Technical Status of Advanced LIGO

PAC #24 Meeting

24-25 June 2008

LIGO Hanford Observatory

Peter Fritschel, Dennis Coyne

Outline

- Technical Overview of Advanced LIGO
- Technical Status of Subsystems
  - 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)
  - Seismic Isolation (SEI)
  - Suspensions (SUS)
  - Facility Modifications & Preparation (FMP)

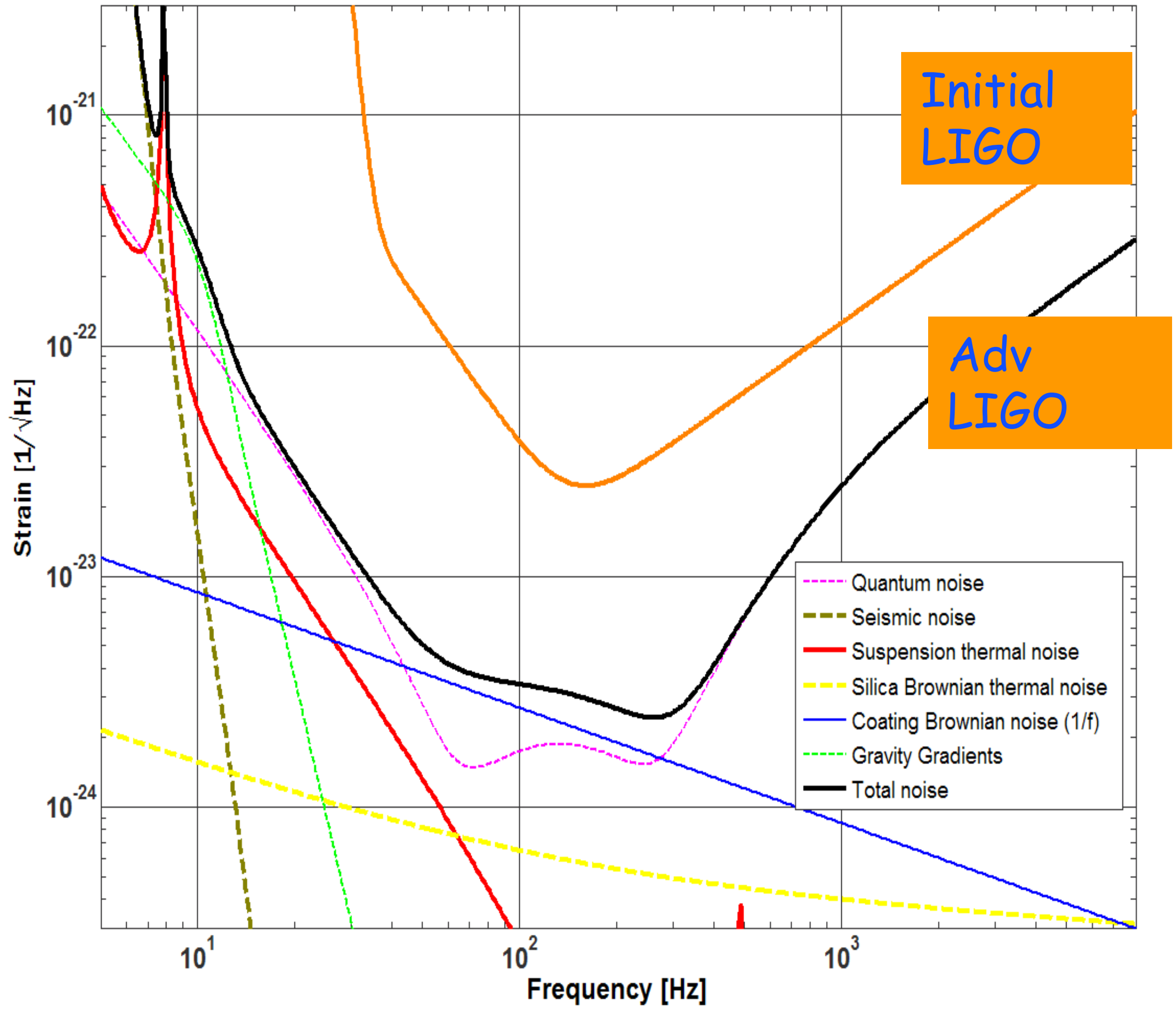
  Note: no activity in this period on Installation (INS) or Data Computing System (DCS)
- Development Status Summary

Comparison of Initial and Advanced LIGO Parameters

Parameter	Initial LIGO	Adv. LIGO
Equivalent strain noise, minimum	3×10^{-23}/rtHz	2×10^{-24}/rtHz
Neutron star binary inspiral range	15 Mpc	175 Mpc
Omega GW	3×10^{-6}	$1.5\text{-}5\times10^{-9}$
Interferometer configuration	Power-recycled MI w/ FP arm cavities	LIGO I, plus signal recycling
Laser Power in Arm Cavities	15 kW	800 kW
Test masses	Fused silica, 10 kg	Fused Silica, 40 kg
Seismic wall frequency	40 Hz	10 Hz
Beam size	4 cm	6 cm
Test mass Q	Few million	200 million
Suspension fiber Q	Few thousand	~30 million

Scope (as in June 2006)

- Replace virtually all initial LIGO detector components
- Three interferometers
  - All 4km in length
  - For initial LIGO, one is 2km
  - Tunable for narrow-band operation.



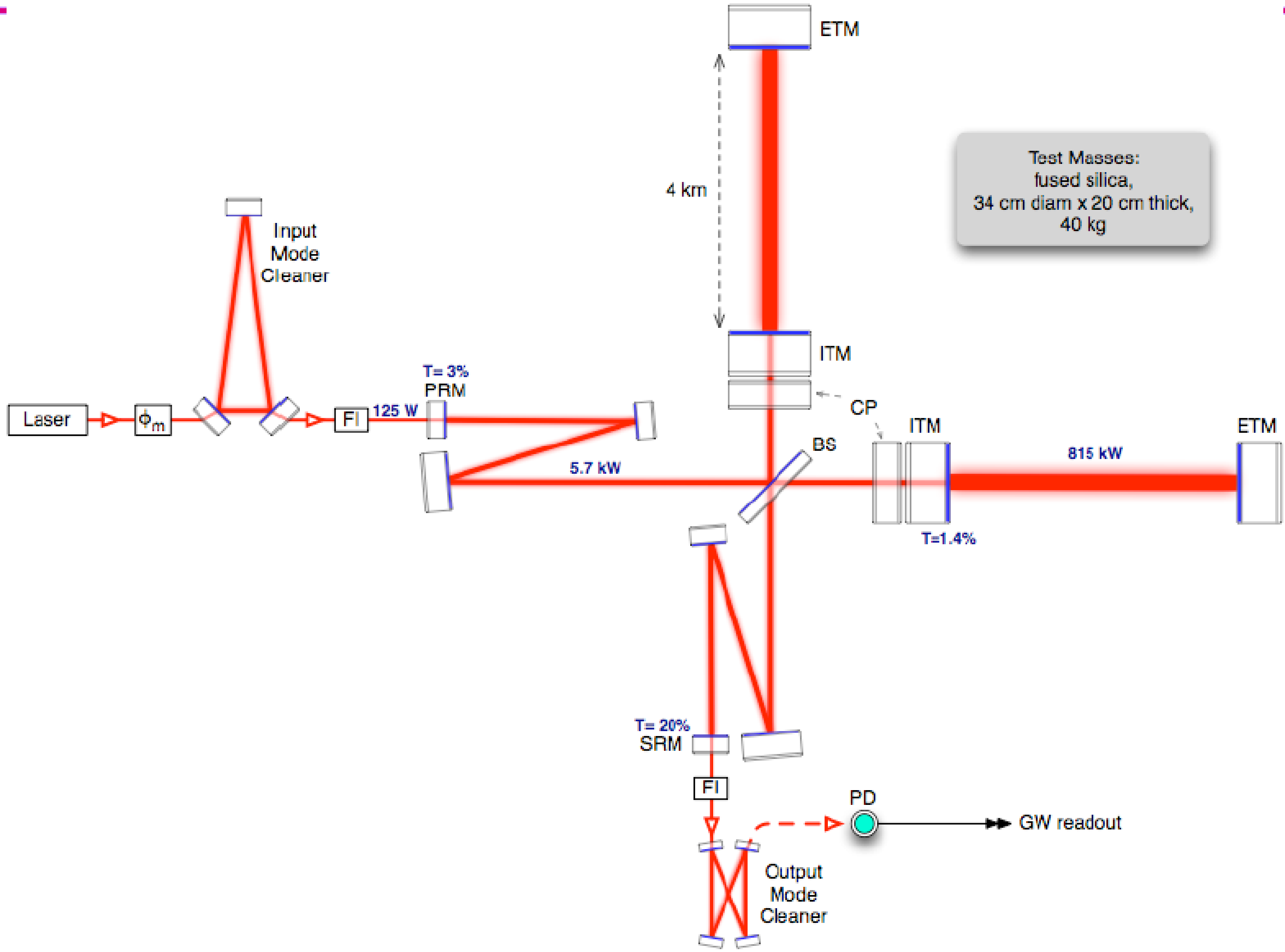
Systems Engineering (SYS)

- Progress since Dec-2007:
  - » Selected Stable Recycling Cavities (power and signal cavities)
    - – TRB report in preparation
    - – CCB change request also in preparation
  - » Formed Technical Review Boards (TRBs) for
    - – Arm Length Stabilization – to decide on which approach to use to assist with arm length lock acquisition
    - – Gold Barrel Coatings – to decide if thermal shields for the thermal compensation system should be adopted for the Compensation Plates and the Input Test Masses
  - » Held a Preliminary Design Review (committee report pending)
  - » Developed a Final Design phase plan
  - » Continued work on understanding Parametric Instabilities and methods to suppress
  - » Optomechanical Layout:
    - – Developed a simpler (small optical wedge angle) layout design
    - – Simplifies AOS baffle/beam dump components
    - – Eliminates the need for a modified LOS suspension
    - – Layout details are being independently checked before adopting

Systems Engineering (SYS)

- Progress since Dec-2007 (continued):
  - Dielectric Coating Optimized Design (non-λ/4 layer thicknesses):
    - Thermal noise formulation correction (Matt Evans) reduces the benefit of optimization
    - Final decision pending
  - Electro-static Charge Mitigation:
    - Electro-static charge working group are formulating/revising a research plan (summer 2008)
    - Most charging scenarios are not problematic for Adv. LIGO
    - Will evaluate interface implications of charge mitigation approaches in order to accommodate in case necessary
  - Particulate Cleanliness:
    - Good start on setting requirements and defining a practical design approach for processes, environment and equipment.
    - Most of the effort for implementing any special requirements will likely fall to the FMP group

System Design



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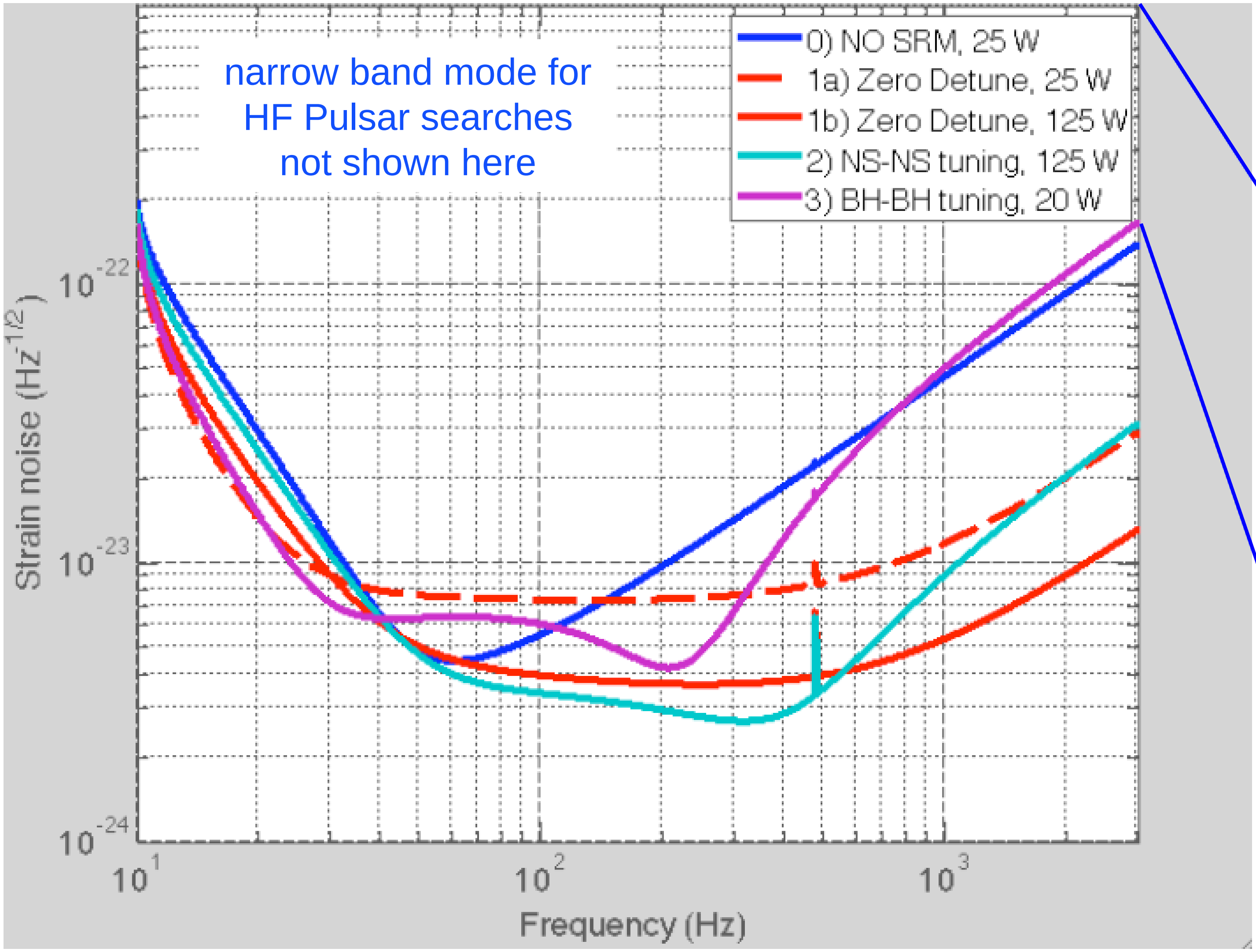
Interferometer configuration

- Arm cavity finesse reduced from 1200 to 450
  - » Originally chosen to be high to reduce absorbed power in the substrates of the vertex optics (input test masses, beamsplitter, compensation plates)
  - » Ultra-low absorption glass from Heraeus makes that problem moot
  - » Lower arm finesse better for:
    - – Lock acquisition
    - – Sensitivity to loss in the signal recycling cavity
    - – Coupling of noise in the signal recycling cavity
  - » Higher arm finesse better for:
    - – Coupling of Michelson noise

Modes of Operation



BNS range:

147 Mpc

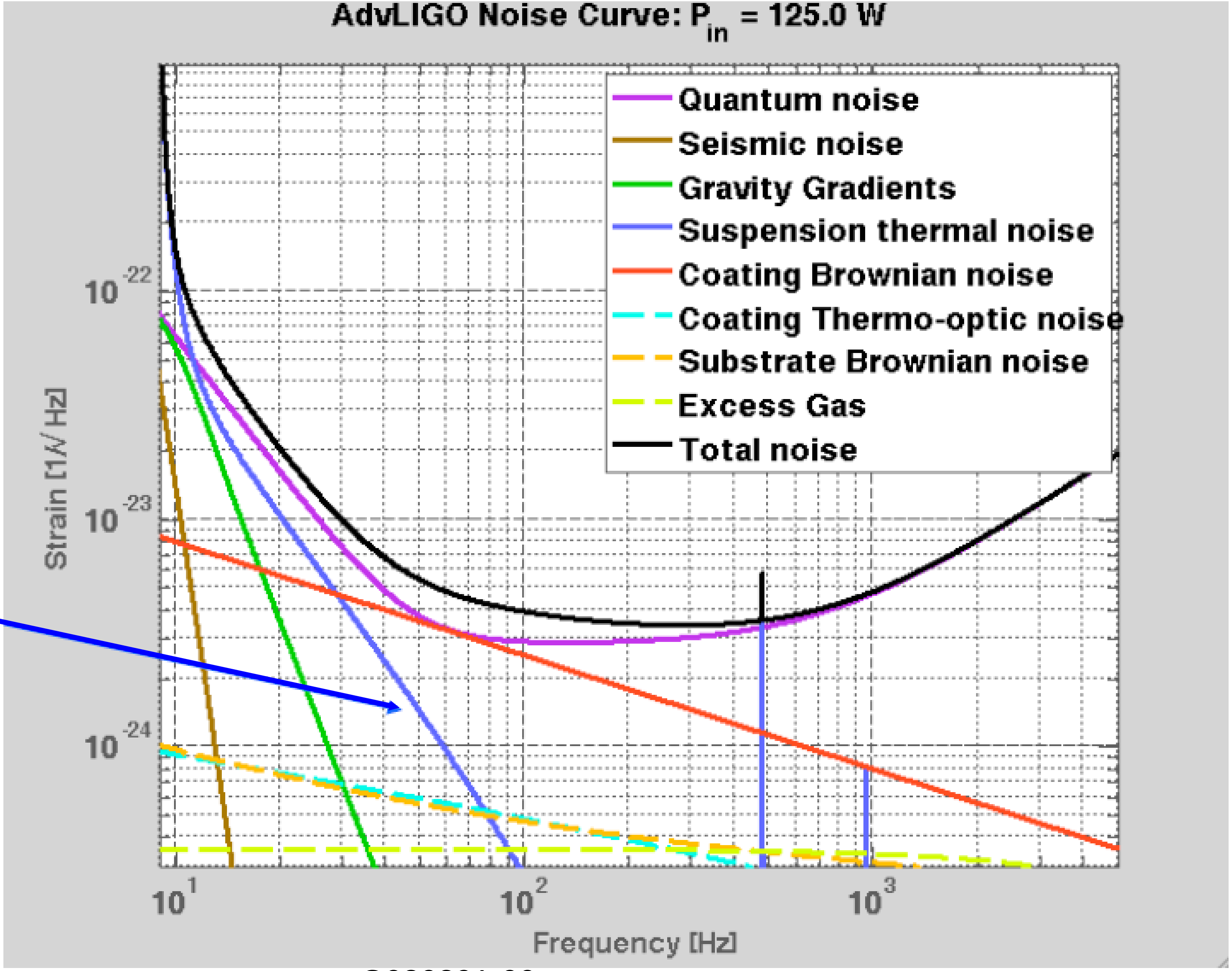
135 Mpc

184 Mpc

198 Mpc

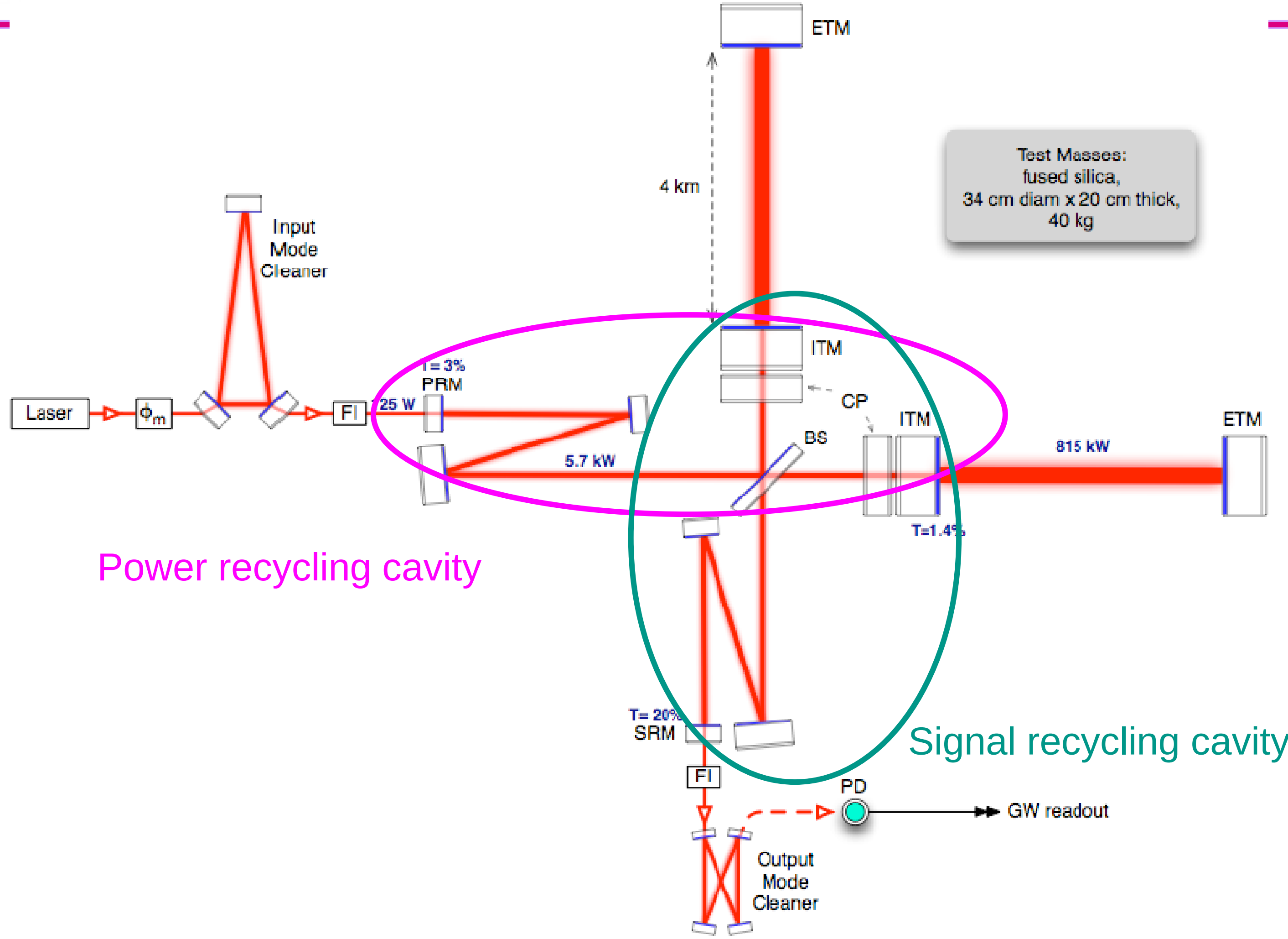
160 Mpc

Interferometer Noise Budget: broadband operation



Suspension thermal noise is reduced by factor of 2-3 with change in fiber geometry

Configuration: stable recycling cavities

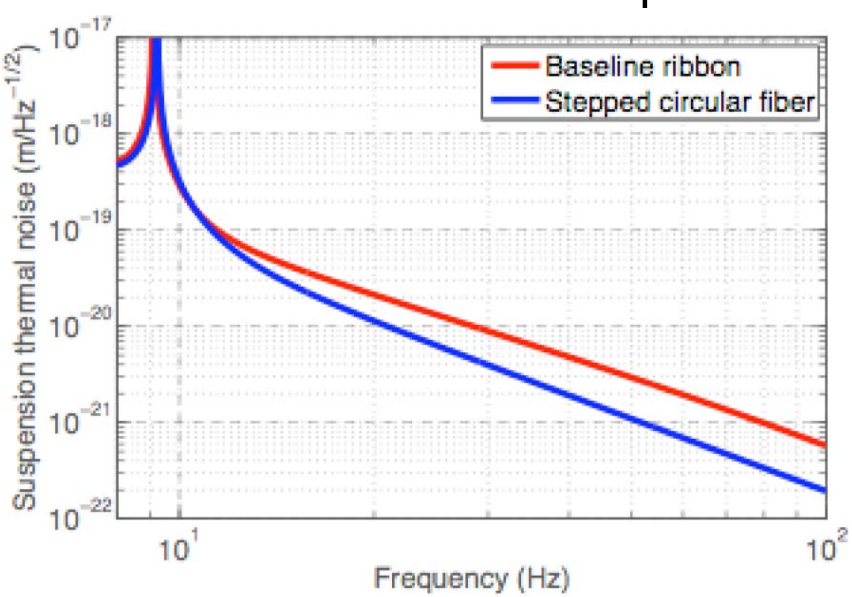


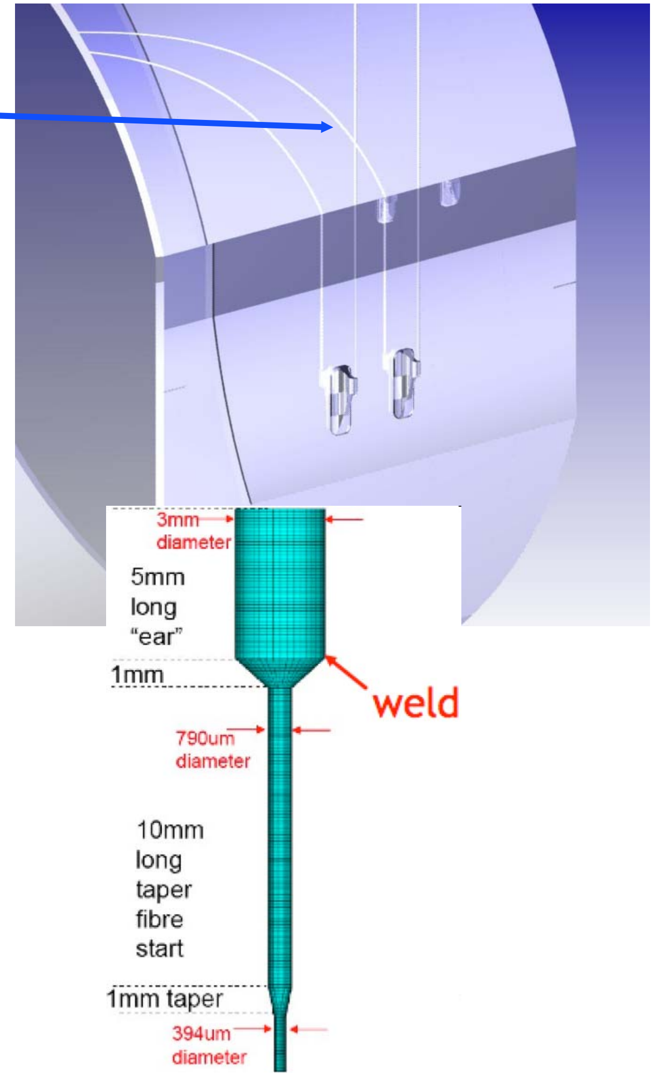
Stable recycling cavities

- Advantages
  - Better for GW sideband field buildup: greater tolerance to optical distortions
  - Better for RF sideband field buildup
  - Optical layout advantages for handling pick-off and ghost beams
  - Easier to change the signal recycling mirror
- Disadvantages
  - Some alignment signals are reduced in amplitude
  - More triple suspensions
  - Tighter tolerances on the telescope radii of curvature
  - More path length noise in the signal recycling cavity

Test Mass suspension fibers: change of geometry

- Glass fibers support the test mass from the penultimate mass
- Old baseline design used a 'ribbon' fiber geometry (10:1 aspect ratio)
- Turns out a circular fiber with a variable diameter gives lower noise, and is easier to make and weld to the suspension



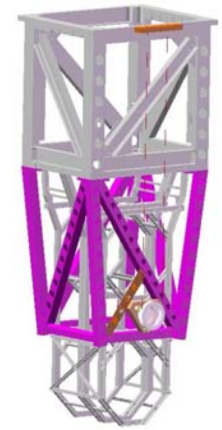


Arm Length Stabilization system

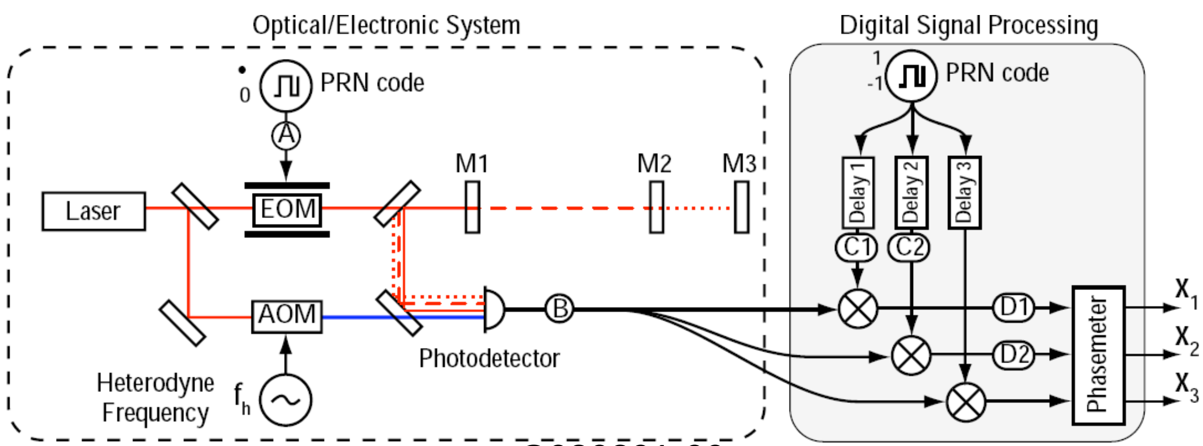
- We want a controlled process for interferometer lock acquisition
- Implement a 'bootstrap' sensing/control system for the arm cavities
  - » Set to the arm cavities at a known length, typically ~10 nm away from the carrier resonance, with a residual deviation of ~1 nm
  - » We've developed a sequence that starts at that point, and brings all cavities to the operating point in a controlled fashion
- Currently considering 3 options for the arm stabilization
  - » We will choose one: all 3 appear capable of working
  - » Choice will be made based on level of complexity, risk, cost

Arm Length Stabilization schemes

- Suspension point interferometer
  - » Hang a simple suspended mirror in front of each TM quad suspension
  - » Form a low finesse cavity in each arm, feedback to the SEI platform

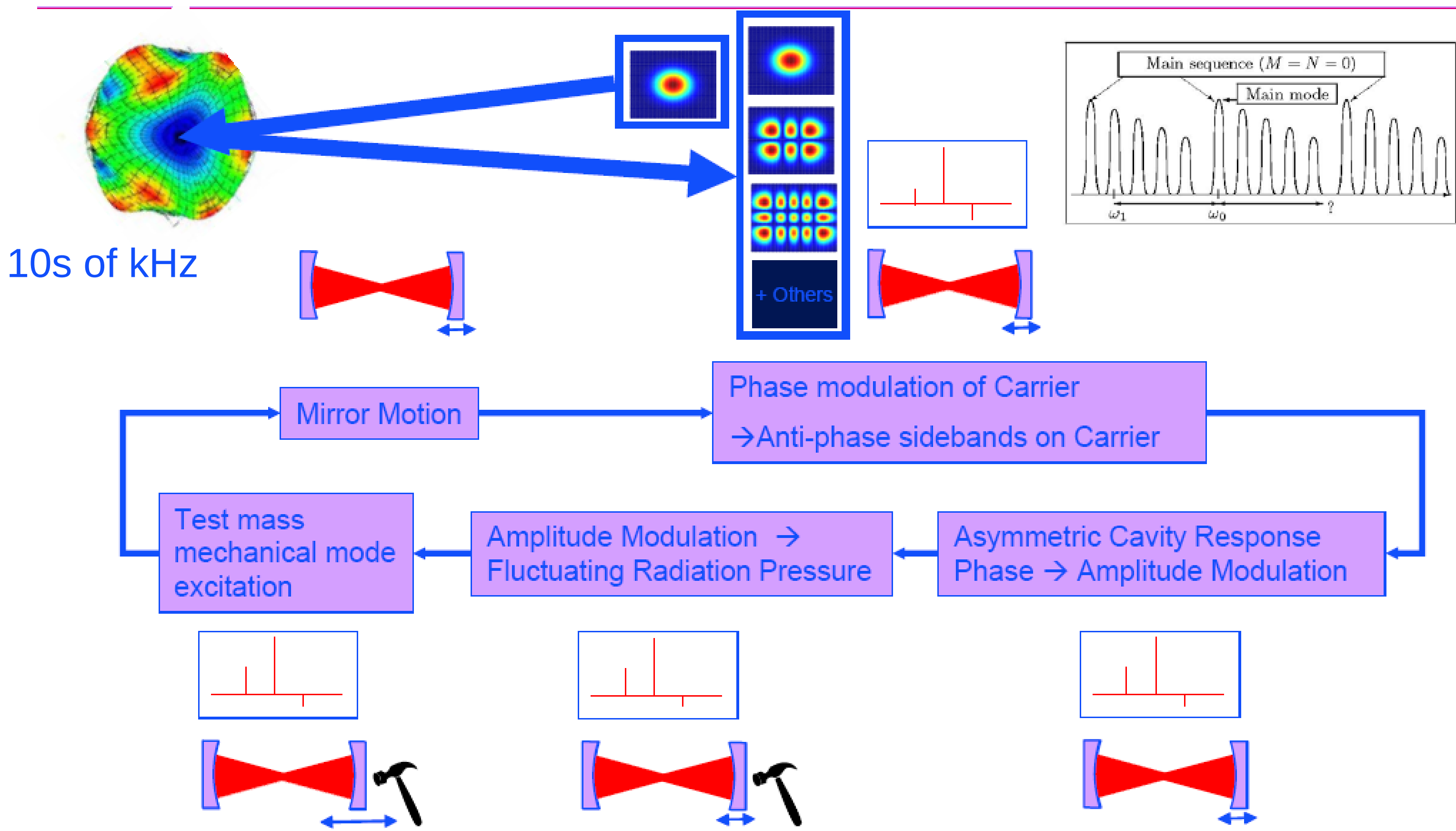


- PDH sensing of the arm cavities at another wavelength
  - » Inject and sense the probe beam from the ends
  - » Second wavelength must be tied to the main beam frequency
  - » Test mass coatings must be designed to work for the second wavelength
- Digital interferometry
  - » Pseudo-random phase modulation applied to a probe beam
  - » Probe is heterodyned with an LO, and decoded with a selectable delay to pick out the desired reflection



Parametric Instabilities

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



Parametric Instabilities

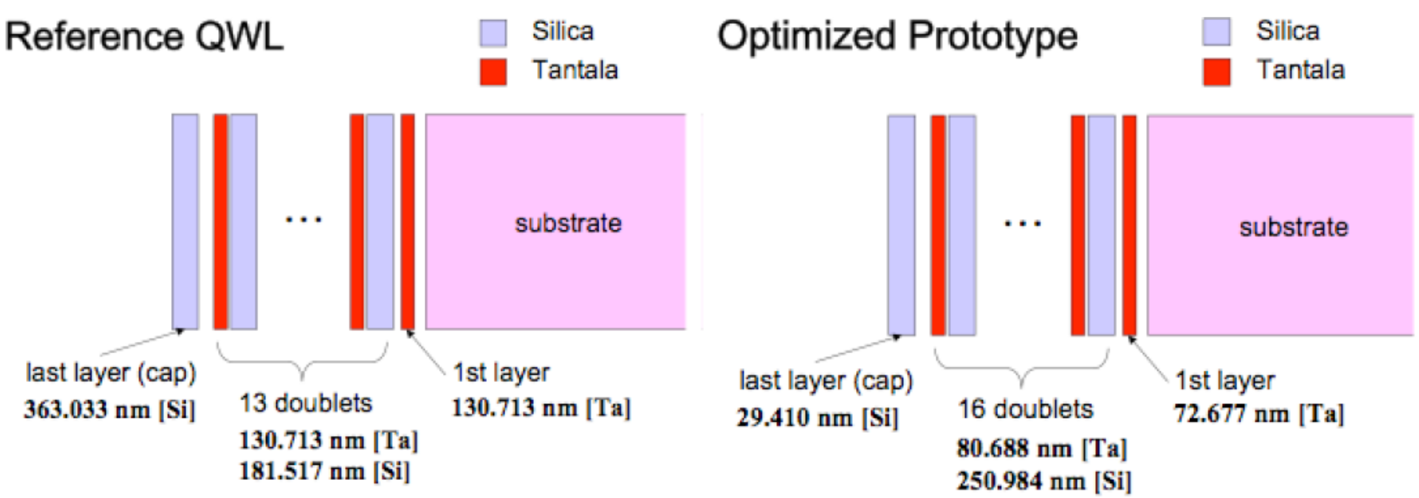
- Modeling predictions (LIGO and U. West. Australia):
  - Suggest a handful of acoustic modes could exhibit instability
  - Very high parametric gains are unlikely, and can be avoided with small tunings of the test mass radii of curvature using test mass ring heaters
- Models assume very high acoustic mode Q-factors
  - Bulk loss model for fused silica, plus loss due to mirror coating
  - Assumed Qs are in the range of 10-30 million
  - For comparison, Qs measured on the GEO test masses range from 1-4 million
  - Mode Qs of a LIGO test mass will be measured on the LASTI quad suspension, starting later this summer
- Mitigation: best defense appears to be in reducing the acoustic mode Qs

Acoustic mode Q reduction

- Apply a lossy material (gold, e.g.) on the barrel of the optic
  - » Trade-off between lowering the mode Qs and increasing thermal noise in the detection band
  - » For damping material on the barrel, mode Qs can be reduced by a factor of 2-3 before thermal noise increase becomes too large: not terribly effective
- Looking for a more frequency selective damper
  - » Active damping using the electro-static actuators
  - » Piezo-electric dampers
  - » Small mechanical resonators outfitted with visco-elastic or eddy current dampers

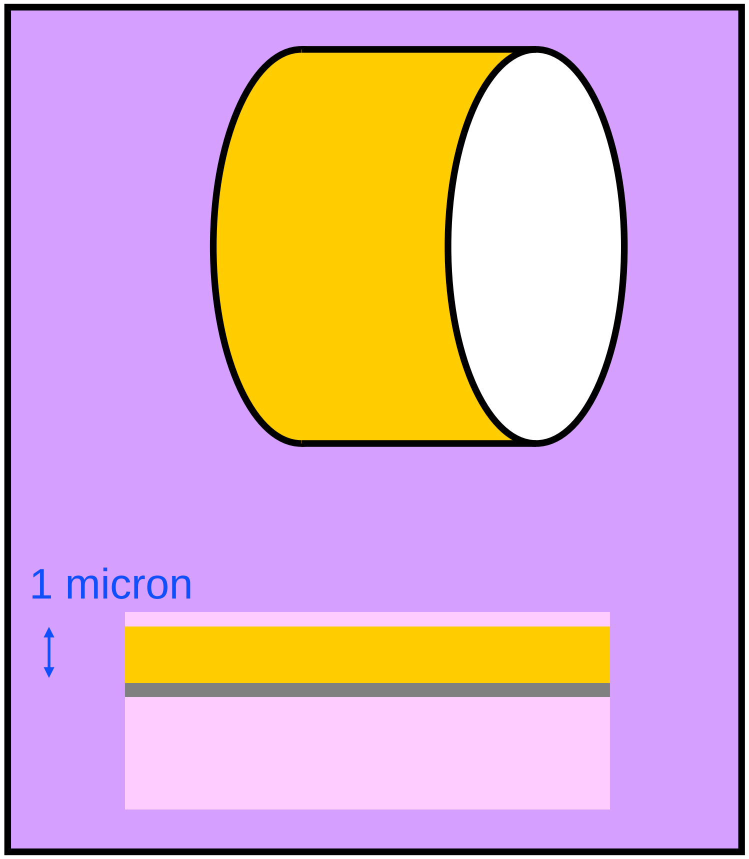
Test Mass dielectric coating design

- Standard coating design uses 1/4-wave layers of alternating materials to achieve desired transmission
- Non-1/4-wave layers introduce the possibility of:
  - » Minimizing thermal noise from the coating
  - » Adjusting layers for desired transmission at another wavelength

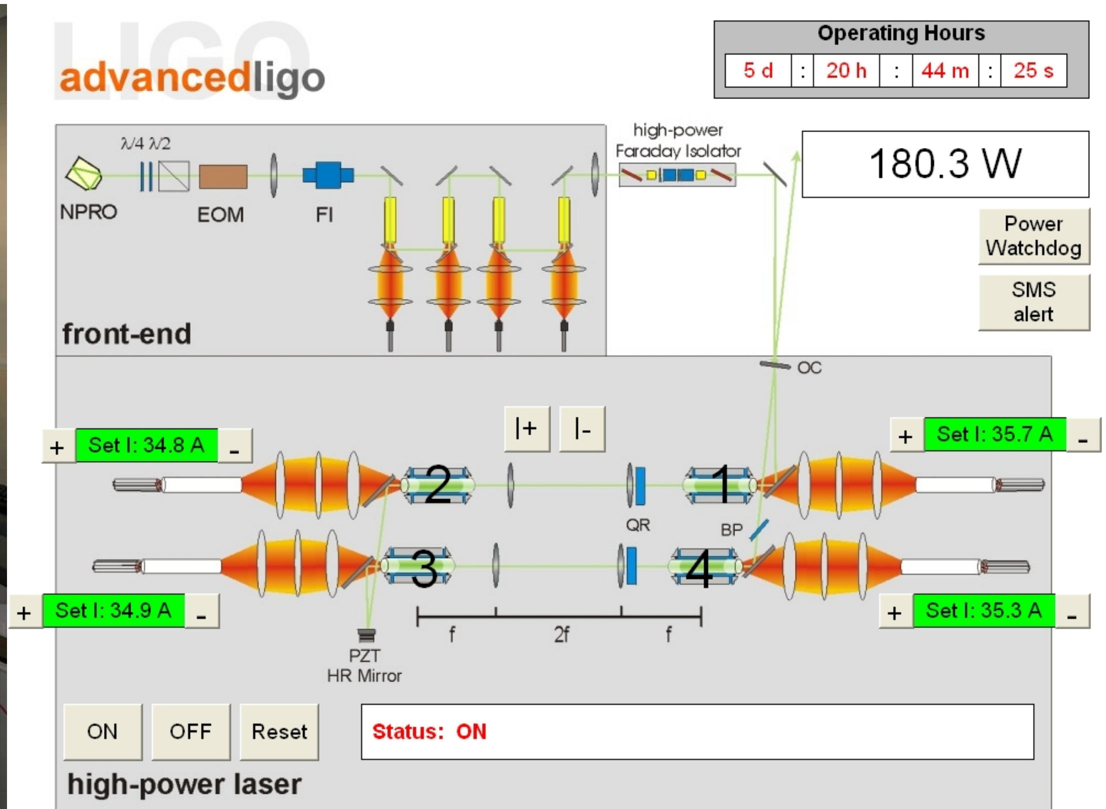


Test Mass barrel gold coating

- Some motivations for coating the barrel with gold
  - » Thermal shield: increases efficiency of the thermal compensation
  - » Damps high-frequency acoustic modes
  - » Could be beneficial for control of electro-static charge buildup
- However -
  - » None of these motivations are very strong
  - » Including a gold coating step in the manufacturing process is not simple
- Issue is being studied by a Technical Review Board



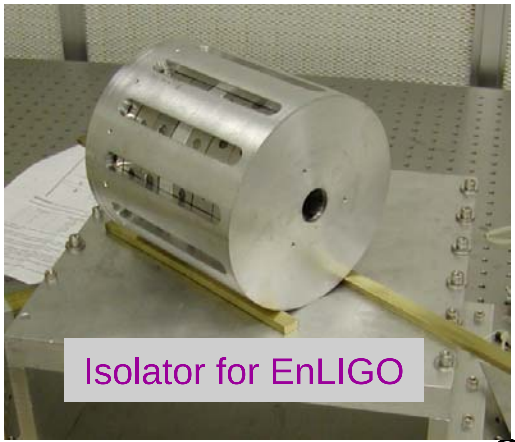
Pre-stabilized laser (PSL)



- 180 W output, about 90% in TEM_{00}
- Component quality: learning to verify the quality of laser crystals and mirrors

Input Optics (IO)

- Main effort has been on modeling the recycling cavity geometry, determining specific design of stable cavities
- Enhanced LIGO
  - » Construction and installation of new Faraday isolators: some thermal problems mitigated with better heat-sinking of crystals
  - » New electro-optic modulators
- Mach-Zehnder modulation: latest interferometer sensing modeling suggests the M-Z is not necessary, but is being kept as a back-up
- Procurement of Advanced LIGO components is beginning
  - » Glass for the mode cleaner mirrors and other in-vacuum custom mirrors

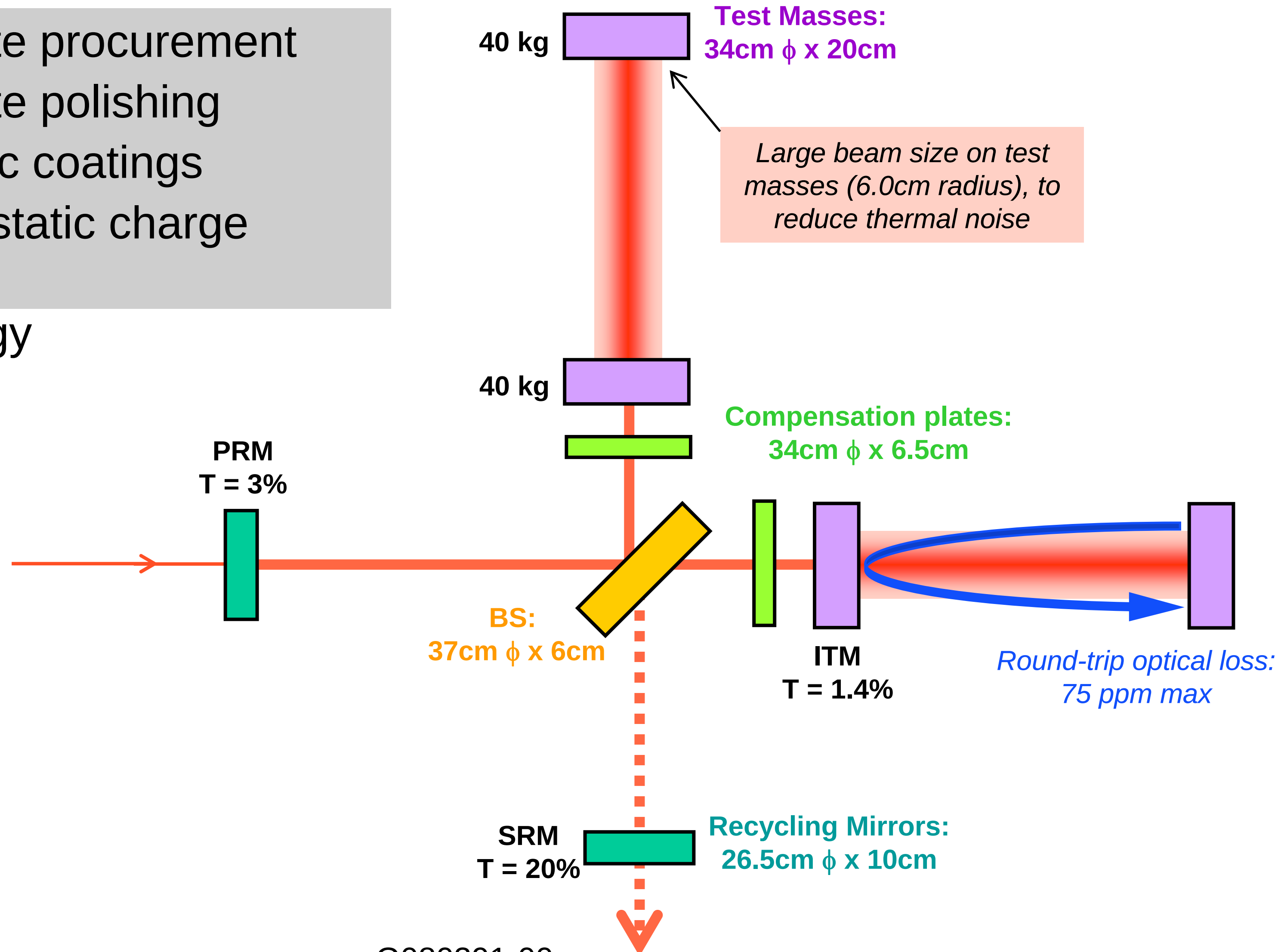


Isolator for EnLIGO

Modulator for EnLIGO

Core Optics Components (COC)

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



Core Optics Components (COC)

- Substrates
  - » Ultra-low-OH (low absorption) fused silica from Heraeus has been adopted for the ITMs, BS, CPs: large sample ordered, and tested OK for homogeneity
  - » Bids for the COC glass were received, and those contracts are in preparation
- Polishing
  - » Pathfinder project with a third vendor was started early in the year, with results due this fall: there are signs they may be the best vendor technically
- Dielectric coatings
  - » Coating materials will be silica & titania-doped tantala: ~3x lower mechanical loss than initial LIGO
  - » LASTI test mass was coated by LMA with this recipe last year; metrology at Caltech showed
    - – 0.3-0.5 ppm absorption
    - – 10-15 ppm scatter
    - – Handful of small regions where the coating was ‘not there’ (bubbles); LMA appears to have solved this problem subsequently

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
- Faraday isolator for the output beam
- Thermal compensation system
  - Senses thermal distortions of core optics and corrects by adding compensating heat

Auxiliary Optics Subsystem (AOS)

- Optical layout & stray light control
  - » Move to very small wedges (~0.1 degree) in the beamsplitter and input test masses -- benefits for ghost beam dumping and for the suspension design
  - » In-vacuum baffle materials: looking at black-porcelainized steel versus black glass
- Optical levers
  - » Would like them to perform a similar function as in initial LIGO: stabilize COC angular fluctuations at the first suspension mode & provide a long-term monitor of COC pointing
  - » Require a more stable mounting platform than initial LIGO
  - » Design team for optical levers has been formed in the past couple of months

Interferometer Sensing & Control (ISC)

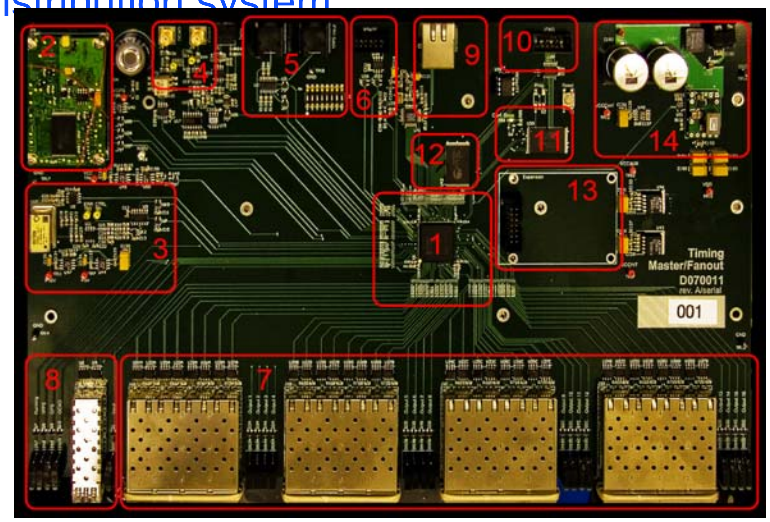
- Design of the input beam modulation scheme to:
  - Sense the global interferometer lengths
  - Sense the global interferometer mirror angles
- Detection tables for all sensed beams
  - Opto-mechanical hardware, photodetectors
  - All beams involved in critical control loops will be detected in-vacuum, 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
- Arm length stabilization system
  - System to stabilize low-frequency fluctuations of the long arms by 1-2 orders of magnitude: aid to lock acquisition

Interferometer Sensing & Control (ISC)

- Requirements & conceptual design review completed earlier this year
- Output mode cleaner and DC readout being tested now in Enhanced LIGO
  - Output mode cleaner: designed for Advanced LIGO
  - Tip-tilt mirrors for beam direction and OMC
  - In-vacuum photodetectors: photodiode with encapsulated preamps
- Length sensing and control
  - New modulation scheme adopted: lower modulation frequency & more flexible interferometer tuning
  - Noise modeling of global control done: 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
  - Alignment controls modeling has begun, using above tool that include radiation pressure/torque
  - Starting with Enhanced LIGO alignment control, which already has the angular instability

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

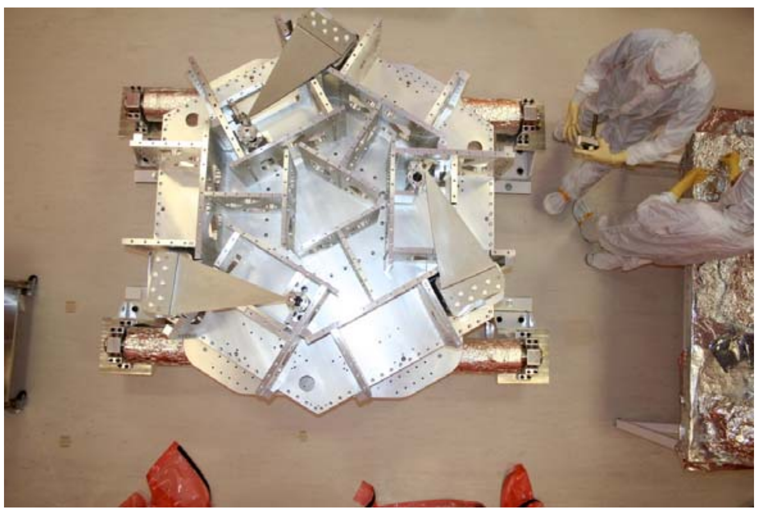
- Progress since Dec-2007:
  - » Held Timing System Conceptual Design Review (committee report pending)
  - » Preparing for DAQ Preliminary Design Review in July 2008
  - » Gained experience with new DAQ infrastructure for DC Readout & Output Mode Cleaner Controls in eLIGO
  - » Continued to gain experience with installed prototype systems at LASTI, ETF, 40m Lab, including software tools for easier control system implementation
  - » Further progress in prototyping DC power distribution system
- Issues/Concerns:
  - » Reliability of hardware
  - » Low error rate, robust software systems
  - » Easy to use software tools for control system development



Master Timing Fanout board

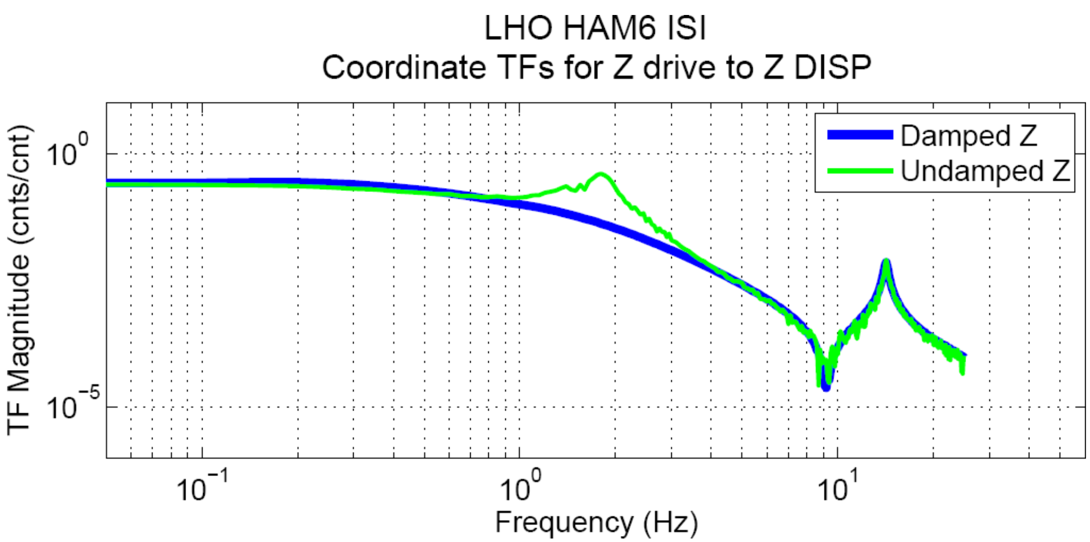
Seismic Isolation (SEI): Internal Seismic Isolation (ISI)

- Progress Since Dec-2007
  - Assembled and Installed HAM ISI systems at both LHO and LLO for eLIGO (Note that it is likely that these units will be used with little or no modification for aLIGO)
  - Minor modifications to the ISI Coil Driver, the GS-13 Interface board, and the Capacitive Position Sensor Interface Board for better performance in eLIGO commissioning.
  - Completed the BSC ISI assembly & installation at LASTI
  - All systems under test and evaluation (characterization & control)
  - Initiating Value Engineering/re-design effort with contractor for small (BSC stage-2) electromagnetic actuators (similar to effort on large stage-1 actuators)
  - Continuing evaluation of Nanometrics seismometer as alternative to the STS
  - Preparing for in-vacuum sensor/reliability review



Seismic Isolation (SEI): Internal Seismic Isolation (ISI)

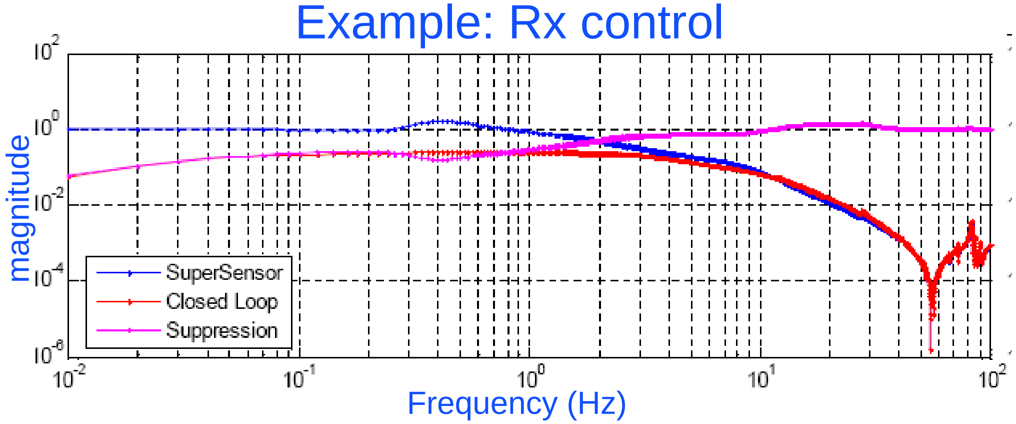
- HAM ISI Characterization/Control
  - Using new DAQ infrastructure
  - Transfer functions taken (except very low frequency due to AWG communication/stability problem)
  - Blended position and geophone “supersensor” filters developed
  - Damping implemented
  - Isolation control soon



Seismic Isolation (SEI): Internal Seismic Isolation (ISI)

- BSC ISI Characterization/Control
  - » Damping loops on stage 1 and stage 2 have been turned on
  - » Low frequency control loops have been implemented on HEPI
  - » Stage2 Rx and Ry control loops have been turned on.
  - » We are currently designing the control loops for Stage2 X,Y,Rz & Z

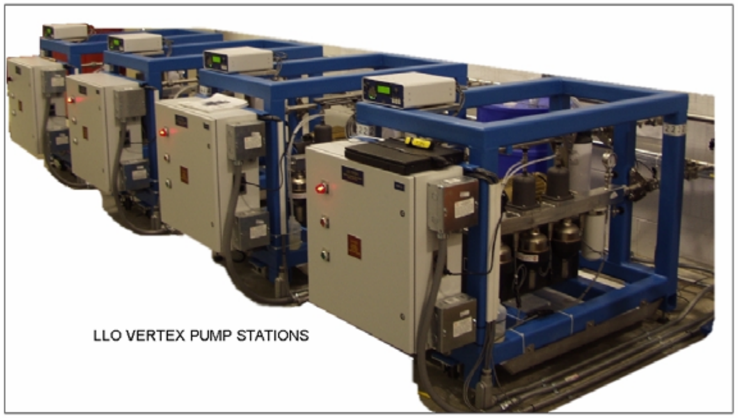
Example: Rx control

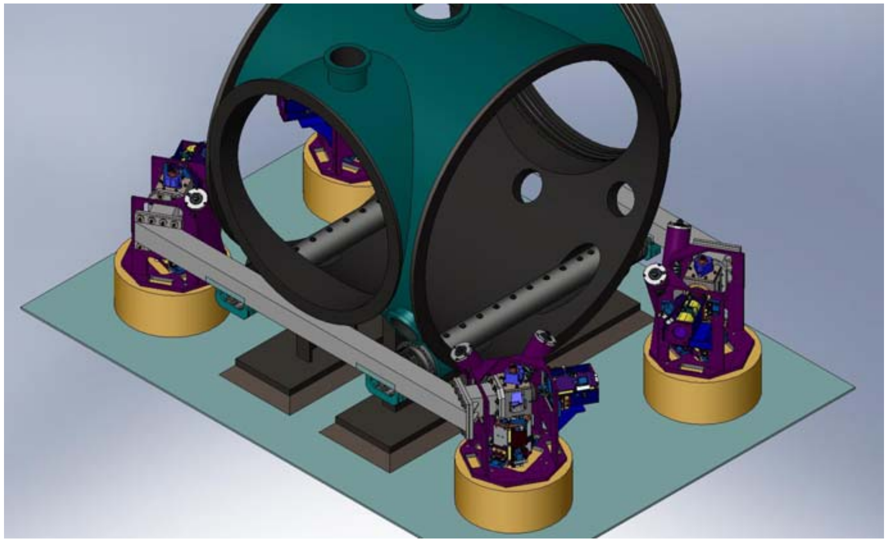


Installation of the BSC ISI (2-stage) Assembly with Upper Quad Suspension Assembly

Seismic Isolation (SEI): Hydraulic External Pre-Isolation (HEPI)

- Progress Since Dec-2007
  - Held Fabrication Readiness Review (Part 1 of 2)
  - Started procurement process on HEPI components
  - Stiffer crossbeam support structure & alternative displacement sensor to be reviewed





The redesigned HAM Support Structure, shown with a partial model of the HAM Chamber. Simple cylindrical spacers are used in the model, in place of the HEPI Piers and grout. Note that we intend to continue using the existing Piers at LLO, without modification.

Seismic Isolation (SEI): Issues/Concerns

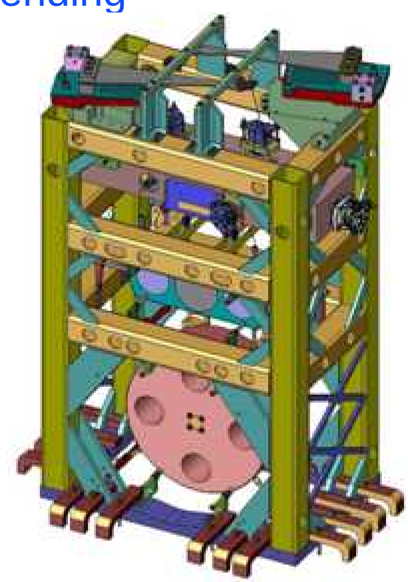
- General ISI concern: in-vacuum component reliability and servicing
  - » Exploring Nanometrics alternative to STS seismometer
  - » Improving alignment & locking of GS-13
  - » Value engineering small actuator (larger gaps for easier alignment, improved strain relief and coil wire termination)
  - » Review soon
- HAM & BSC ISI:
  - » BSC ISI behind schedule ~3 months
  - » Exploring a switch in the production order with HAM-ISI
  - » Plan to hold HAM-ISI Final Design and Fabrication Readiness Reviews as soon as eLIGO commissioning results indicate no issues in achieving isolation performance requirements (Aug or Sept 2008)
- HEPI
  - » May need to select lower noise position sensors (potentially ~$1/4M)

Suspensions (SUS)
Quadruple Pendulum (UK)

- Progress since Dec-2007:
  - » Decision to switch fused silica suspension geometry from ribbon to tapered fiber
  - » Held Fabrication Readiness Reviews:
    - – Quad structural weldment
    - – Quad mechanics
    - – Quad non-optical glass
    - – Birmingham-style Optical Sensing and Electro-Magnetic Actuators (BOSEMs)
  - » UK has gone into production on Quad structure/mechanics and BOSEMs
  - » Caltech has begun to procure non-optical glass for UK (funds transfer)
  - » Performed detailed review of UK delivered prototype electronics (analog front ends)
  - » Fiber welding facility close to ready at LASTI

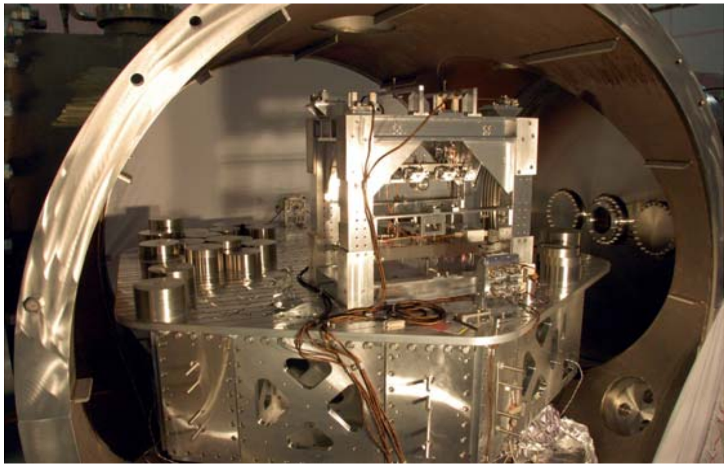
Suspensions (SUS):
BS, HAM Small & Large Triple Suspensions

- BeamSplitter (BS) & Folding Mirror (FM) Triple Suspensions (UK)
  - » Prototype structure to be completed soon June 2008
  - » Final Design Review planned for July 2008
- HAM Small Triple Suspension (US)
  - » No work in this period
  - » Final Design Review & Fabrication Readiness Reviews are pending
- HAM Large Triple Suspension (US)
  - » Mechanical design work has been completed
  - » Preliminary Design Review to be held soon WHEN??
  - » Electronics range and noise current to be determined soon



Suspensions (SUS): Output Mode Cleaner (OMC, double)

- OMC assembled & installed at LLO for eLIGO
- OMC parts fabricated for LHO eLIGO
  - » Minor design changes to improve upon the LLO unit
- Both LLO & LHO units are likely to only require slight modifications for use in aLIGO



The prototype OMC for Enhanced LIGO is shown in LHAM6 atop the prototype HAM Internal Seismic Isolation (ISI) system.

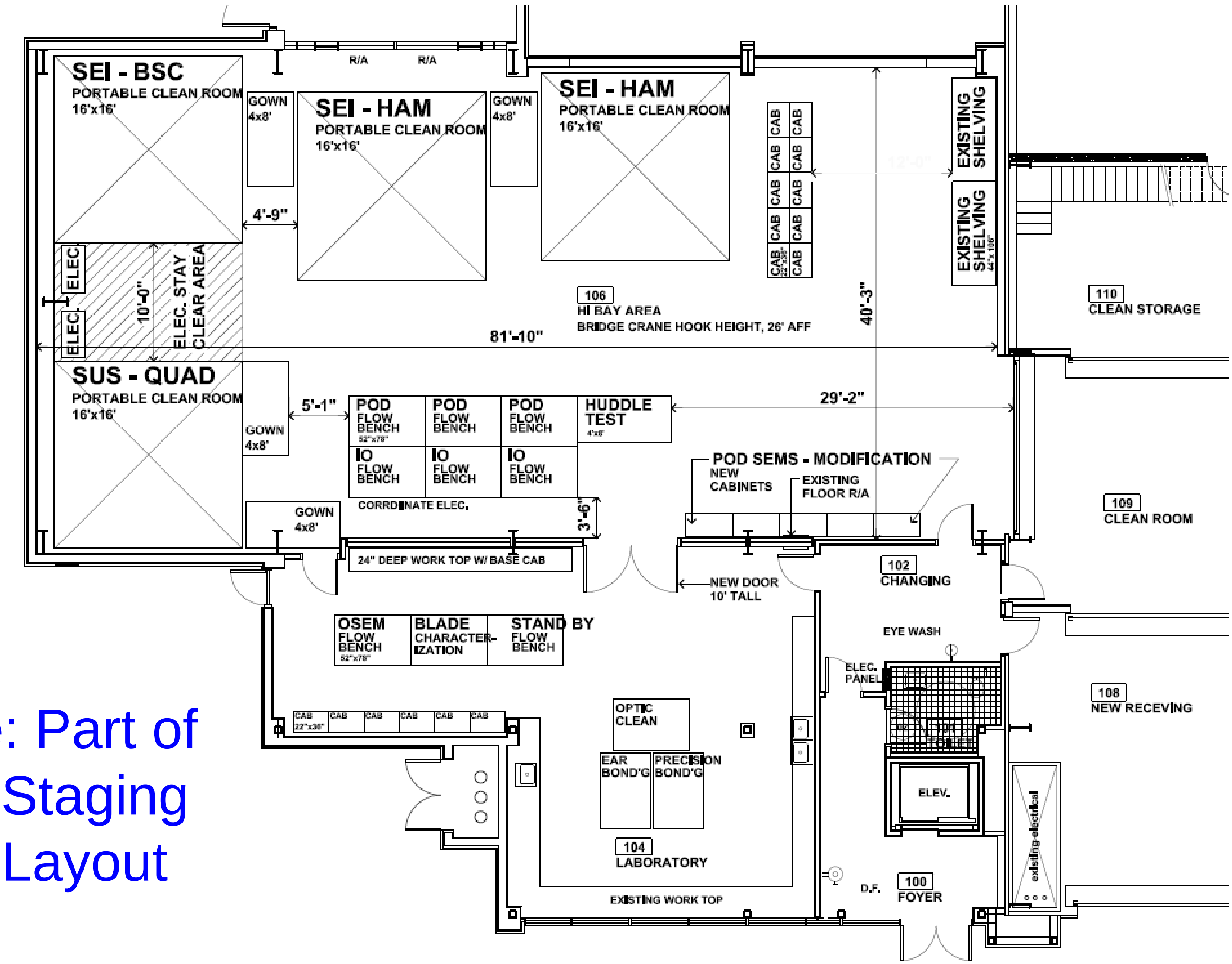
Suspensions (SUS): Concerns/Issues

- Wire hysteresis causing static misalignment during assembly
  - » large displacement operations
- Coupled payload dynamics
  - » have been unsuccessful in predicting eigenfrequencies of coupled SIS & quad
- Maraging steel blade spring corrosion
  - » nickel plating (new process for us) must be capable of high strains without peeling
- Maraging steel blade rolling tolerances
  - » Wire EDM for thin maraging steel blades is not practical
  - » Rolled blades have poor tolerances – looking into peening and other techniques

Facilities Modification & Preparation (FMP)

- Progress since Dec-2007:
  - » Held a Procurement/Fabrication Readiness Review for the following scope:
    - Physical modifications to lab facilities at LHO and LLO
    - Portable softwall cleanrooms requirements/concept to be installed in those locations
    - Also reviewed cost estimates
  - » Made progress in the definition of the balance of FMP scope:
    - Inventory control software
    - Vacuum equipment modifications
    - Installation support equipment
- Building layouts established for assembly areas
  - » LHO and LLO staging buildings
  - » LHO and LLO warehouses
  - » the LHO vertex Mechanical Equipment Room
  - » LLO LVEA
  - » Incorporated flexibility & reserve capacity to support adaptation as workflow or schedule contingencies unfold
  - » Detailed consideration of requirements permitted descoping or deletion of some elements foreseen at the prior concept stage, thereby keeping overall costs under control

Facilities Modification & Preparation (FMP)



Example: Part of the LLO Staging Building Layout

Facilities Modification & Preparation (FMP)

- Design/Requirements Changes:
  - » Simplified Assembly Cleanroom design (considerable savings)
  - » Less extensive LLO staging building renovations than originally budgeted
  - » Retrofit both site warehouses as clean process and storage facilities
    - – Required by volume of SEI and SUS assembly tasks currently envisioned after R&D and ELI assembly experience
  - » Large air bake oven for LHO
    - – Vulnerability of large assemblies in shipment & overall production pipeline capacity
  - » SEI weights require added material-handling equipment
  - » Redundant vacuum bake capacity
    - – To maintain production given realistic equipment downtime
  - » Dual SEI assembly stations, plus separate staging cleanroom
    - – To achieve required production at each site without serializing assembly and test phases for each build
  - » SEI laminar-flow “pod factory” at LLO to process and test vacuum sensor pods for both sites
  - » Dedicated cleanroom spaces at each site for SUS assembly
    - – SEI stations are fully and continuously occupied

LIGO

Development Status Summary

Subsystem	Review	Review Level				Test Facility
		DRR/CDR	PDR	FDR	F/PRR	
SYS	Systems Engineering Prelim Design Review			Apr-09		
SUS	TM Quad (UK)					LASTI
	BS/FM Triple (UK)			Jul-08		
	BOSEMs					LASTI & eLIGO
	Fiber Pulling, Welding & Ear Attachment			Aug-08		LASTI
	HAM Small Triple (IMC)			May-09		LASTI
	HAM Large Triple (RM3)		Jan-09	Aug-09		LASTI
	OMC Double		Oct-08	May-09		eLIGO
	Aux. SUS (single)		Sep-08	Apr-09		iLIGO
	UK SUS Electronics				Sep-08	LASTI
SEI	HEPI					iLIGO, eLIGO, LASTI
	In-Vacuum Sensor & Actuator Reliability Review				Jul-08	eLIGO, ETF, LASTI
	HAM-ISI		Aug-08	Jan-09		eLIGO, ETF
	BSC-ISI		Jan-09	May-09		LASTI, ETF
FMP	Assembly PrepFab Readiness Review					
	Inventory Control				Aug-08	
	FMP Vacuum Equipment Modifications	Sep-08				
ISC	ISC		Mar-09	Jan-10		40m Lab
AOS	Auxiliary Optics System (sans TCS)	Oct-08	Feb-09	May-09 -- Feb-10		eLIGO Baffles
	Thermal Compensation System (TCS)		Aug-08	May-09		eLIGO
PSL	Pre-Stabilized Laser				front end Dec-08?	eLIGO
			Sep-08	Dec-09	180W	
DAQ	Timing System			12/1/208		
	DAQ		Jul-08	Feb-09		eLIGO, LASTI, 40m Lab
COC	COC Optics			Jul-08	glass	
					polish	
					coat	
	COC Metrology				metrology	
IO	Input Optics			Apr-09	long lead	
					balance	

Key:

	completed
	in-process
mo-yr	planned TBD date

Design/Technical Readiness

- As planned, the development program continues at a significant level through FY2009
  - Development phase delivers Final Designs to the Project
- Extensive experience with prototypes, installation and commissioning of key elements
  - Many issues and concerns being addressed, but none are significant surprises or hold-ups
  - No significant technical baseline changes
  - eLIGO yields a robust set of early tests for a key subset of aLIGO subsystems
- Acting on cost elements planned for Project start & thereafter
  - Have initiated procurement on long lead elements/designs planned for 1st year
  - Workable schedule for the remainder of production, with most subsystems starting production in 2009