Current Driver



Thermal Compensation System (TCS) -- Status

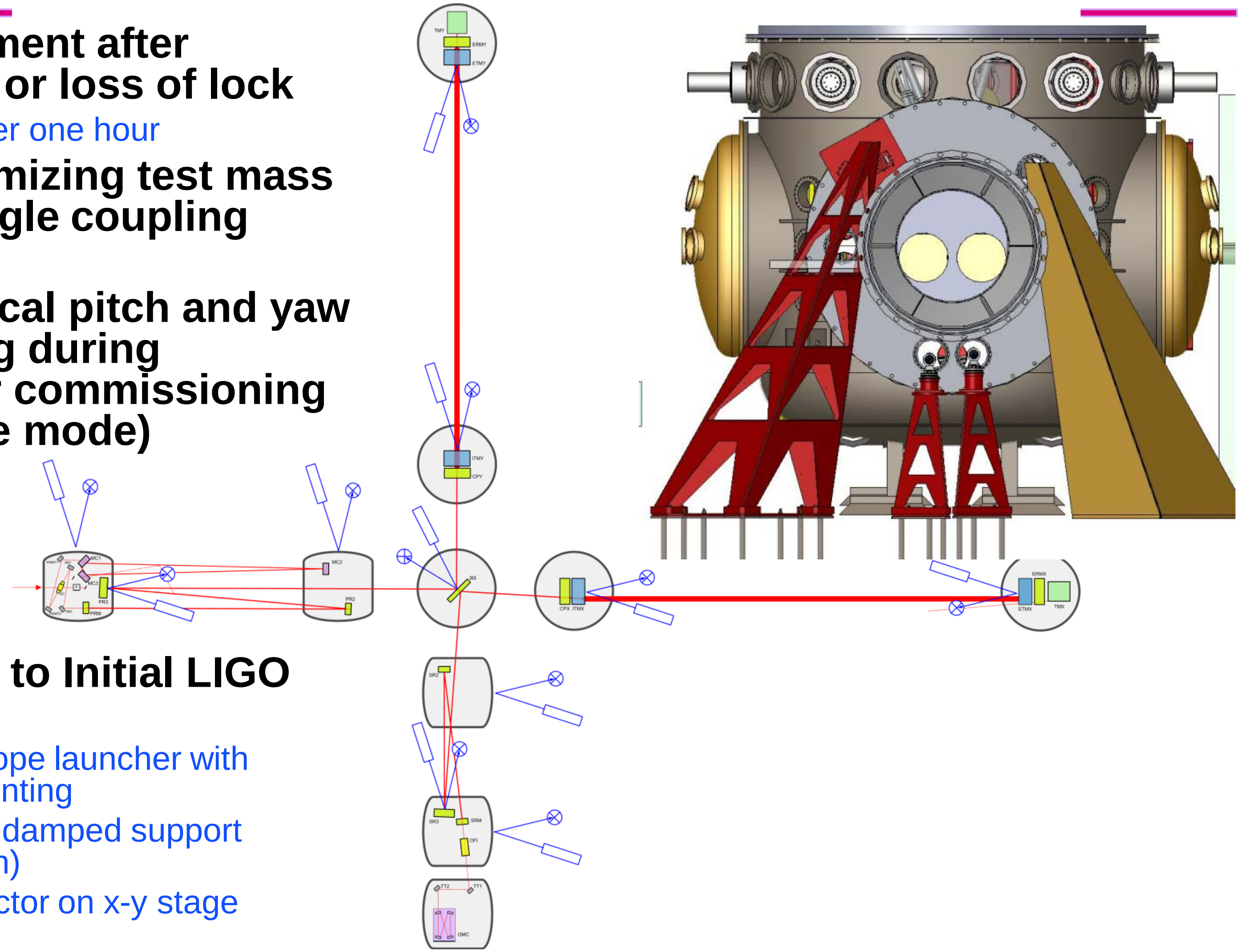
- **Laser Projection**
  - Canceled 1st laser source contract – failed to meet specs
  - Exploring alternate sources – cost risk, not technical or schedule risk
  - Likely plan:
    - Procure commercial-off-the-shelf unit that meets specs at 35W
    - Contract for modification to this unit to achieve 50W
  - Completed FDR for in-vacuum relay mirror – fabricated first article
  - Completed FDR for vacuum window – in fabrication
  - Subsystem FDR Nov-2011
    - Only in-vacuum elements are schedule critical

Power Control Waveplate Assy

In-Vacuum Relay Mirror Assy

Optical Levers (OptLev)

- **Restore alignment after invasive work or loss of lock**
  - » 1 μrad drift over one hour
- **Assist in minimizing test mass position-to-angle coupling**
  - » ≤ 100 nrad/μm
- **Sensing for local pitch and yaw mode damping during interferometer commissioning (not in science mode)**



- **Improvements to Initial LIGO design**
  - » Fiber to telescope launcher with goniometer pointing
  - » Stiffer & better damped support structure (pylon)
  - » Quadrant detector on x-y stage

Optical Levers (OptLev) -- Status

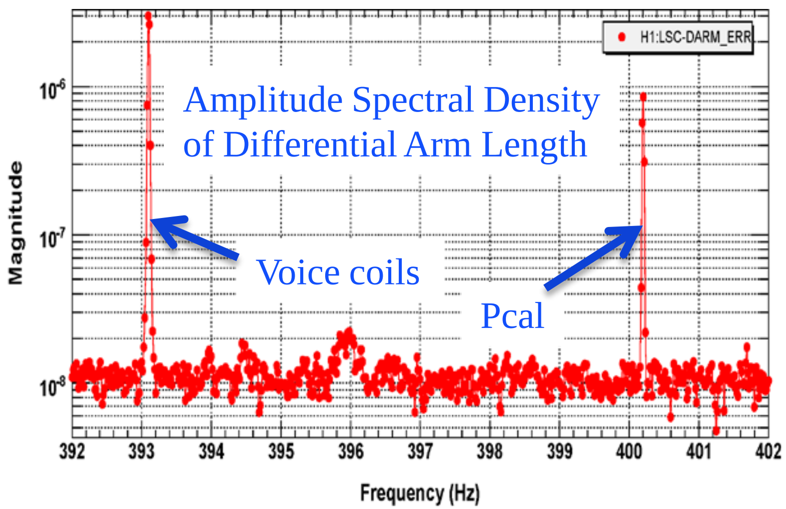
- **Completed FDRs**
- **Pylon fabrication to be completed May-2011**
- **Most parts received or on order**
  - » except BS/FM OptLev components and enclosures
- **Assembly started**
- **No technical risks**

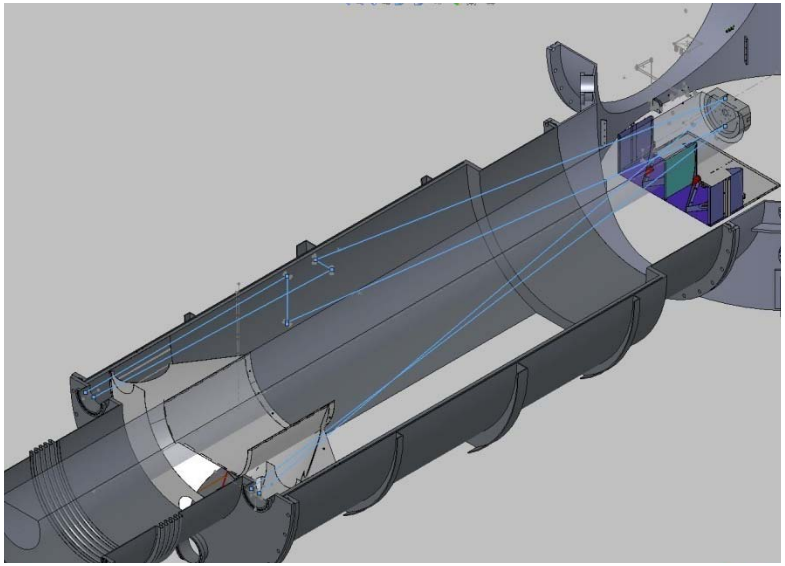
RR3/SR3 Receiver Pylon

Transmitter Pylons

Photon Calibration (Pcal)

- **Apply sinusoidal photon pressure to the End Test Masses to calibrate the displacement response of the interferometer**
  - » SNR>10 over the expected aLIGO sensitivity curve with an integration time of 1 s for frequencies up to 500 Hz
  - » ± 5% calibration accuracy
- **Provide an independent timing standard**



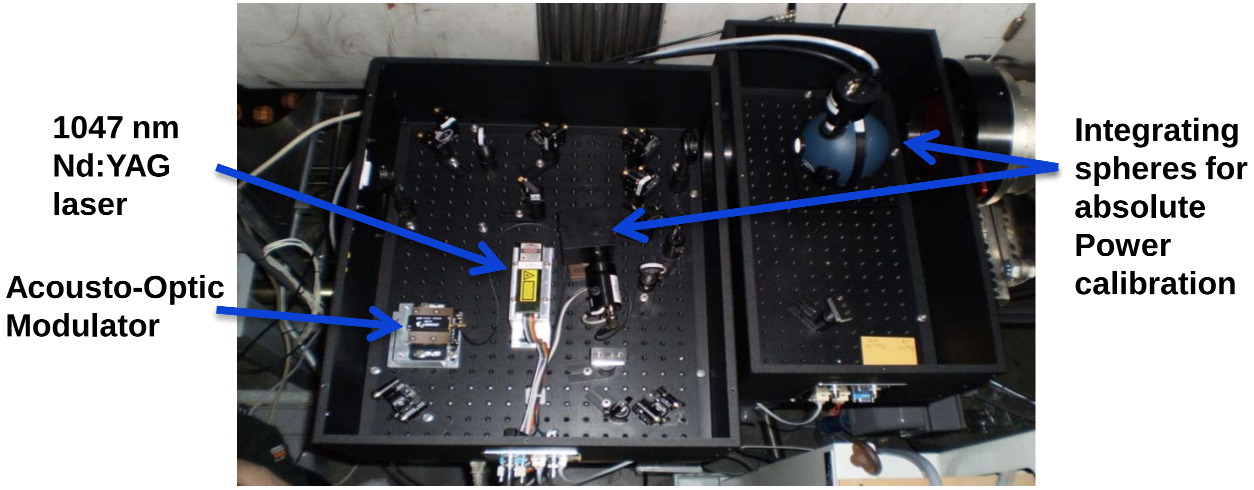


- **Same concept as for initial LIGO:**
  - » Vary the diode-pumped, solid state, laser power with an acousto-optic modulator
  - » Measure the light power with a NIST traceable integrating sphere

- **Enhancements:**
  - » Higher power
  - » Calibrated receiver
  - » Reduced modulation harmonics
  - » Two beams
    - – torque free excitation
    - – prevent apparent recoil due to mirror elastic deformation

Photon Calibration (Pcal) -- status

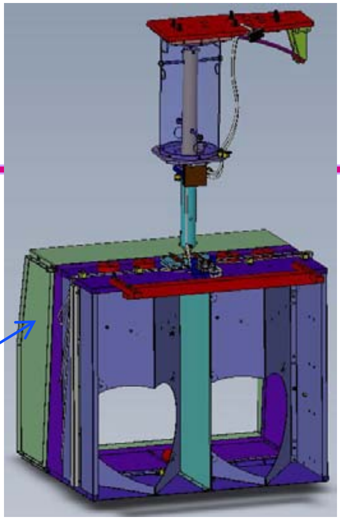
- **Enhanced LIGO PCal system operated well**
  - Achieved ± 10% calibration magnitude accuracy
- **Intentionally delayed PCal development completion**
  - Completed work on layouts and interfaces
  - Little risk remains with the possible exception of maintaining beam positioning relative to optic center +/- 1 mm
  - Final Design Review Nov-2011 -- Intentionally delayed (limited resources) -- project does not need Pcal until shortly before science runs start

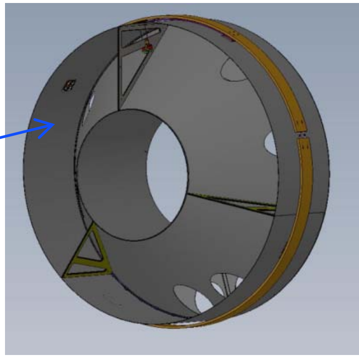


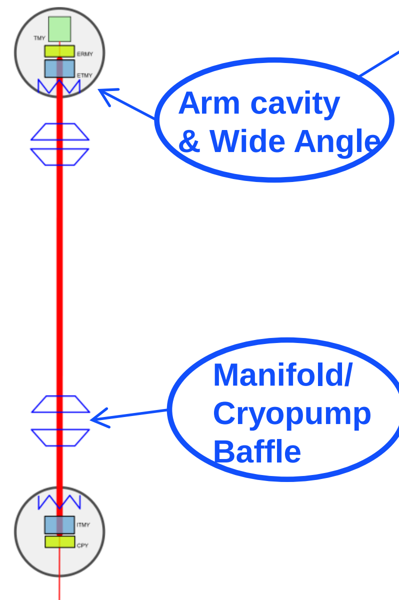
eLIGO Pcal Assy

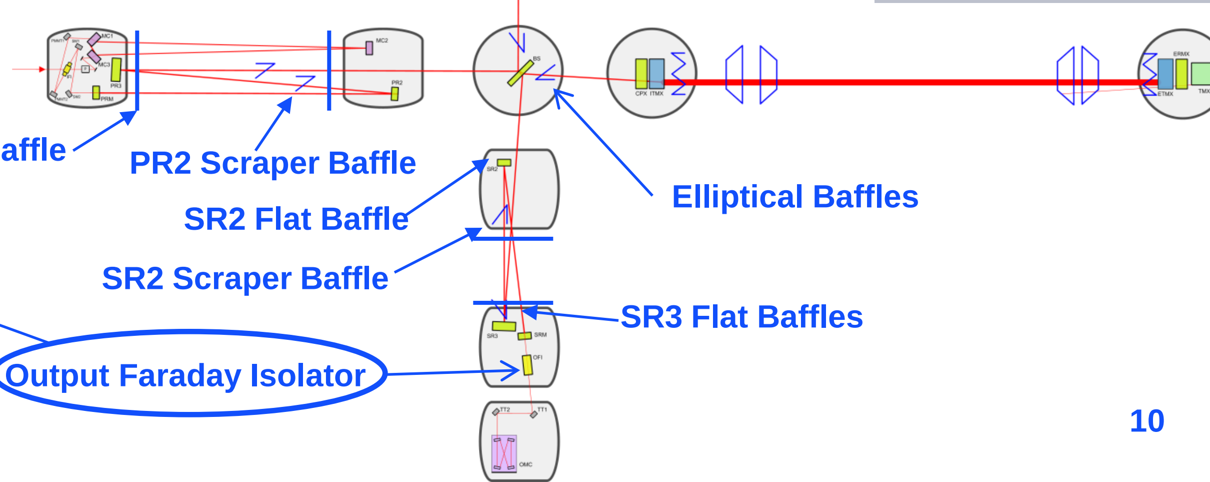
Stray Light Control (SLC)

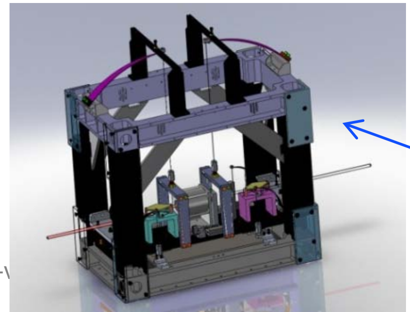
- Ensure that phase noise due to scattered light and ghost beams does not compromise interferometer performance
- All baffles (except the scraper baffles) and the Output Faraday Isolator are suspended
- All baffles & beam dumps are either black porcelain coated steel sheet or AR coated black glass









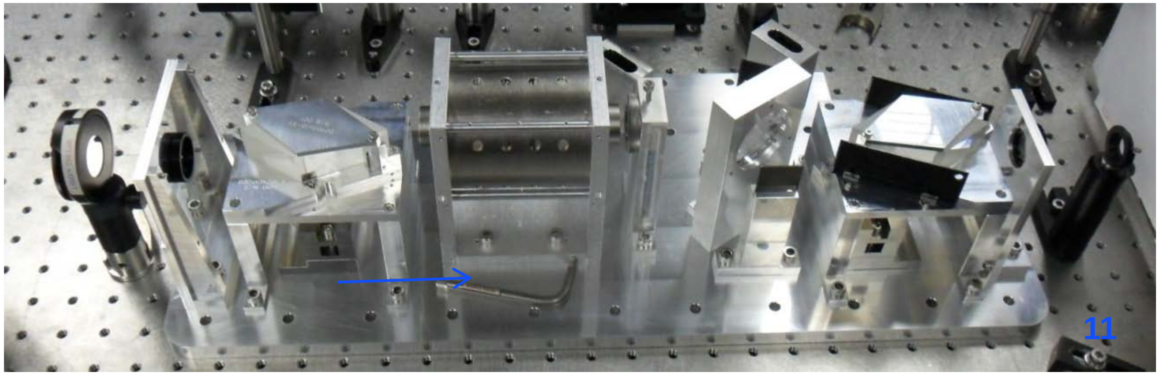


Stray Light Control (SLC) -- Status

- **Output Faraday Isolator**
  - » Tested suspension
  - » Completed FDR (Oct 2010)
  - » Shipped assembled & tested 1st article (for LHO Squeezer test)
- **Arm Cavity Baffle**
  - » Tested suspension
  - » Completed FDR (Apr 2011)
- **Manifold/Cryopump Baffle**
  - » Completed FDR
  - » Completed 1st article assembly & test
- **All other baffles**
  - » Most designs & drawings completed
  - » FDR Jun-2011
- **No remaining technical risks**

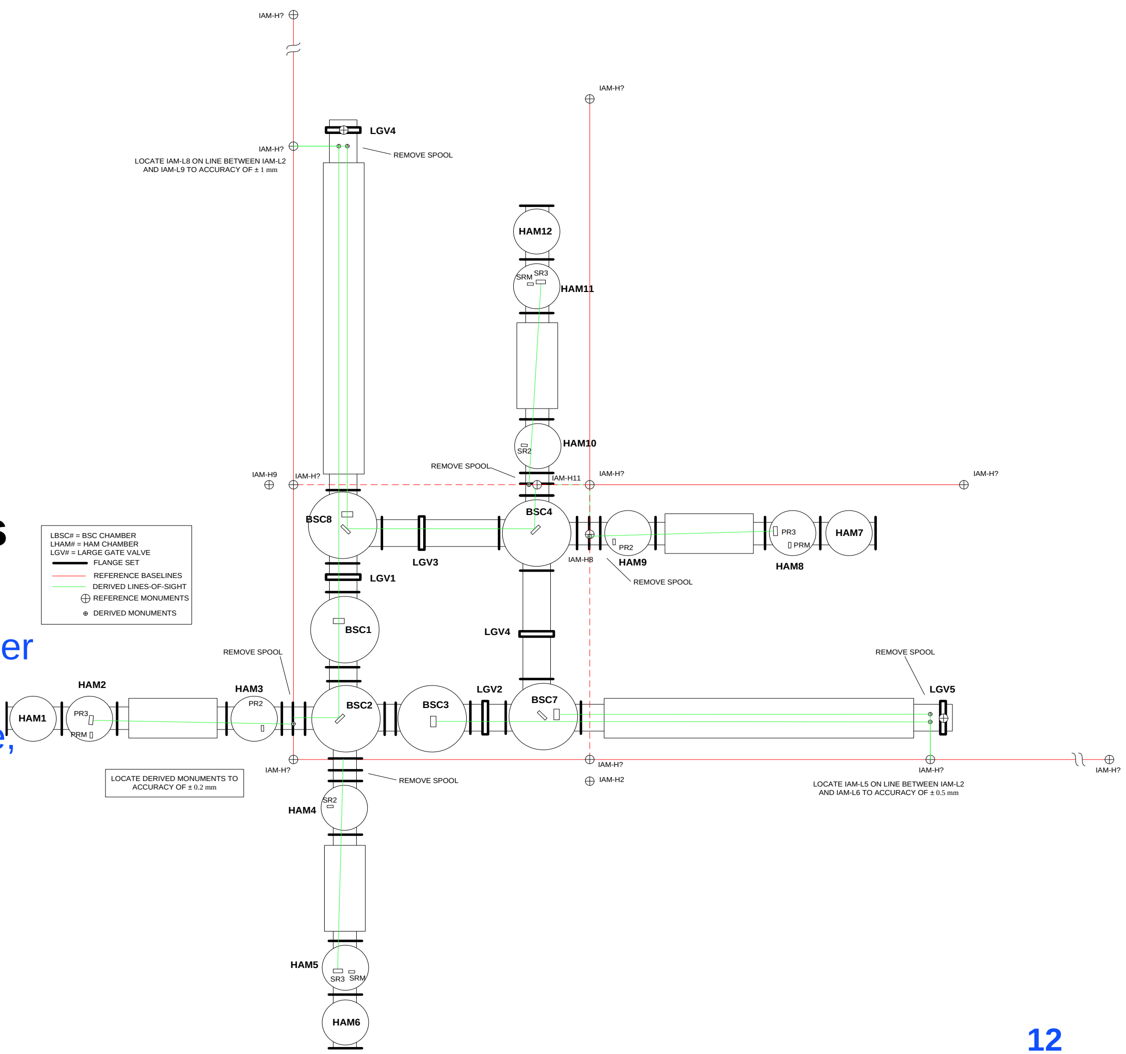
Manifold/Cryopump Baffle

Output Faraday Isolator



Initial Alignment System (IAS)

- **Provide initial positioning/alignment of the interferometer optics**
- **Requirements & methods are similar to Initial LIGO, plus:**
  - » Electro-static drive alignment
  - » Transmission Monitor Suspension
  - » BSC “Cartridge” alignment
  - » Finding optic centers with CMM
- **Optics are positioned and aligned to survey monuments with survey equipment**
  - » Total Station Theodolite, prism/corner cube, laser autocolimator, lateral transfer retroreflector, transit square, …
- **Optics are aligned relative to each other using an IR laser autocolimator**



Initial Alignment System (IAS) -- Status

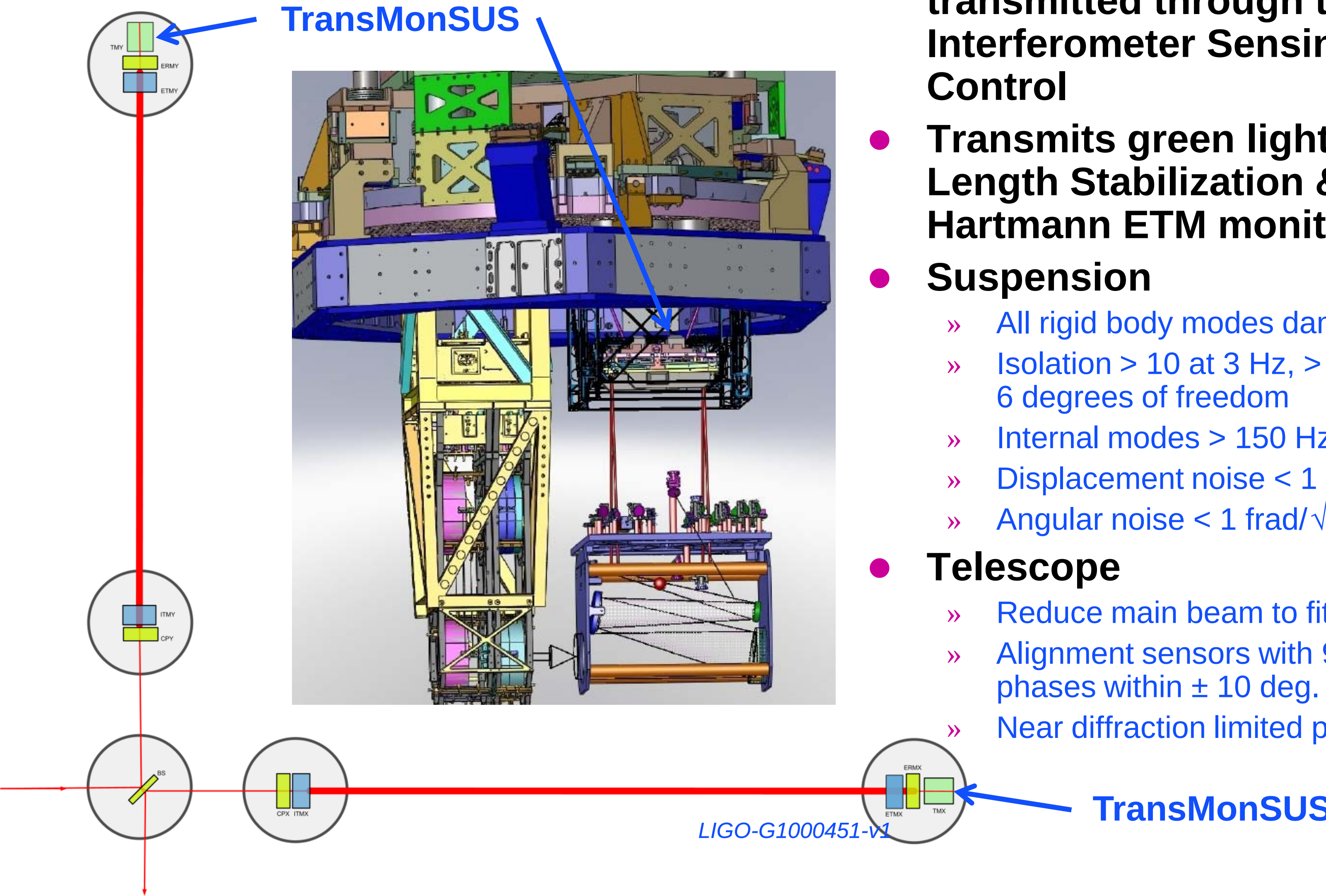
- Completed Final Design Review (Jan 2011)
- All major equipment on order (all expected by Jun 2011)
- Re-survey of monuments in buildings at each site nearing completion
- Will be ready for initial alignment activities at LHO (long arm test) and LLO (input mode cleaner & power recycling cavity)

Cross-hair target integrated with retroreflector

Coordinate Measuring Machine (CMM)

Laser Autocollimator co-boresighted with Total Station (theodolite)

Transmission Monitor Suspension (TMS)

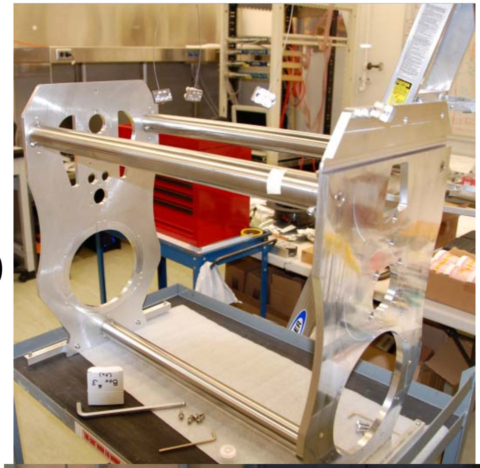


- **Collects main arm cavity light transmitted through the ETM for Interferometer Sensing and Control**
- **Transmits green light for Arm Length Stabilization & intermittent Hartmann ETM monitoring**
- **Suspension**
  - » All rigid body modes damped to Q<10
  - » Isolation > 10 at 3 Hz, > 1000 at 10 Hz, all 6 degrees of freedom
  - » Internal modes > 150 Hz
  - » Displacement noise < 1 pm/√Hz
  - » Angular noise < 1 frad/√Hz
- **Telescope**
  - » Reduce main beam to fit 2 inch optics
  - » Alignment sensors with 90 degree Gouy phases within ± 10 deg.
  - » Near diffraction limited performance

Transmission Monitor Suspension (TMS) -- Status

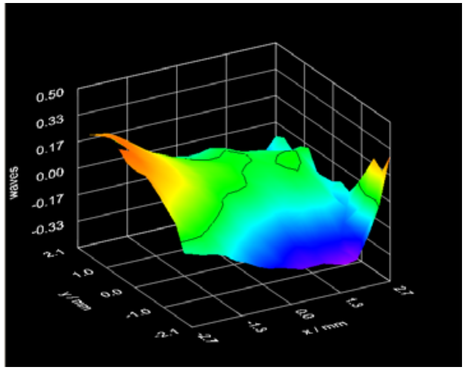
- **Completed preliminary design review (May 2010)**
- **Fabricated all components of 1st article**
- **Assembled, tested the 1st article suspension**
- **Performing Shack-Hartmann alignment/test of off-axis parabolic telescope optics (require < $\lambda/20$ @ 1064 nm)**
- **Telescope 1st article being assembled, aligned now – to be completed May 2011**
- **Final design review Jun-2011**
- **Will deploy first article in H2 Long Arm Test**

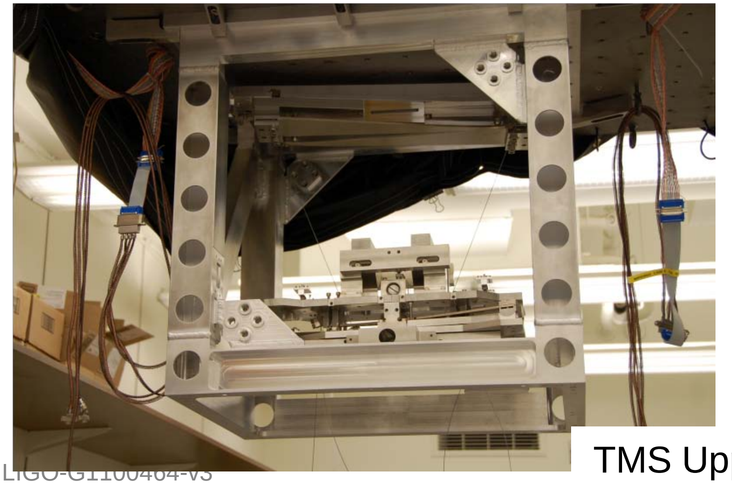
Telescope Structure



Bench for measuring wavefront quality of telescope optics

Wavefront Map

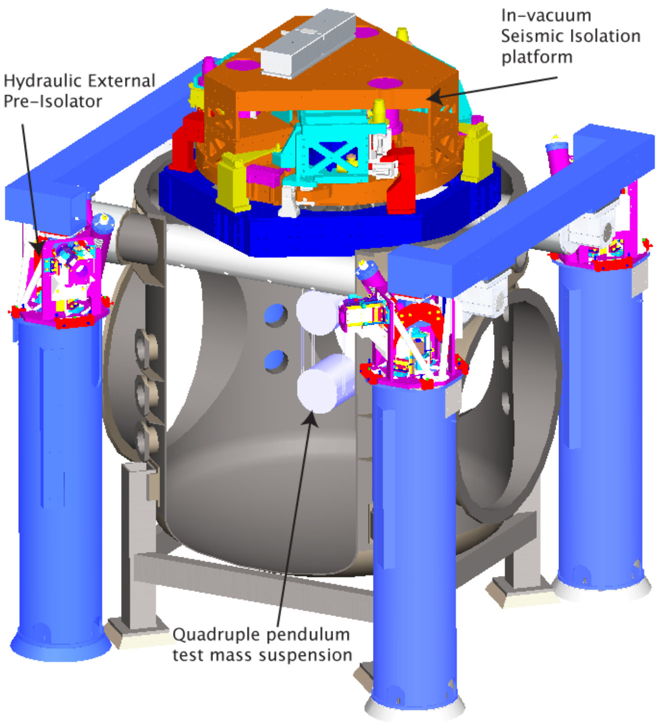




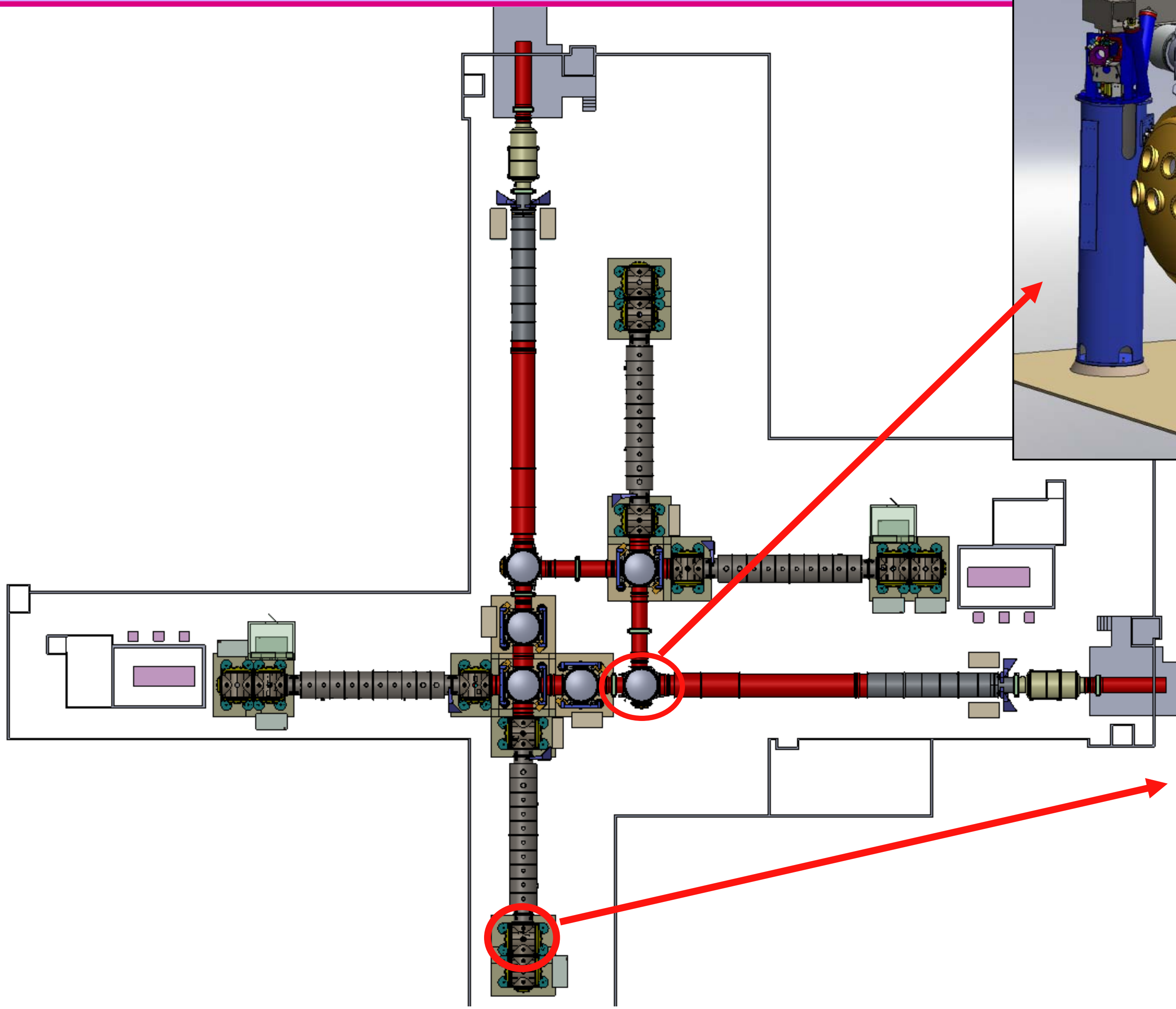
TMS Upper Mass and Upper Structure

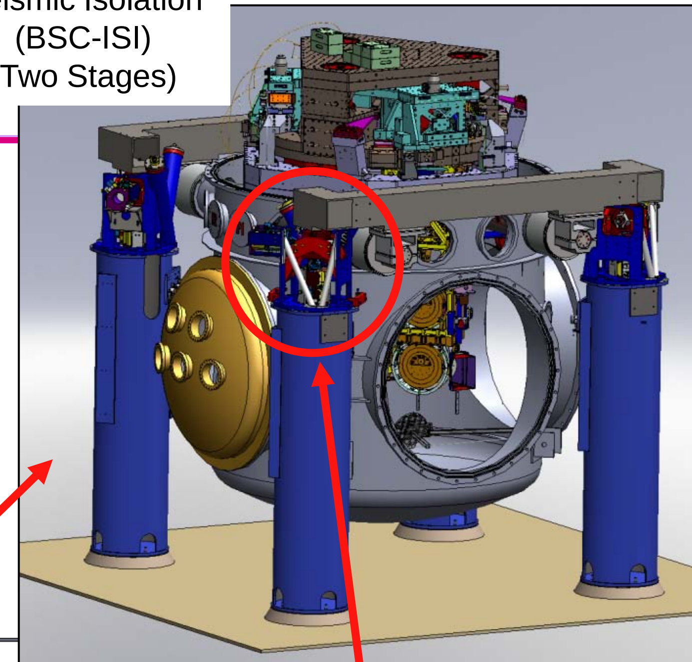
Seismic Isolation: Multi-Stage Solution

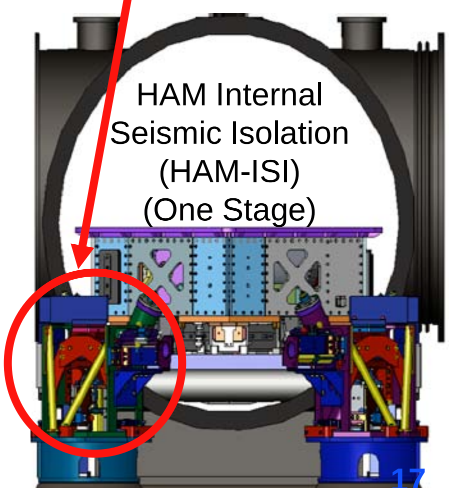
- **Render seismic noise a negligible limitation to GW searches**
- **Reduce actuation forces on test masses**
- **Both suspension (SUS) and seismic isolation (SEI) systems contribute to attenuation**
  - Significant participation & co-leadership by Stanford University in SEI
  - Financial support & leadership by the United Kingdom in SUS
- **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



BSC & HAM Vacuum Chambers & Seismic Isolation Systems





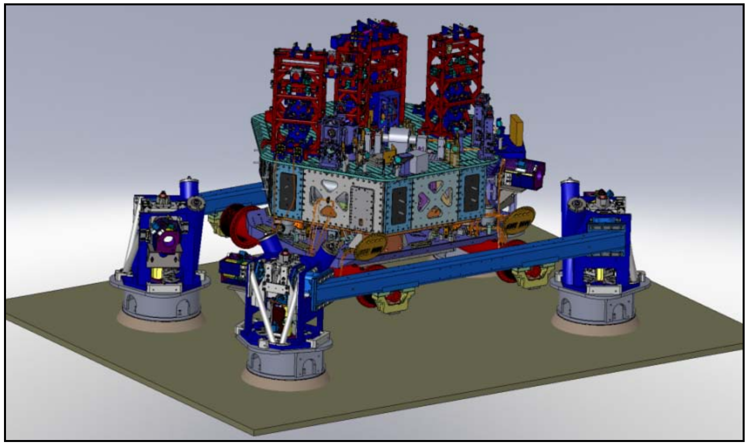


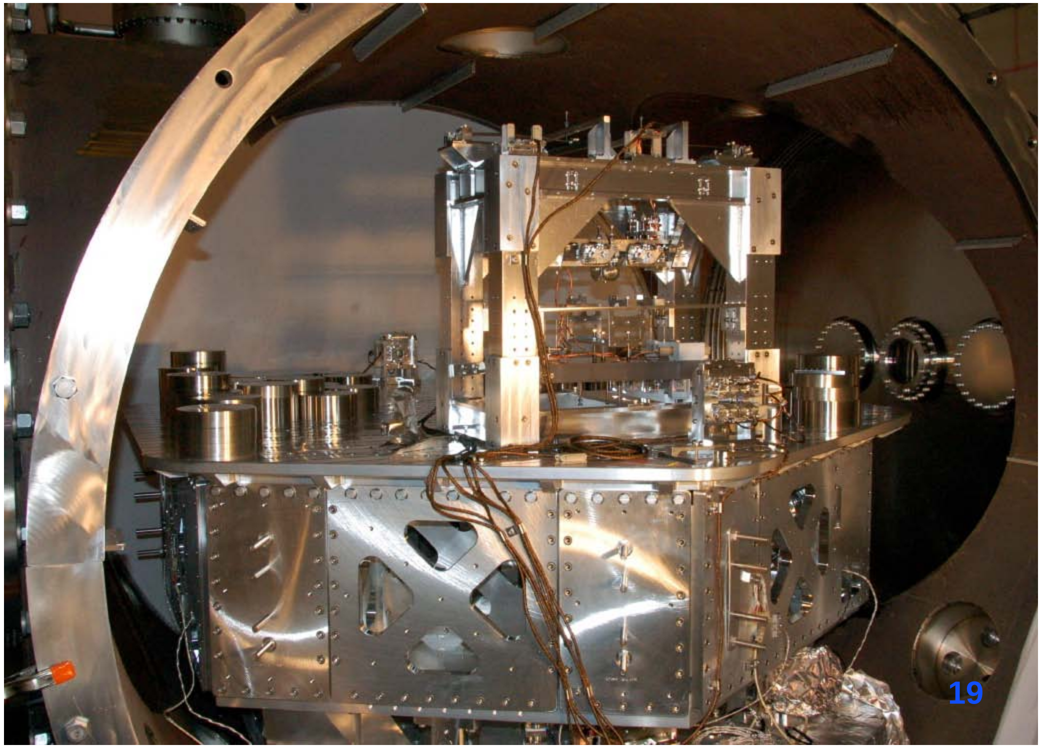
Seismic Isolation System (SEI) Status: HEPI

- **Hydraulic External Pre-Isolator (HEPI)**
  - » Operational system installed on 9 chambers at LLO for the 4th science run (S4)
  - » Measured isolation performance meets requirements – recent performance improvement (<0.5 Hz) from optimal feedforward filtering based on interferometer signals
  - » LLO gets new electronics and controls, new HAM units (to match new stiffer crossbeams)
  - » LHO gets full installation
  - » Pump stations have been assembled at LHO
  - » All subassembly completed to extent possible now
  - » All HEPI electronics modules completed
  - » All sensors, most actuators tested (continuing)
  - » Installation has begun

Seismic Isolation System (SEI) Status: HAM-ISI

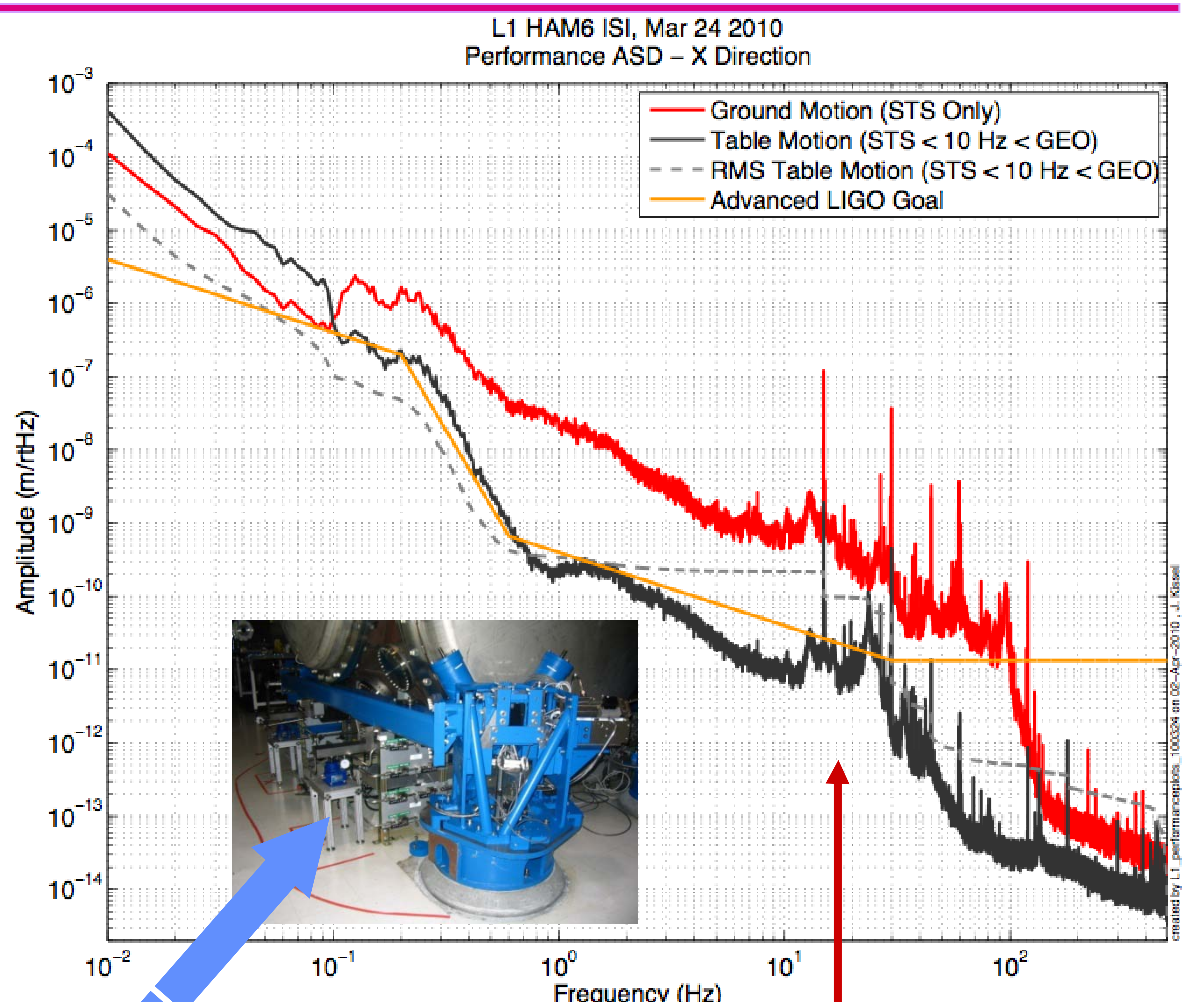
- **Internal Seismic Isolation (ISI) for the HAM Chamber**
  - » Single stage (6 DOF) isolator with positioning/alignment capability
  - » Active isolation (.1 Hz to ~25 Hz)
  - » Passive isolation (~3 Hz to ~100 Hz)
  - » Two operational first articles in Enhanced LIGO (1 at each observatory)
  - » Measured isolation performance, coupled with modeling, projects meeting isolation requirements





HAM ISI Performance

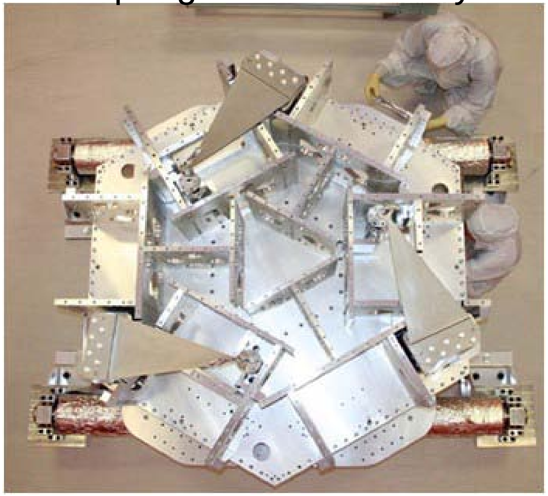
- **Performance of system installed for eLIGO**
- **AdvLIGO installation adds HEPI**
  - » increases isolation at low frequencies, shifts up and damps16Hz feature
  - » Can further reduce platform differential motion based on interferometer signals (<.5 Hz)
- **Sensor correction (feed-forward) improvement at ~10 Hz to be implemented for Signal Recycling Cavity HAMs**
  - » Likely factor of 3-5 isolation from 10-20 Hz



Seismic Isolation System (SEI) Status: HAM-ISI Assembly

- **8 of 15 HAM-ISI units have been assembled**
  - » 3 of 8 require re-assembly and re-testing due to a manufacturing flaw (unauthorized weld repair)
  - » Can re-assemble & re-test in 3 wks duration (H2 HAM3 has been re-assembled)
- **Assembly schedule is on-track with installation schedule**
  - » May build an additional HAM-ISI at LLO and ship to LHO if required

Top View of Cantilevered Spring Blade Assembly



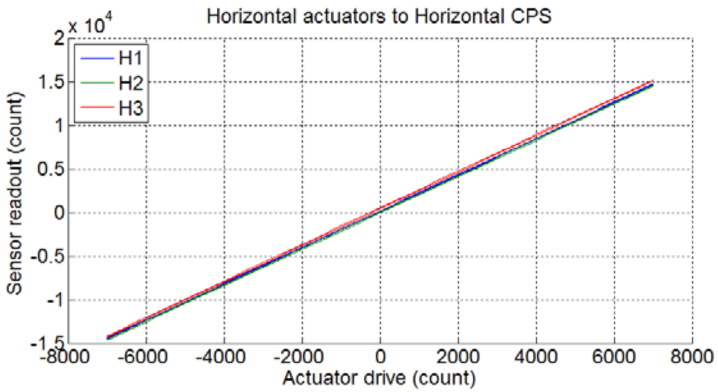
Seismometers & Actuators

Position Sensor

Seismic Isolation System (SEI) Status: HAM-ISI Testing

- **6 units Tested (3 at each observatory)**
- **Much of the testing is automated**
  - » Transfer functions
  - » Calibrated power spectrum
  - » Hysteresis/linearity
  - » Dynamic range
  - » etc.
- **Tested units go into storage containers**

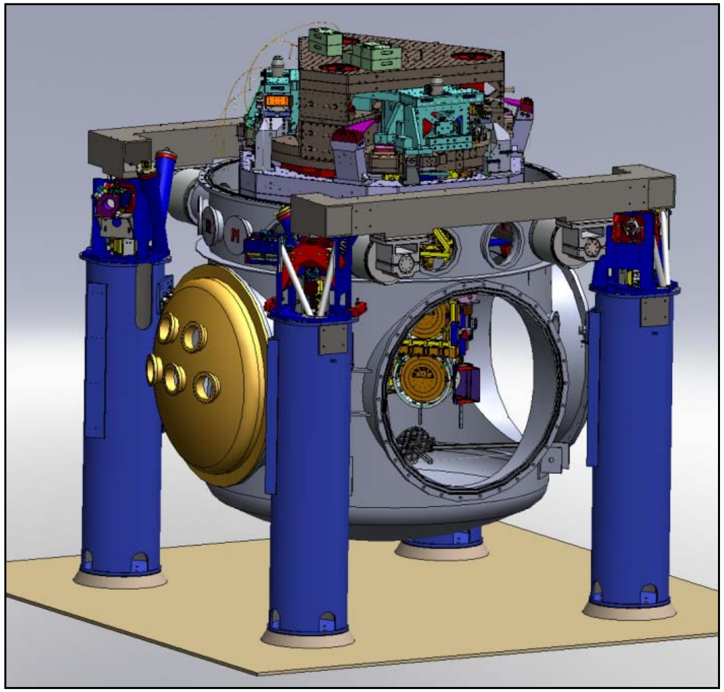
HAM-ISI Testing

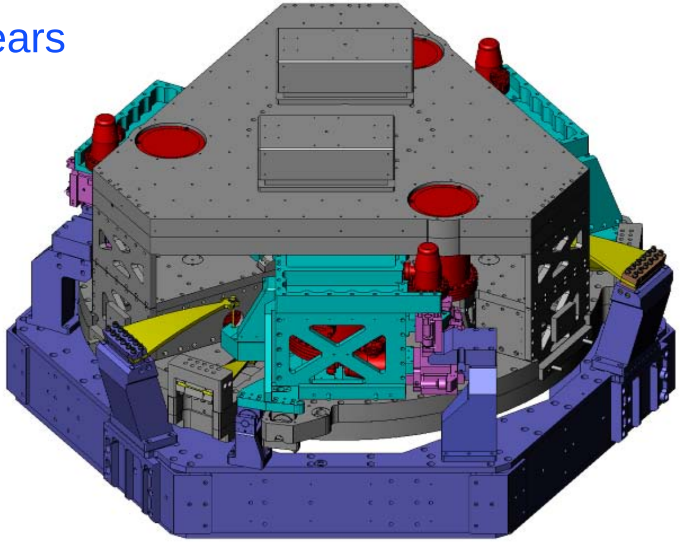


HAM-ISI in Storage Container

Seismic Isolation System (SEI) Status: BSC-ISI

- **Internal Seismic Isolation (ISI) for the BSC Chamber**
  - » Support structure plus two sequentially suspended stages
    -- 12 DOF isolator with positioning/alignment capability
  - » Active isolation (0.1 Hz to ~25 Hz)
  - » Passive isolation (~3 Hz to ~100 Hz)
  - » Full scale prototype has been in test at LASTI for 4 Years

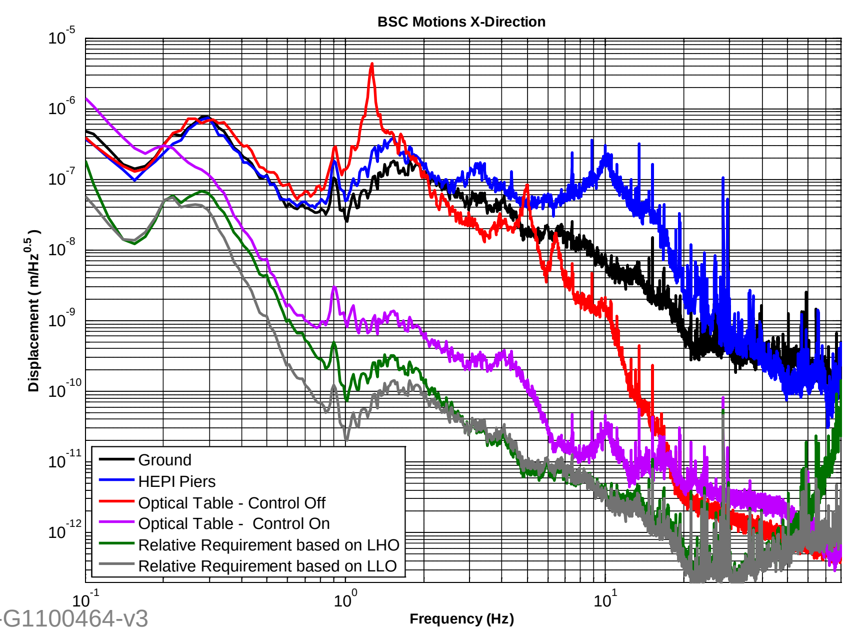


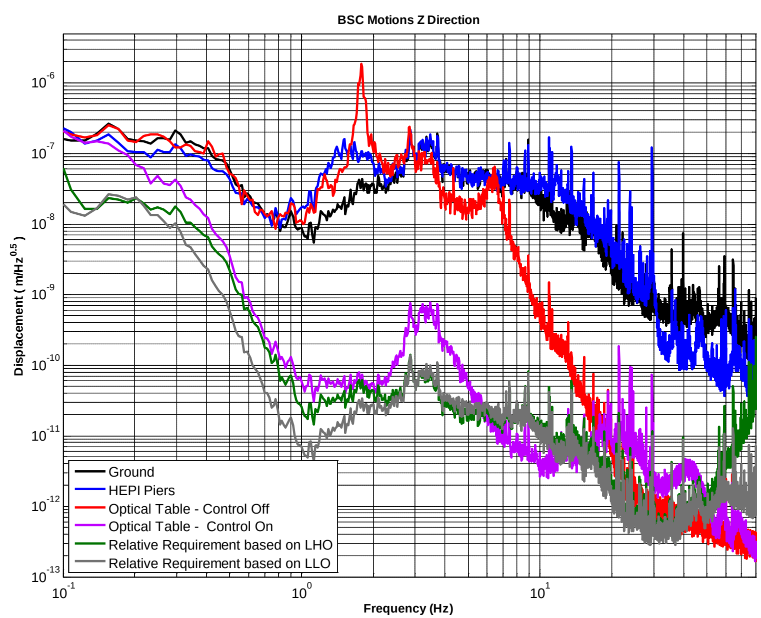


- Stage 0 in violet
- Stage 1 in cyan
- Stage 2 in grey
- Blades and flexure in yellow
- Sensors in Red
- Actuators in Pink

Seismic Isolation System (SEI) Status: BSC-ISI Performance

- **Controls and isolation performance testing at LASTI**
  - Integrated with quadruple pendulum suspension
  - Continued controls development has improved low frequency isolation performance
  - Experimenting with passive vibration absorbers
  - Performance is close to goals and below other noise sources > 10 Hz



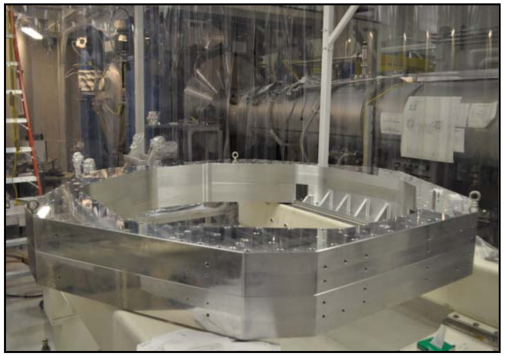


Seismic Isolation System (SEI) Status: BSC-ISI Assembly

- **Assembled 1 BSC-ISI unit at LASTI**
  - » Confirmed design improvements
  - » Developed final assembly procedures
  - » Trained assembly staff
- **Assembly of the first 2 BSC-ISI units, for the H2 long arm test, has begun**
- **Several deliverables on the critical path, but confident we can make milestones**

Electromagnetic Actuators

Stage 0 – Support Ring



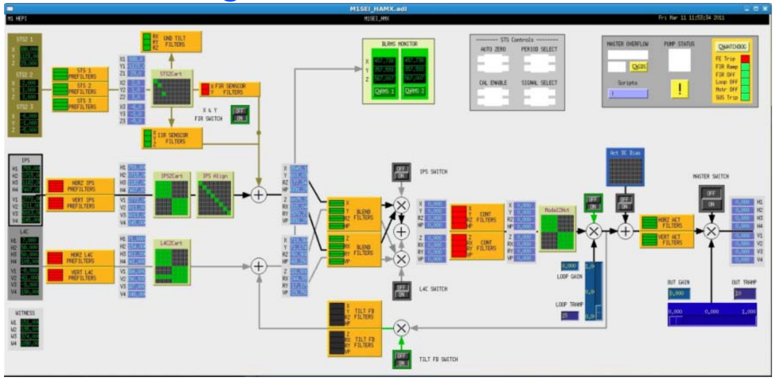
Stage 1 Structure

Stages 0, 1 and 2

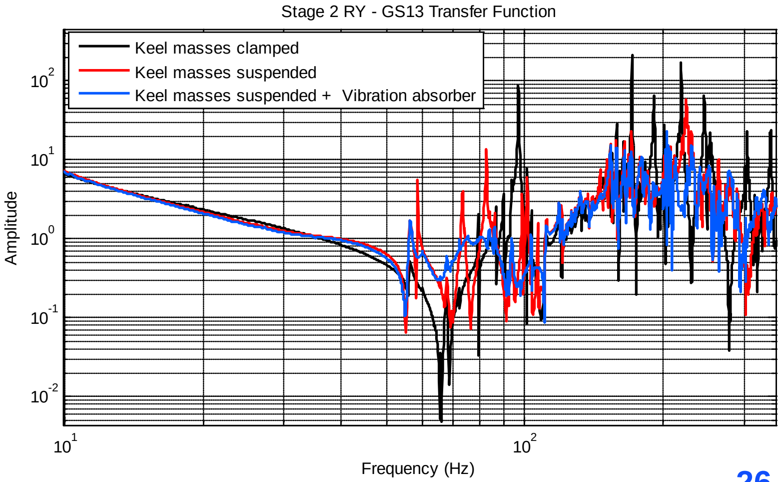
Seismic Isolation System (SEI) Status: BSC-ISI Testing

- **Investigated**
  - Passive damping
  - Sensor/actuator electromagnetic coupling
- **Testing**
  - Synthesized control
  - Developed user interfaces (MEDM screens)
  - Defined test procedures
  - Prepared automated scripts, templates, acceptance criteria
  - Training

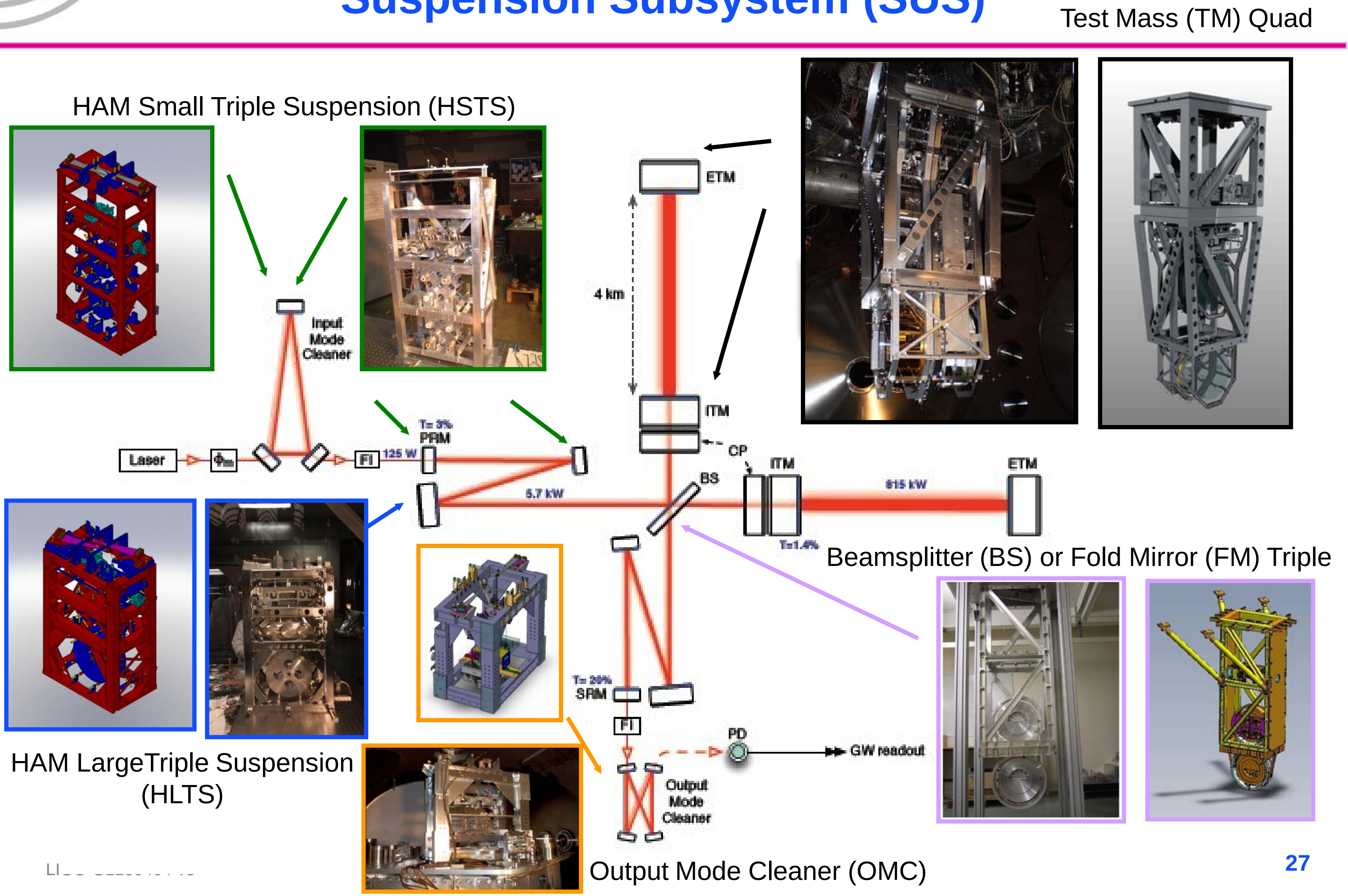
BSC First Article “dirty” build at LASTI



User Interface (MEDM) Control Screen

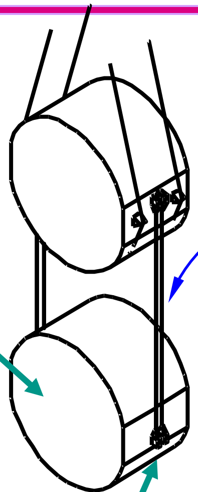


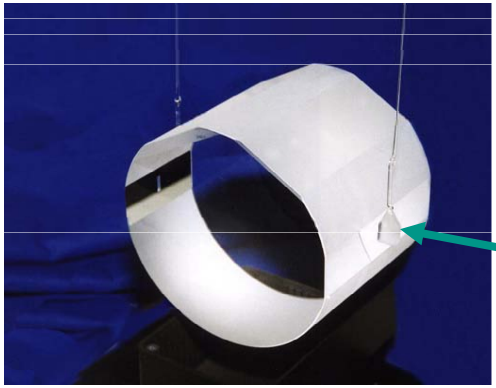
Suspension Subsystem (SUS)

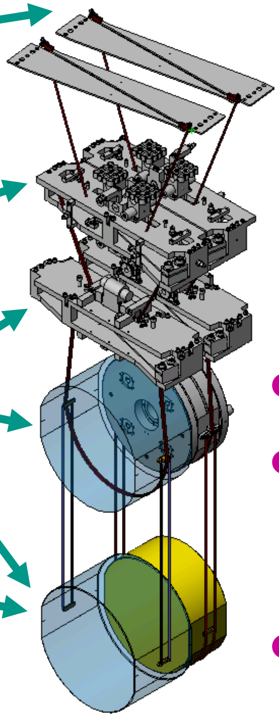


Suspension Subsystem (SUS): Test Mass Quadruple Pendulum

- Minimize noise from damping controls and global control actuation
- Minimize 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





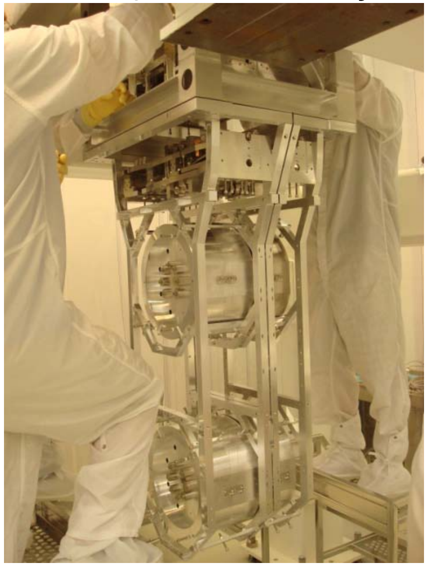


- <u>Adopted UK/GEO Project suspension concepts</u>
- Choose quadruple pendulum suspensions for the main optics and triple pendulum suspensions for less critical cavity optics
- Create quasi-monolithic pendulums using fused silica ribbons to suspend 40 kg test mass

Suspension Subsystem (SUS): Test Mass (TM) Quadruple Pendulum

- **TM Quad**
  - » Essentially all suspension parts now delivered from UK (RAL)
  - » Assembly and testing well underway at LHO and LLO
    - – Assembled 5 suspensions in metal form
    - – Assembled subassemblies of remaining 7 units + spares
  - » Reviewing/revising tooling, procedures & design (minor) based on assembly experience to address difficulty in alignment
  - » Successful monolithic hang at LASTI (May 2010)
    - – Locked in cavity for hierarchical control, modal damping, electrostatic charging experiment
  - » Silicate bonding, fiber pulling & welding training (25 person wks)
  - » Bonding, fiber pulling and welding operational at LHO
  - » Bonding of four penultimate masses & 1st test mass completed

Quad Assembly

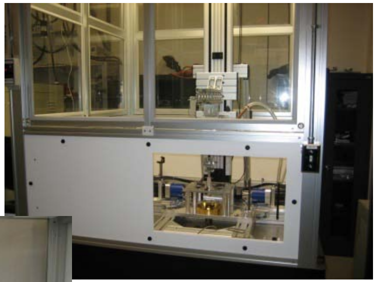


Monolithc Assy (LASTI)

Fiber Welder (LHO)

Fiber Welding (Glasgow)

Ear Bonding



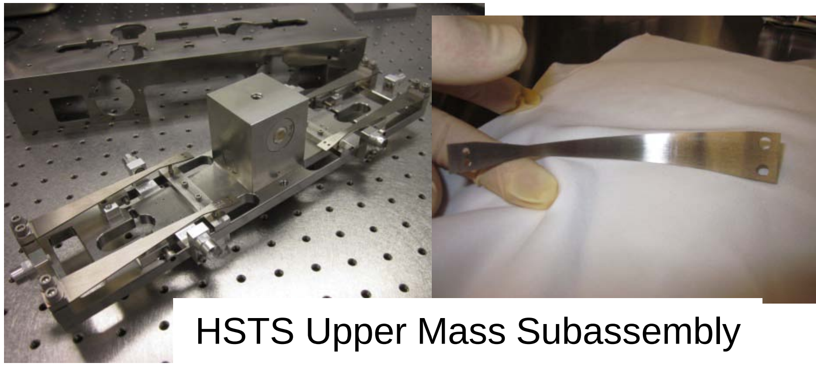
Fiber Puller (LHO)

Suspension Subsystem (SUS): Triple Suspensions

- **BS/FM Triple:**
  - Subassembly work begun at both LLO & LHO
  - One FM suspension assembled & under test at LHO
    - To be installed in BSC8 at LHO for H2 long arm test
    - Optic not needed & not yet available
  - Established proper placement of 2nd prism to minimize thermal noise for wire suspension (assembly jig)
  - Defined location of stiffening struts for each instance
  - Finalizing procedures for optic replacement in situ
- **HAM Chamber Large & Small Triple Suspensions (HLTS, HSTS)**
  - First ~100 cantilevered spring blades delivered & tested
  - All HSTS machined parts delivered – clean, bake & assembly underway
  - ~50% HLTS machined parts received
  - Welded stainless steel structures being fabricated – delays in procurement & quality issues in fabrication
  - Tight schedule for short Michelson test at LLO

BS/FM Lower Assy

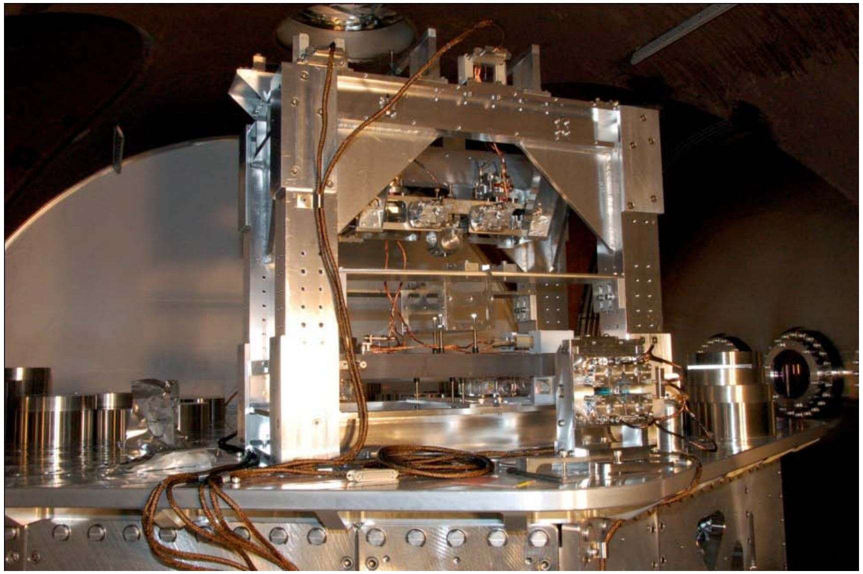
Blade Characterization



HSTS Upper Mass Subassembly

Suspension Subsystem (SUS): Output Mode Cleaner (OMC) Suspensions

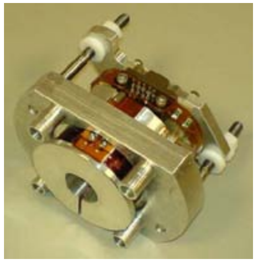
- **Successful implementation for Enhanced LIGO**
  - » Two units to be re-used
- **Parts for 3rd unit (except spring blades) are on hand**



Suspension Subsystem (SUS): Sensor/Actuators & Electronics

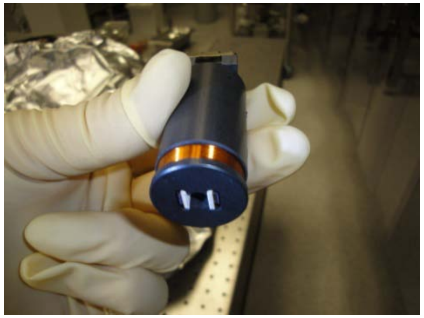
- **Optical Sensors & Eletro-Magnetic actuators (OSEMs)**
  - » All 670 BOSEMs received & tested (UK units)
  - » 350 of 400 AOSEMs received & tested (US units)
  - » Discovered need to plate SmCo magnets – just in time rework
- **Electronics**
  - » UK: Coil Drivers, Satellite Amplifiers, Electrostatic drivers -- all delivered & tested
  - » US: Anti-Aliasing & Anti-Imaging Filters, Binary I/O, Chasis, Racks, etc -- builds & testing underway, no schedule or technical concerns
  - » Cable materials, assembly, routing, & attachment all resolved

SUS Satellite Amplifier



SUS Filter Module

AOSEM



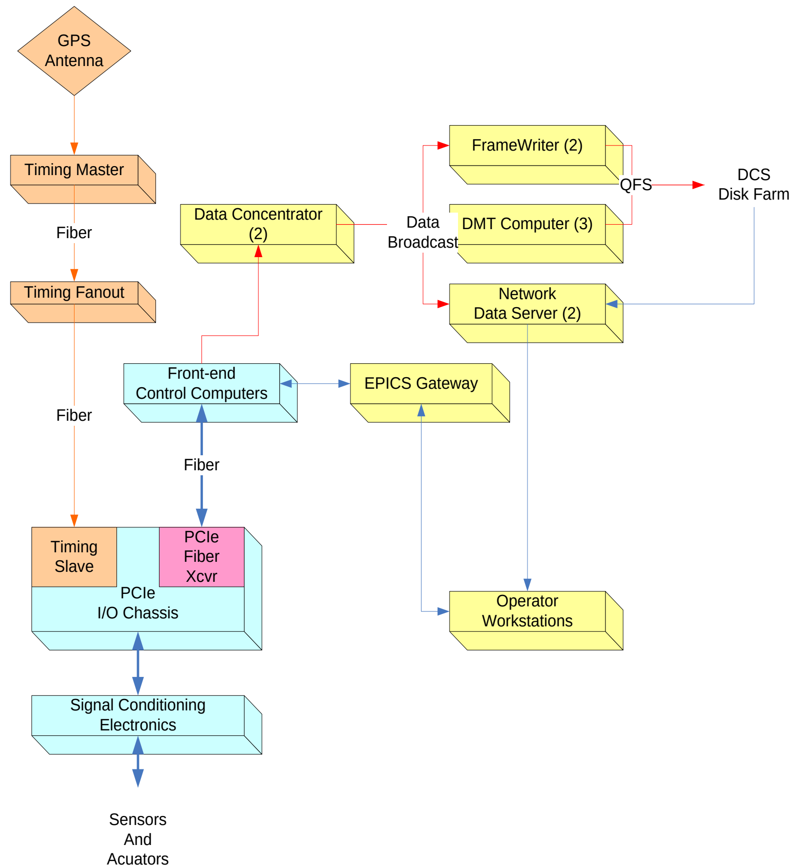
BOSEMs

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

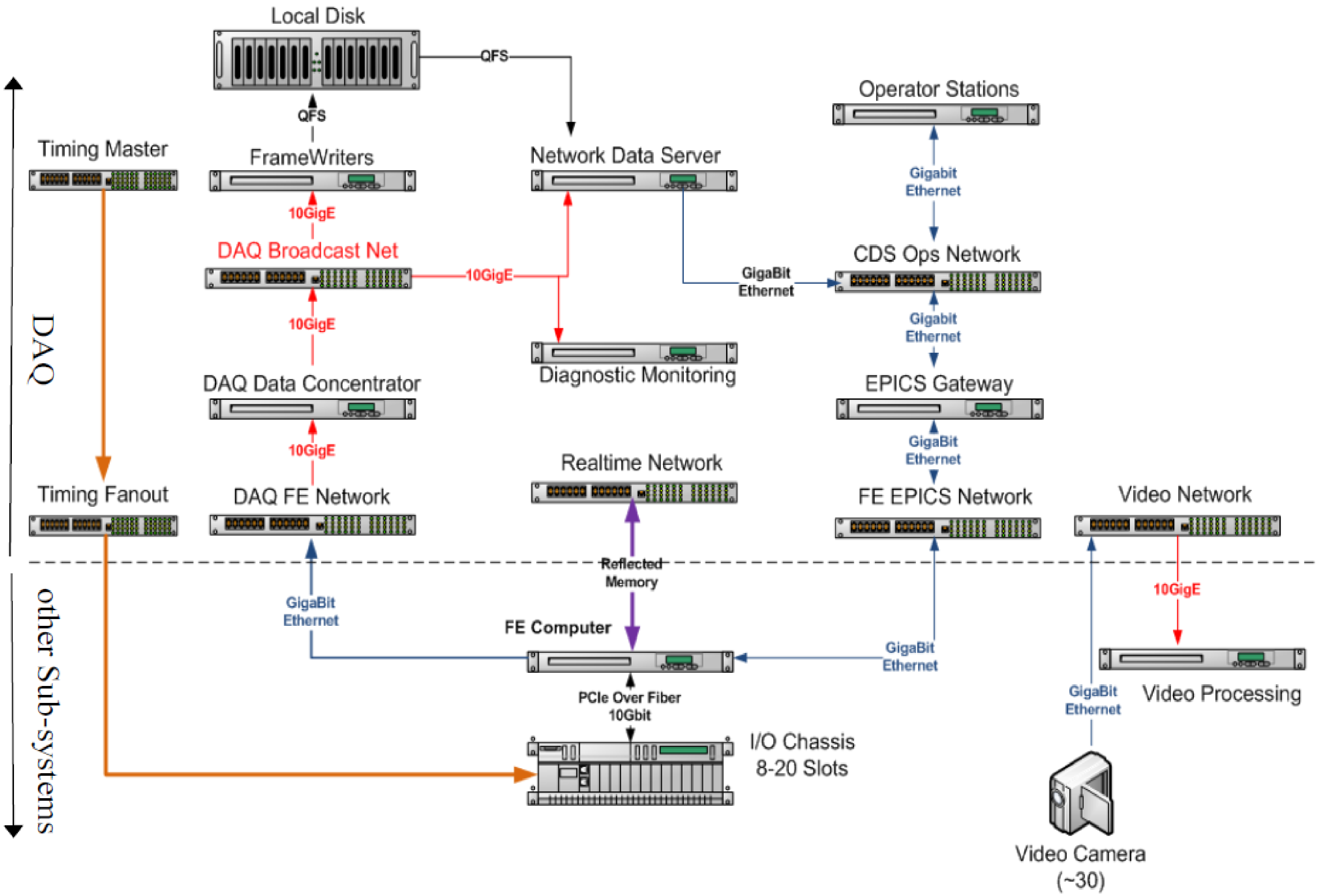
- **Timing System**
  - » GPS derived timing system for synchronizing all real-time systems and data acquisition
  - » Columbia University delivering parts under subcontract following joint design effort
- **Control & Data System (CDS) Infrastructure (Hardware & Software)**
  - » Data Acquisition System 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
  - » Mass Storage Systems
    - – Provide quick look-back data for commissioning & control room diagnostic functions
  - » Real-time application development tools & code library
  - » Test Stand at each Observatory
    - – Enables offline component and software testing
- **Diagnostics Monitoring and Test Tools**
  - » Control room network, computers & software toolset for operators
  - » Computers & software to perform real time and look-back diagnostics

DAQ System
Design Overview

- Timing system provides clocks to PCI Express (PCIe) modules in I/O chassis.
- PCIe modules interface to control computer via PCIe fiber link.
- Control computer acquires data and transmits to DAQ data concentrator (DC) via network.
- DC assembles data from all controllers and broadcasts full data blocks every 1/16 second.
- FrameWriter computers format data and write to disk (32sec. data frame)
- Network Data Server (NDS) provides data on demand either live or from disk.

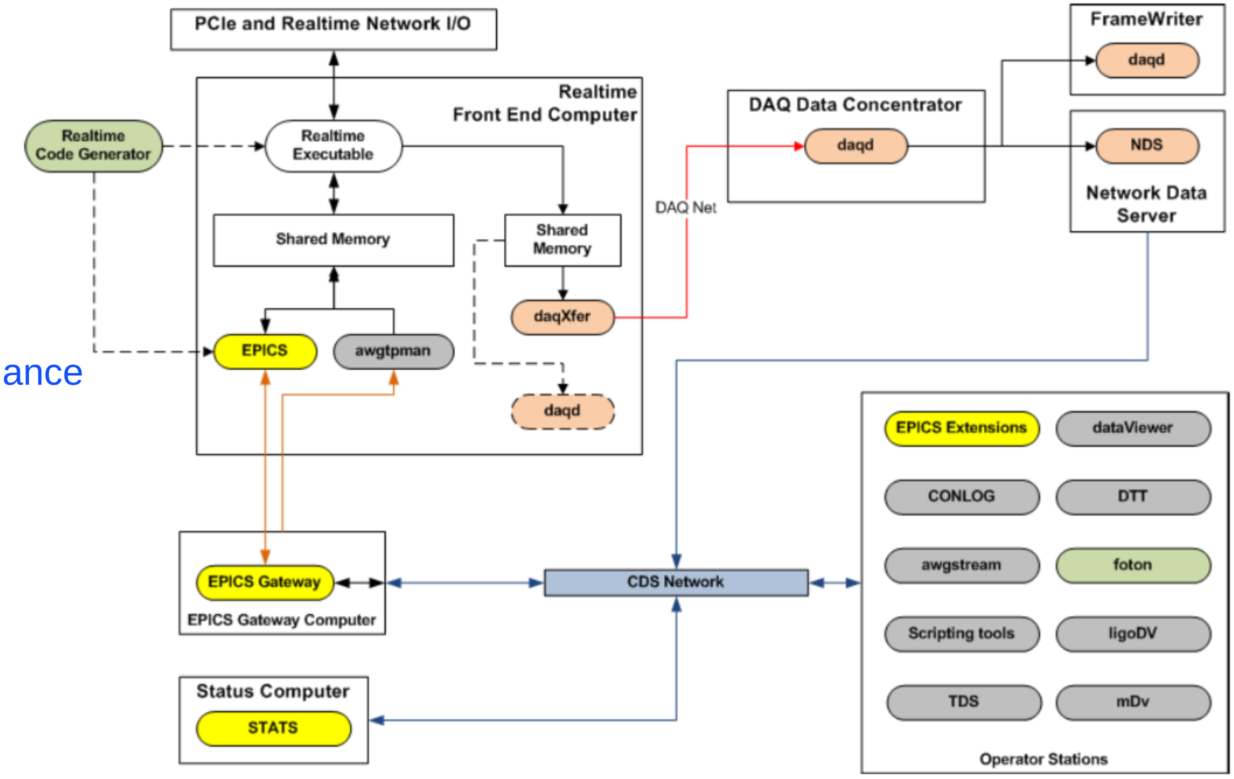


DAQ Scope -- Hardware



DAQ Scope -- Software

- **Real-time control and data acquisition**
  - » Application development tools
  - » I/O and network drivers
- **Collection, formatting and archival of DAQ data**
- **Control room operations**
  - » Operator displays
  - » Alarm managers
  - » Scripting tools
  - » Diagnostic test tools
- **Code Management**
  - » Archive repository
  - » Bug reporting and maintenance
  - » Code reviews



DAQ Status

- **Timing System**
  - » Delivered and installation to support H2 & L1 early testing complete
  - » Balance of production and installation on track for end of year completion
- **Computer, Networking and Mass Storage**
  - » L1 operational – currently supporting PSL testing
  - » H2 operational in temp location (until new H2 electronics bldg complete)
  - » H1 delivery May
- **Computers for operator stations & diagnostic applications**
  - » Being specified
  - » Will use existing systems for early interferometer testing
- **Physical Environment Monitoring Infrastructure**
  - » 50% of Anti-Aliasing chassis are built and tested
  - » LLO end station system under test
- **Software installed and meets specifications**
  - » Test and code documentation continues

Data Computing System

- **Data Archival**
  - 30 Mb/s raw data rate for 3 interferometers
    - 1.8 PB/year storage (3 copies)
  - Data stored on 3 disk copies
    - Complete set of data for all 3 interferometers stored at each of LHO, LLO and CIT
- **Data Distribution**
  - Existing LIGO WAN will handle AdL bandwidth
- **Computing**
  - Dominated by coalescing compact binaries
  - Based on S5 analysis
  - Scaled by Moore's law
  - Assumes 50% capacity provided by LSC centers

Data Computing System Status

- Enhanced LIGO (S6) offers useful experience:
  - » **Added 5,000 CPU-cores and 1.5PByte of disk storage**
  - » **Currently 16,000 CPU cores distributed in 9 clusters**
  - » **5 PB central data archive**
- Established new data center at MIT
- DCS is currently a planning package
  - » **Start project activities late 2013 and complete in early 2015**

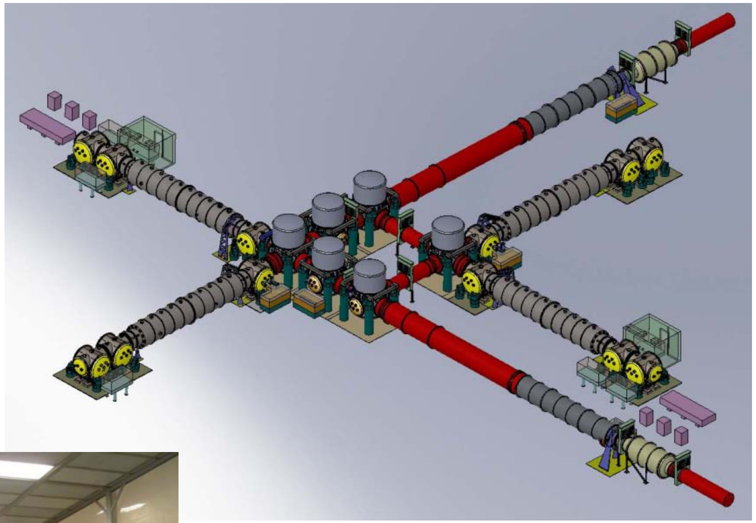
Facilities Modifications & Preparations (FMP)
Brief Description/Scope

- **Prepare for assembly:**
  - » 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, cleaning/baking
  - » Prepare an inventory control system and include staff to maintain inventory
  - » Purchase additional material handling equipment, optics lab supplies, clean room supplies, etc.
  - » Purchase supplies for wrapping, palletizing, storing assembled components
  - » Does not include assembly (subsystem WBS scope)
- **Design & Build Vacuum System Modifications**
  - » Convert 2 km at Hanford Observatory to 4 km
  - » Move HAM Chambers for Input Optics (IO) & Interferometer Sensing & Control (ISC) use
  - » Does not include installation (INS WBS scope)
- **Prepare for installation:**
  - » Purchase installation fixtures, clean room supplies, etc.
  - » Purchase supplies for wrapping, palletizing, staging
  - » Stage completed assemblies
  - » Plan the installation task
  - » Identify Government Equipment to be Scrapped or ‘Surplused’
  - » Does not include installation (INS WBS scope) or system/subsystem test/acceptance (PM/systems WBS scope)

Facilities Modification & Preparation (FMP): Status

- **Vacuum Equipment**
  - » Problems with testing to qualify cleanliness at required level – working with contractor to resolve
  - » First shipment of the Mid-Station spool (tube) to LHO ~5/1– enables conversion of H2 to a 4km interferometer
  - » Deliveries expected just in time

I/O Tube Rollups



Flange Sets

Mid-Station Spool

Facilities Modification & Preparation (FMP): Status

- **Clean and Bake for Ultra-High Vacuum (UHV) Service**
  - » Underestimated effort – hired more staff
  - » Procured additional vacuum bake ovens required to minimize downtime & meet throughput required
  - » Cleanliness certification (by FTIR testing)
- **Assembly preparation - completed**

Clean & Bake Lab (LHO)

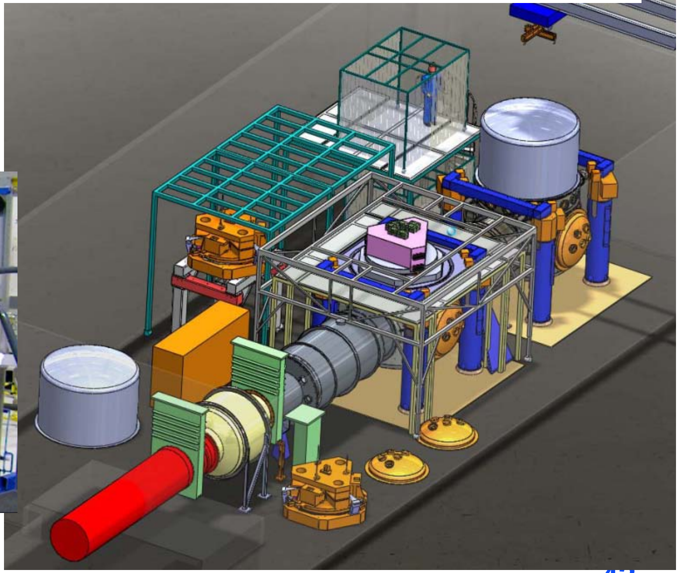
Vacuum Bake Oven

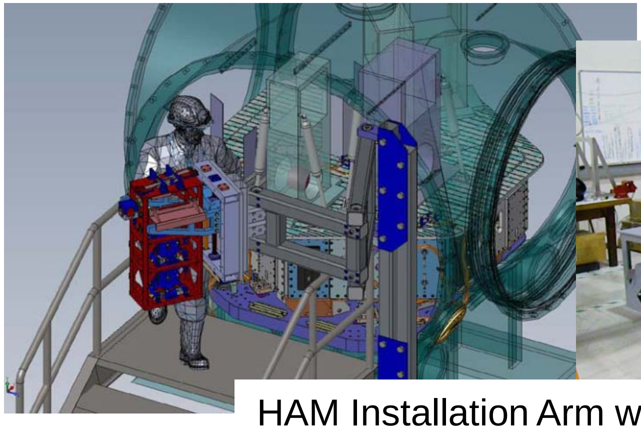
Facilities Modification & Preparation (FMP): Status

- **Installation preparation:**
  - HAM Installation arms: one complete, ready to ship to LLO, two more to ship in Sept
  - BSC Installation arms: one unit at LHO, two more to ship in June
  - 5-axis table & vertical lift: one unit at LHO, two units in testing & will ship soon
  - BSC Installation cleanrooms – shipped to observatories
  - Cartridge Installation Test Stand – first unit to ship ~4/24
  - Work Platforms – design & build contract underway
  - H2 Electronics Building – completion 5/5
  - Remaining work: HVAC for H2, H1 electronics racks & Laser diode chillers

5-axis Table on Lift Cart

Install Cleanroom, Work Platform, Cartridge Test Stand (LHO Y-end)





HAM Installation Arm with HSTS Structure

Systems Engineering (SYS): Layouts, interfaces, etc.

- **Review/approve**
  - Significant Technical Revisions (through the TRB)
  - Subsystem acceptance test plans & test reports
  - Standards/specifications (welding, machining, cleaning, EMI/EMC etc.)
  - Vacuum Qualification of Materials
- **Contamination Control**
- **Maintain technical configuration management**
  - Optical layout
  - Integrated layout drawings
  - Optical table mass budgets
- **Maintain Interface Control**
- **Modeling/Simulation**
- **Define integrated test plans & procedures**

DRAWING COMPLETION STATUS		
	Apr-11	
Subsystem	#	%
AOS	1430	54%
AOS/IAS	27	73%
AOS/OptLev	88	85%
AOS/Pcal	20	0%
AOS/SLC	349	82%
AOS/TCS	632	23%
AOS/TMS	314	80%
COC	95	99%
DAQ	53	59%
FMP	675	85%
IO	193	81%
ISC	106	70%
PSL	561	81%
SEI	744	100%
SUS	1396	98%
SYS	234	76%
	5487	81%

LIGO

Chamber Cleaning

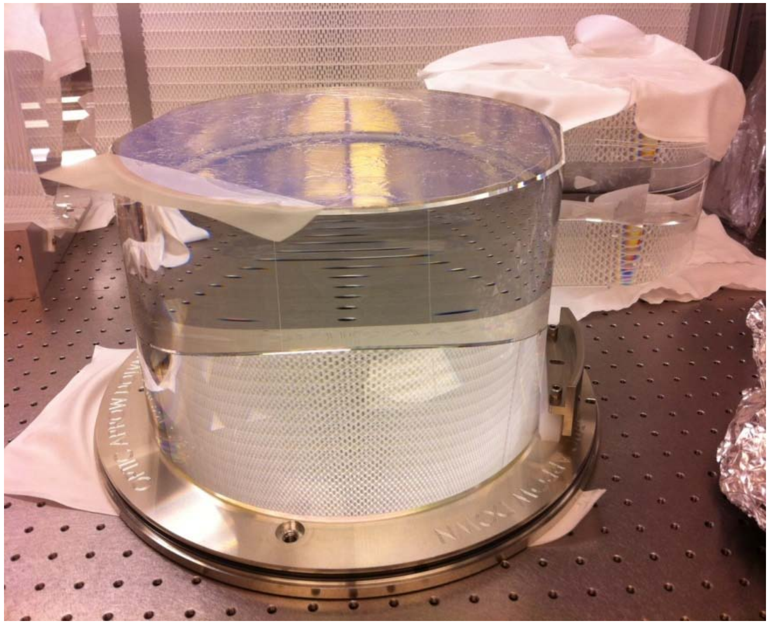

Wire Brush Rotary Tool
(in HAM12)

- **Developed tooling & procedure for removing oxide layer from interior of chambers**
  - Three entries into WHAM12 chamber in Dec and Jan
  - Developed clean rotary air tool with HEPA suction
  - Developed logistics, procedures, surface sampling method/tooling
  - Air particulate count undetectable
  - Surface Non-Volatile Residue (NVR) meets requirements
  - Surface particulate count, after isopropanol wipe, meets requirements
  - Method is successful – proceeding to WHAM11 this week
- **Inadvertent contamination of WHAM12**
  - Accidently used the wrong compressor during a WHAM12 chamber cleaning test (not oil free)
  - FTIR sample measurement of surface indicates higher than acceptable NVR level
  - Chamber was disconnected from other chambers
  - Several options for cleanup & re-bake being discussed

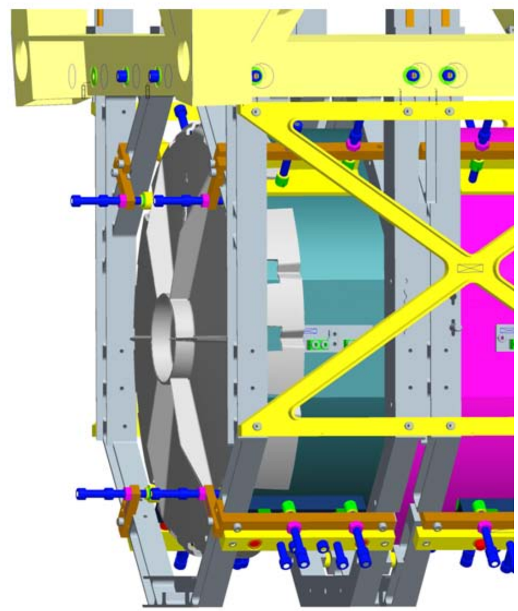

Oxide Layer
Removed
(HAM12)


Surface
Sampling

Optic Protection and Final Cleaning



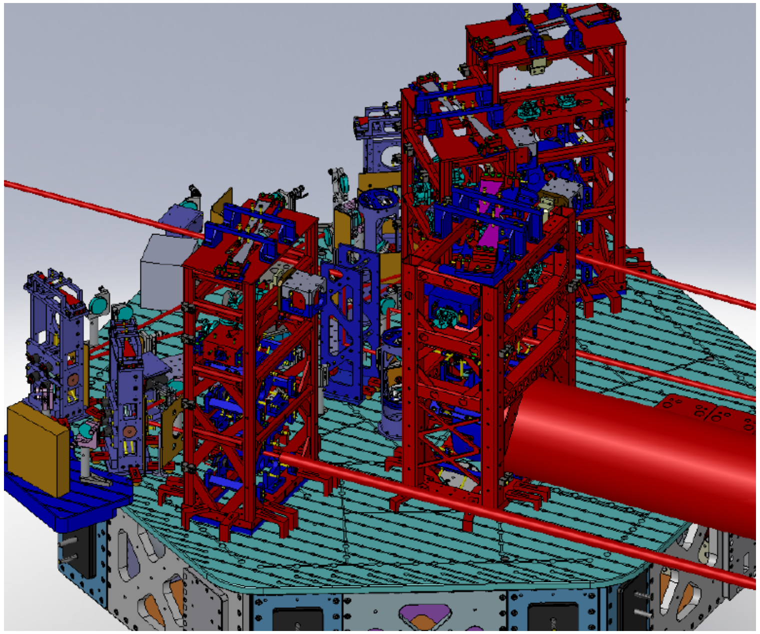
- **First contact on test mass for single arm test.**
  - » PEEK mesh on the edge for a cleanroom compatible way of removing the dry film.



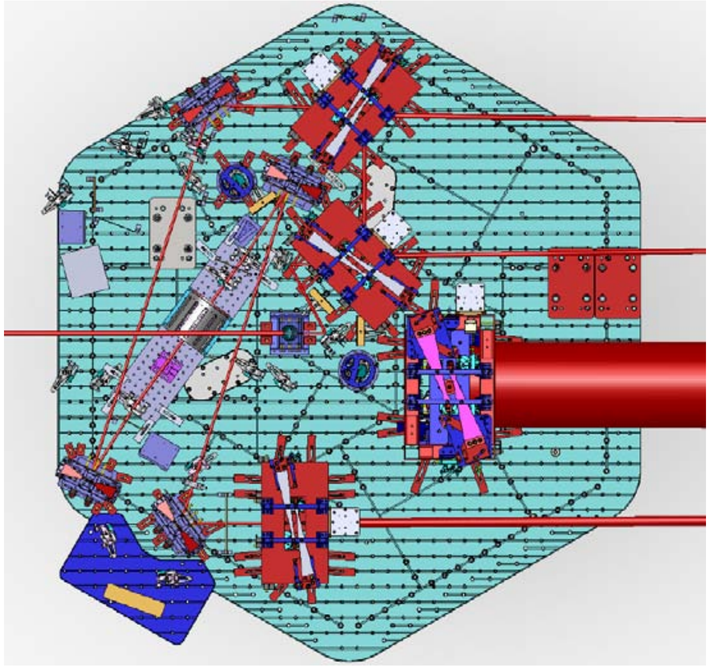
- Procuring optics caps molded in PETG GN007
  - » to provide further protection during assembly & installation

Advanced LIGO Integrated Layouts

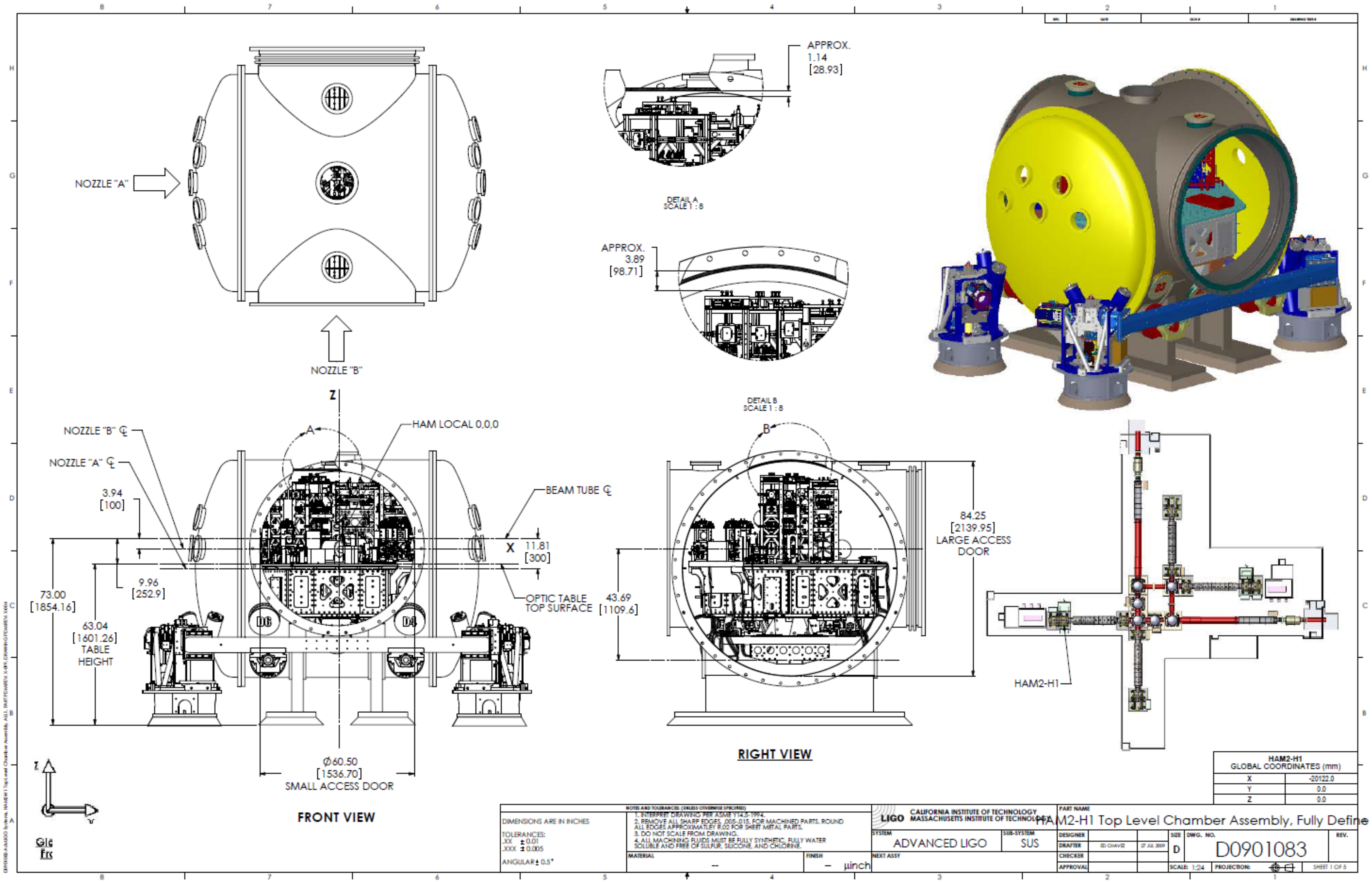
- **Integrated layouts are defined in drawings**
  - » Document Control Center (DCC)
  - » Solid models/drawing repository (PDMWorks vault)
  - » Mirrored to all sites for easy/quick access
  - » Linked in hierarchical order (drawing tree) within the DCC



HAM2 is the most crowded chamber and among the first to be installed. Includes SUS, IO, AOS, IO and ISC elements

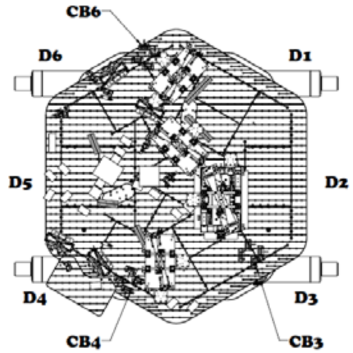


Integrated layouts – chamber by chamber

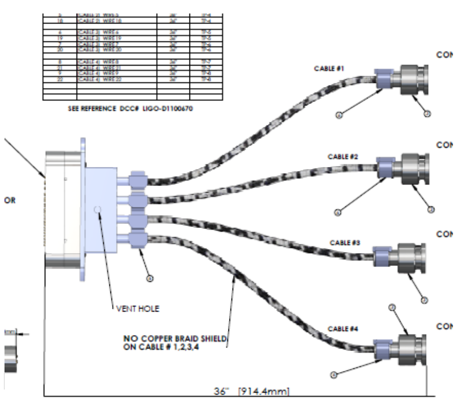


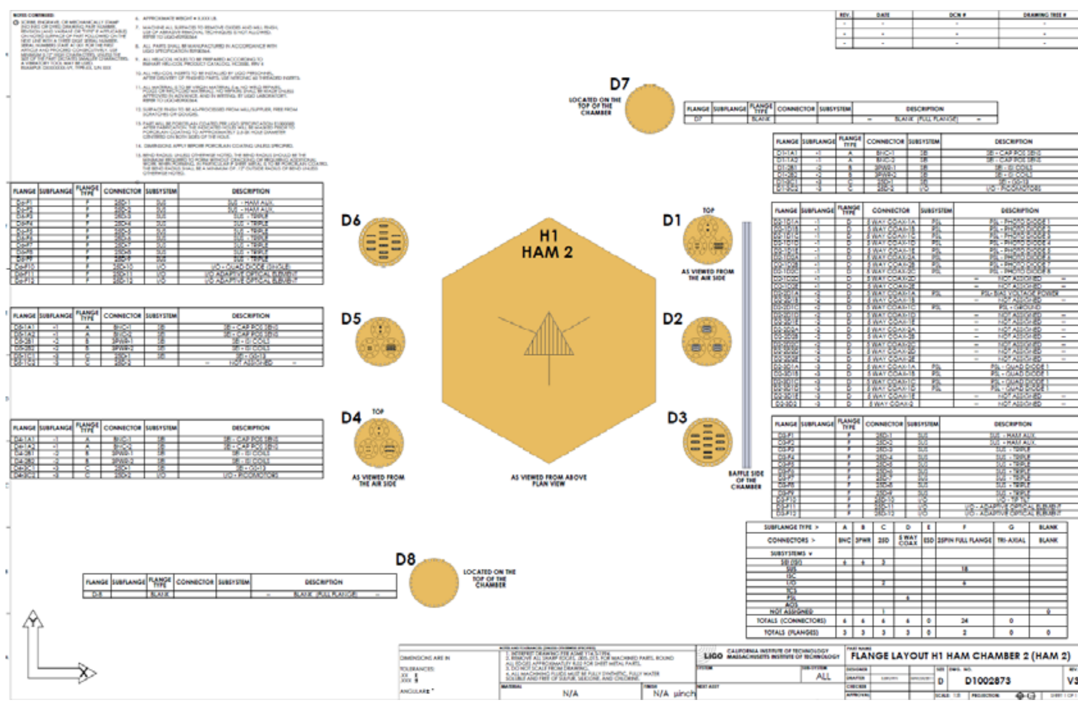
Cabling integration

- Defined cable routing based on detailed chamber layouts



FLANGE TO CABLE BRACKET CLUSTER							
FLANGE	CBL BRKT CLUSTER DESIGNATION	"L" FLANGE TO SERVICE LOOP	"L" TO SERVICE LOOP	SERVICE LOOP TO CB3	SERVICE LOOP TO CB4	SERVICE LOOP TO CB6	MAX CABLE LENGTH
D1	-	-	-	-	-	-	?
D2	-	-	-	-	-	-	?
D3	CB3	24	72	12			108
D3	CB4	24	72	-	72		168
D4	-	-	-	-	-	-	?
D5	-	-	-	-	-	-	?
D6	CB6	24	72	-	-	12	108
D6	CB4	24	72	-	72		168
D7	-	-	-	-	-	-	?
D8	-	-	-	-	-	-	?





Mass Budget and balancing

HAM2-H1								
	Suspended		Inc/Dec			Non-Sus		Inc/Dec
	Full	Simple				Full	Simple	
	Kg	Kg	Kg			Kg	Kg	Kg
PR3 (HLTS)	93.03	93.61	-0.58			57.51	57.04	0.47
MC1 (HSTS)	61.20	66.37	-5.17			52.17	59.35	-7.18
MC3 (HSTS)	61.20	66.37	-5.17			52.17	59.35	-7.18
PRM (HSTS)	61.20	66.37	-5.17			52.17	59.35	-7.18
4X SOS	24.00	35.58	-11.58			24.00	35.58	-11.58
2X VibAbs PR3	6.00	6.00	0.00			6.00	6.00	0.00
2X VibAbs MC1	5.92	5.92	0.00			5.92	6.00	-0.08
2X VibAbs MC3	5.92	6.08	-0.16			5.92	6.00	-0.08
2X VibAbs PRM	5.92	6.08	-0.16			5.92	6.00	-0.08
Spacer PR3	0.00	0	0.00			0.00	0	0.00
Spacer MC1	8.47	2.56	5.91			8.47	2.56	5.91
Spacer MC3	8.47	2.56	5.91			8.47	2.56	5.91
Spacer PRM	8.93	4.54	4.39			8.93	4.54	4.39
Dog Clamp PR3	3.50	5.27	-1.77			3.50	5.14	-1.64
Dog Clamp MC1	3.88	6.17	-2.29			3.88	4.03	-0.15
Dog Clamp MC3	4.93	6.17	-1.24			4.93	4.03	0.90
Dog Clamp PRM	4.19	6.17	-1.98			4.19	4.03	0.16
Dog Clamp 4XSOS	2.08					2.08		
6X Baffles	1.04	9.76	-8.72			1.04	9.76	-8.72
MC3 AR Baffle	0.15					0.15		
PRM AR Baffle	0.36					0.36		
3X Gost Beam Baffle	1.29					1.29		
4X SOS Baffles	1.68					1.68		
Faraday I.	7.49	24.85	-17.36			7.49	24.85	-17.36
Dog Clamp FI	0.82					0.82		
Periscope	2.67	10.55	-7.88			2.67	10.55	-7.88
DLC mounts	8.63	28.31	-19.68			8.63	28.31	-19.68
Cabling		27.21						
Cabling Brackets	4.62	3.57				4.62		
Diving Board	22.32	8.374				22.32	8.374	
2X Refl Periscope	3.51	8.374				3.51	8.374	
Parking BD Baffle	1.06					1.06		
3X Refl Beam D.	6.28	8.374				6.28	8.374	
Counterbalance Mass	206.16	135.26	70.90			206.16	135.26	70.90
ISO Table (2)	1338.75	1338.21				1338.75	1338.21	
(3)								
Sub-TOTAL	636.92	650.45	-1.79			574.31	555.41	-0.15
TOTAL (1)	1975.67	1988.66	-12.99			1913.06	1893.62	19.44
Table Mass Total	545.88	559.40	-13.53			483.27	464.37	18.90

Sub-TOTAL	Sum of all items on table (including Keel Mass)	(B5:B29)(C5:C29)(G5:G29)(H5:H29)
TOTAL	Sum of "Sub-TOTAL + HAM Table"	(B30+B32)(C30+C32)(G30+G32)(H30+H32)

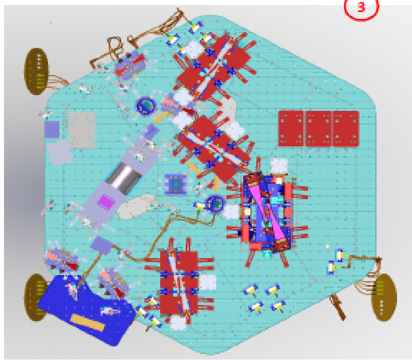
Table Mass Total	Sum of all items on table (excluding Keel Mass)	(B32-P6)(C32-P4)(G32-P7)(H32-P5)

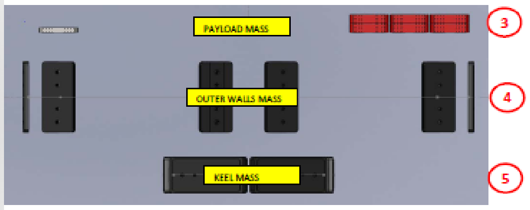
(1) As per DCC # E1100006 (Pg 7) this is TOTAL MASS ON STAGE 0-1 SPRINGS = 1973 Kg

(2) As per DCC # E1100006 (Pg 7) this is STAGE 1 HAM-ISI SUSPENDED MASS = 1337

(3) As per DCC # E1100006 (Pg 7) this is LEFT FOR "OPTICS + TRIM MASSES" = 636 KG

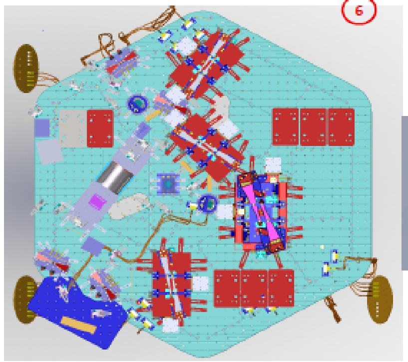
HAM2-H1										
		Table Mass Total	Payload Mass	Outer Wall Mass	Keel Mass	X = 0 ± 10 mm	Y = 0 ± 10 mm	Z = 217.42 ± 100 mm	"Z" Target (-8.56 in)	Counter balance
		Kg	Kg	Kg	Kg	mm	mm	mm	-4.62 ≤ Z ≤ -12.50	Kg
Simple	CG XY-Calc (SUS Mass)	559.40	0	44.213	91.047	-2.47	2.69	-149.87		135.260
	CG Z-Calc (Non-Sus Mass)	464.37	0	44.213	91.047	-8.75	4.62	-167.61	-6.599	135.260
Full	CG XY-Calc (SUS Mass)	545.88	55.341	59.774	91.047	4.50	4.33	-158.57		206.162
	CG Z-Calc (Non-Sus Mass)	483.27	55.341	59.774	91.047	-1.05	4.78	-177.19	-6.976	206.162
			(3)	(4)	(5)					

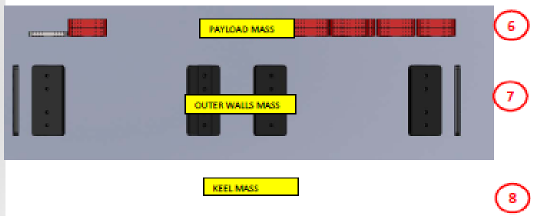




When using nominal Keel Mass (Pg 8 DCC E1100006) = 90 Kg, CG-Z is -6.976" (1.584" FROM TARGET)

Full	CG XY-Calc (SUS Mass)		145.964	59.774	0	7.27	-8.45	-128.36		205.738
	CG Z-Calc (Non-Sus Mass)		145.964	59.774	0	1.81	-8.41	-145.99	-5.748	205.738
			(6)	(7)	(8)					





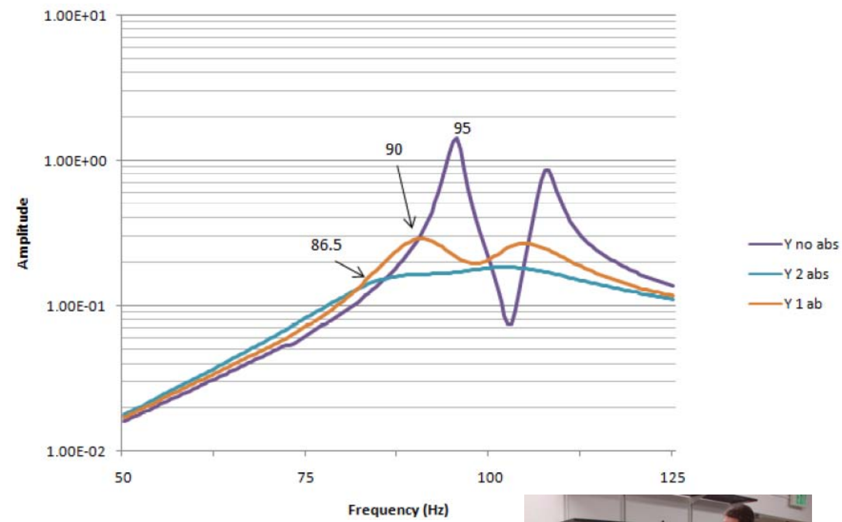
When using Zero Keel Mass, CG-Z is -5.748" (2.812" FROM TARGET)

Systems Interface Summits

- **Hosted a series of interface summits**
  - » Remind/review key interfaces
  - » Decision point for any remaining open technical questions
  - » Transmisison Monitor Suspension (TMS) with Interferometer Sensing & Control (ISC)
  - » Input Optics (IO)
  - » Fold Mirror / Beam Splitter Suspensions (SUS)
- **Several more planned in the coming weeks**
  - » Test Mass Quadruple Pendulum Suspension (SUS)
  - » ETM / ITM (SUS)
  - » SEI table balance and mass budget – final call
  - » Integrated Layout of WSC6 and WBSC8
  - » Integrated Layout of LHAM2 and HAM3L
- **Leading an Assembly Review of the Test Mass Quadruple Suspension**
  - » Team drawn from SYS, SUS, SEI, FMP and QA/Manufacturing Eng.

Suspension Frame Passive Damping

- **BS/FM Suspension**
  - » SYS, SUS and SEI working on stiffening strut details (intrinsic part of the design)
- **Vibration Damper**
  - » Finalized location, number & parameters of vibration dampers
  - » Production units delivered (in clean & bake queue)



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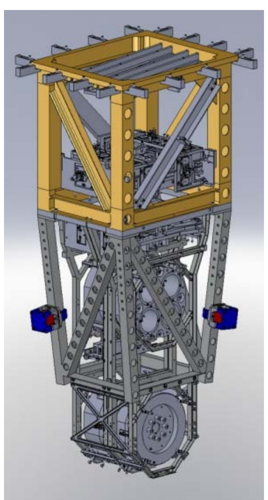

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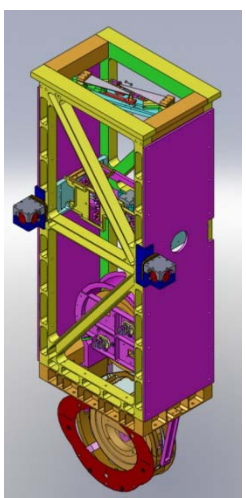

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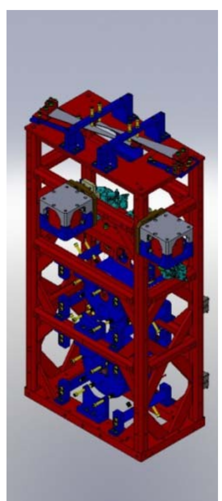

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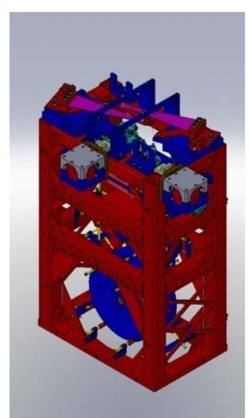

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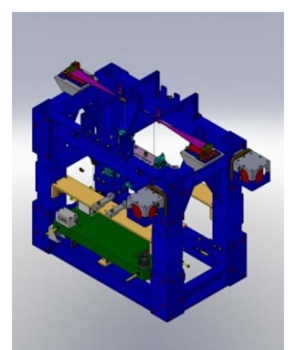
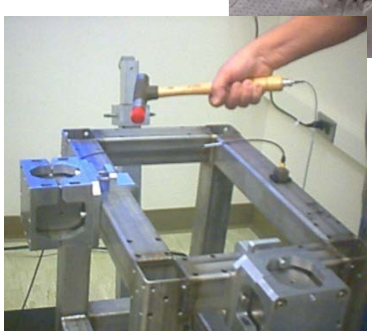


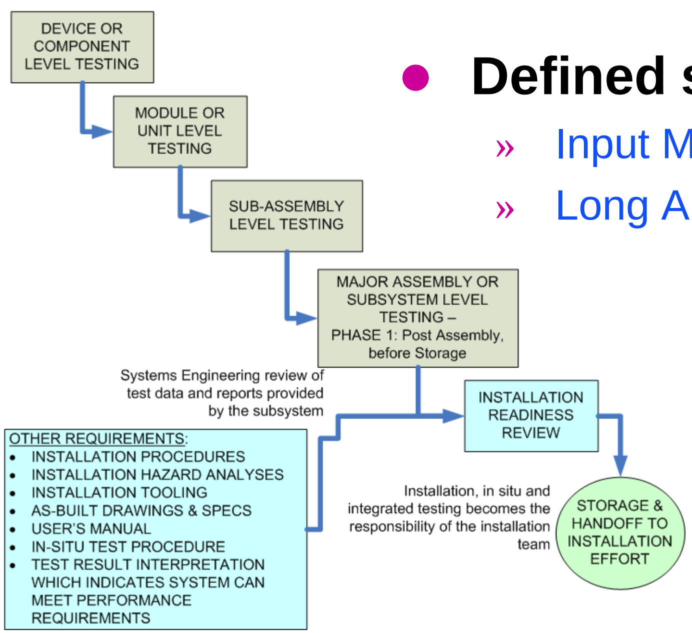
Modal Testing

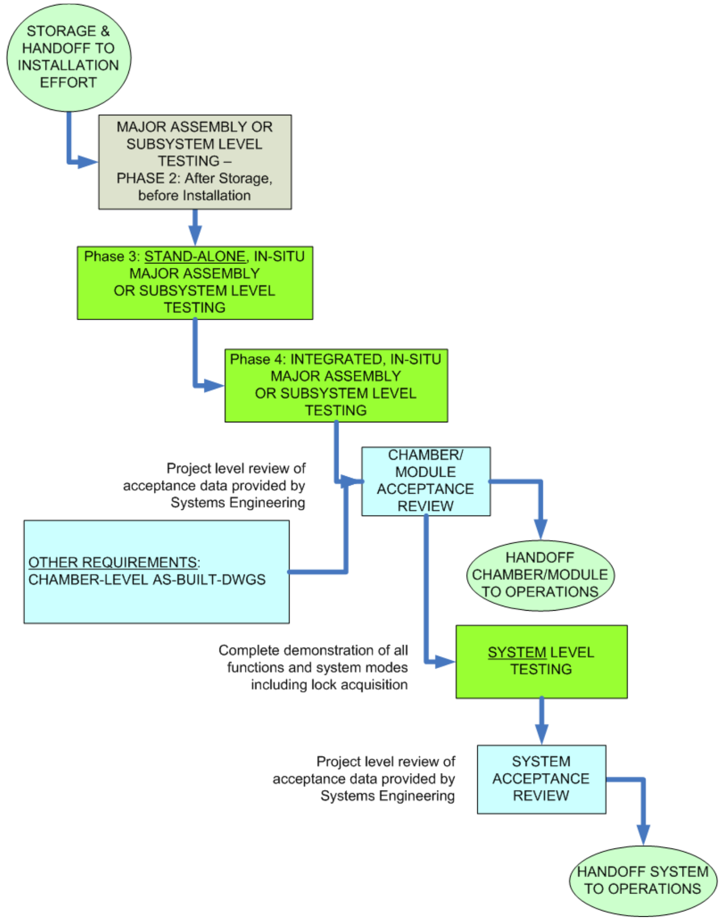


Sub-system and System Testing

- **Defined requirements for Subsystem and System level testing**
  - » Documentation
  - » Review
  - » Data archival
  - » Acceptance criteria

- **Defined system test plans**
  - » Input Mode Cleaner
  - » Long Arm Cavity





Summary

- **Development (essentially) completed for all subsystems except TCS & PCal**
- **Yet to Resolve:**
  - » Continuing R&D (lower loss PZT & bond) on Acoustic Mode Damper (possible retrofit)
  - » ETM-ERM squeezed film damping – final approach to be taken when force required for lock acquisition is established
- **Fabrication issues**
  - » TCS Laser contractor failed – restarting procurement
  - » Corning material warps under annealing – replacing with Heraeus material (FMs and ETMs)
  - » Test mass coating 2 x wavefront distortion spec – contractor pursuing techniques to improve
    - – Installing temporary ITM & ETM in H2 Y-arm
  - » Challenging particulate cleanliness requirements
- **Tight schedules**
  - » Vacuum equipment near critical path
  - » BSC-SEI units for LHO Y-arm test
  - » HAM chamber triple suspensions (HSTS, HLTS) for LLO near Michelson test
  - » SLC baffles
- **No significant technical issues**
- **Assembly & Testing generally proceeding well**