Advanced LIGO Systems Requirements Review

3 July 2001

Agenda

- Systems requirements & design, 1 hr (Peter F)
- Optical layout, 20 min (Dennis C)
- Generic requirements & standards, 10 min (Dennis C)
- LIGO Observatory environments, 20 min (David S)
- Summary

Outline for systems design

- Upgrade approach & philosophy
- System level requirements
- System level design
- Subsystem requirements

Upgrade approach & philosophy

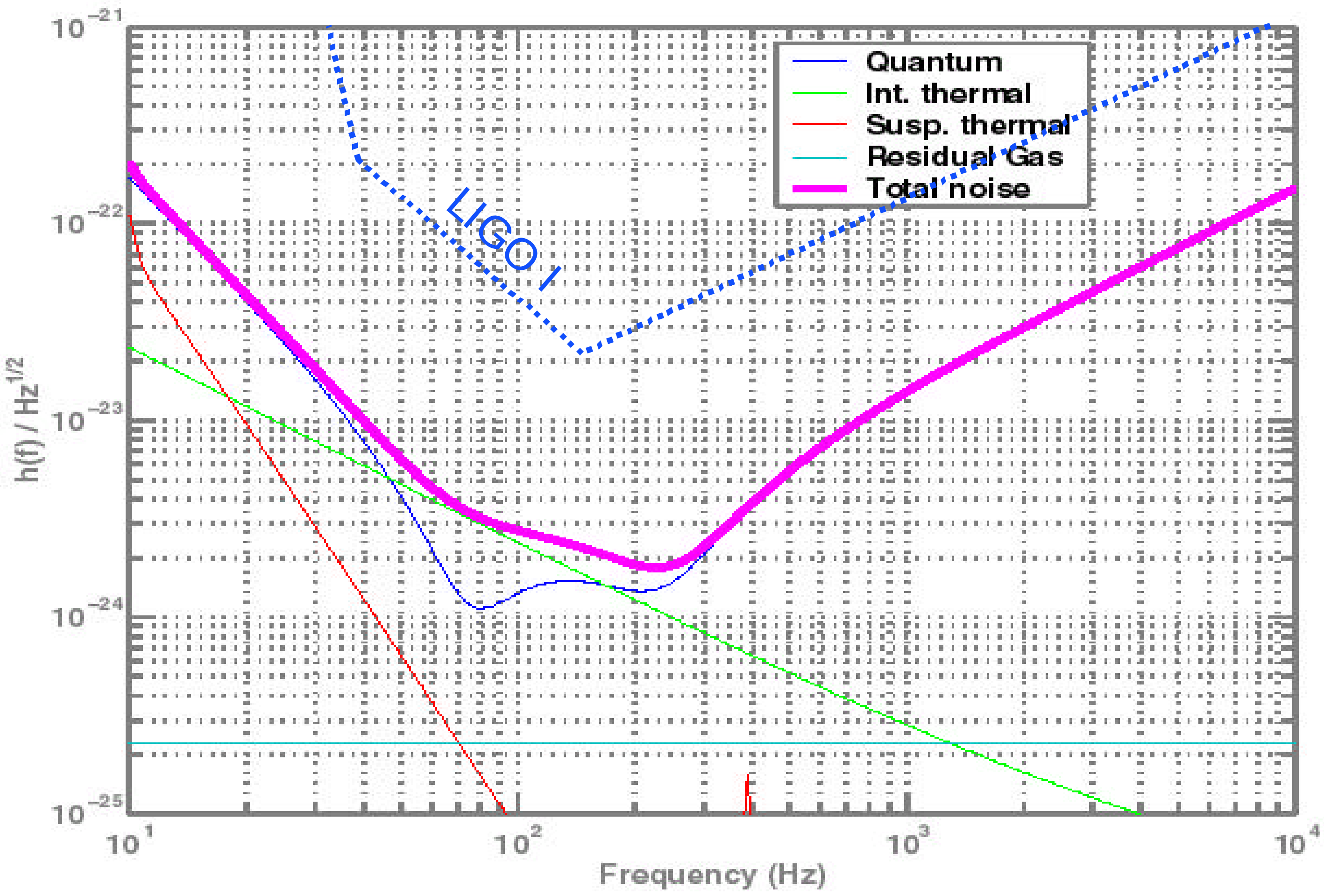
- We don’t know what the initial LIGO detectors will see
  - » Design advanced interferometers for improved broadband performance
- Evaluate performance with specific source detection estimates
  - » Optimizing for neutron-star binary inspirals also gives good broadband performance
- Push the design to the technical break-points
  - » Improve sensitivity where feasible - design not driven solely by known sources

Upgrade approach, cont'd

- Design approach based on a complete interferometer upgrade
  - » More modest improvements may be possible with upgrades of selected subsystem/s, but they would profit less from the large fixed costs of making any hardware improvement
- Two interferometers, the LLO and LHO 4k units, would be upgraded as broadband instruments
- Current proposal for third interferometer (LHO 2k):
  - » increase length to 4 km
  - » implement a narrowband instrument, tunable from ~500 Hz-1 kHz

Estimated strain sensitivity

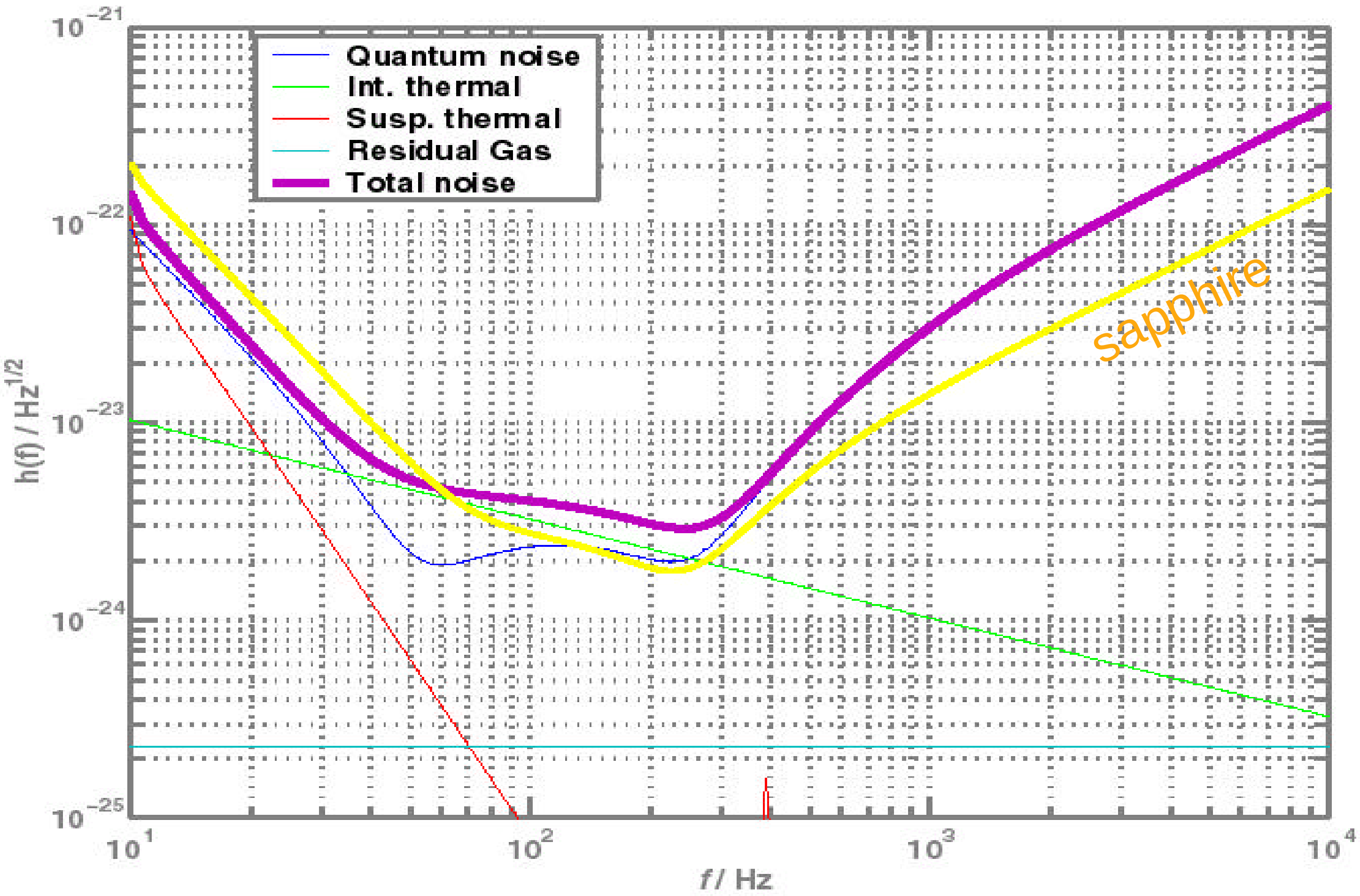
40 kg sapphire test masses



Top level performance & parameters

Parameter	LIGO I	LIGO II
Equivalent strain noise, minimum	$3x10^{-23}$/rtHz	$2x10^{-24}$/rtHz
Neutron star binary inspiral range	19 Mpc	300 Mpc
Stochastic backgnd sens.	$3x10^{-6}$	$1.5\text{-}5x10^{-9}$
Interferometer configuration	Power-recycled MI w/ FP arm cavities	LIGO I, plus signal recycling
Laser power at interferometer input	6 W	125 W
Test masses	Fused silica, 11 kg	Sapphire, 40 kg
Seismic wall frequency	40 Hz	10 Hz
Beam size	3.6/4.4 cm	6.0 cm
Test mass Q	Few million	200 million
Suspension fiber Q	Few thousand	~30 million

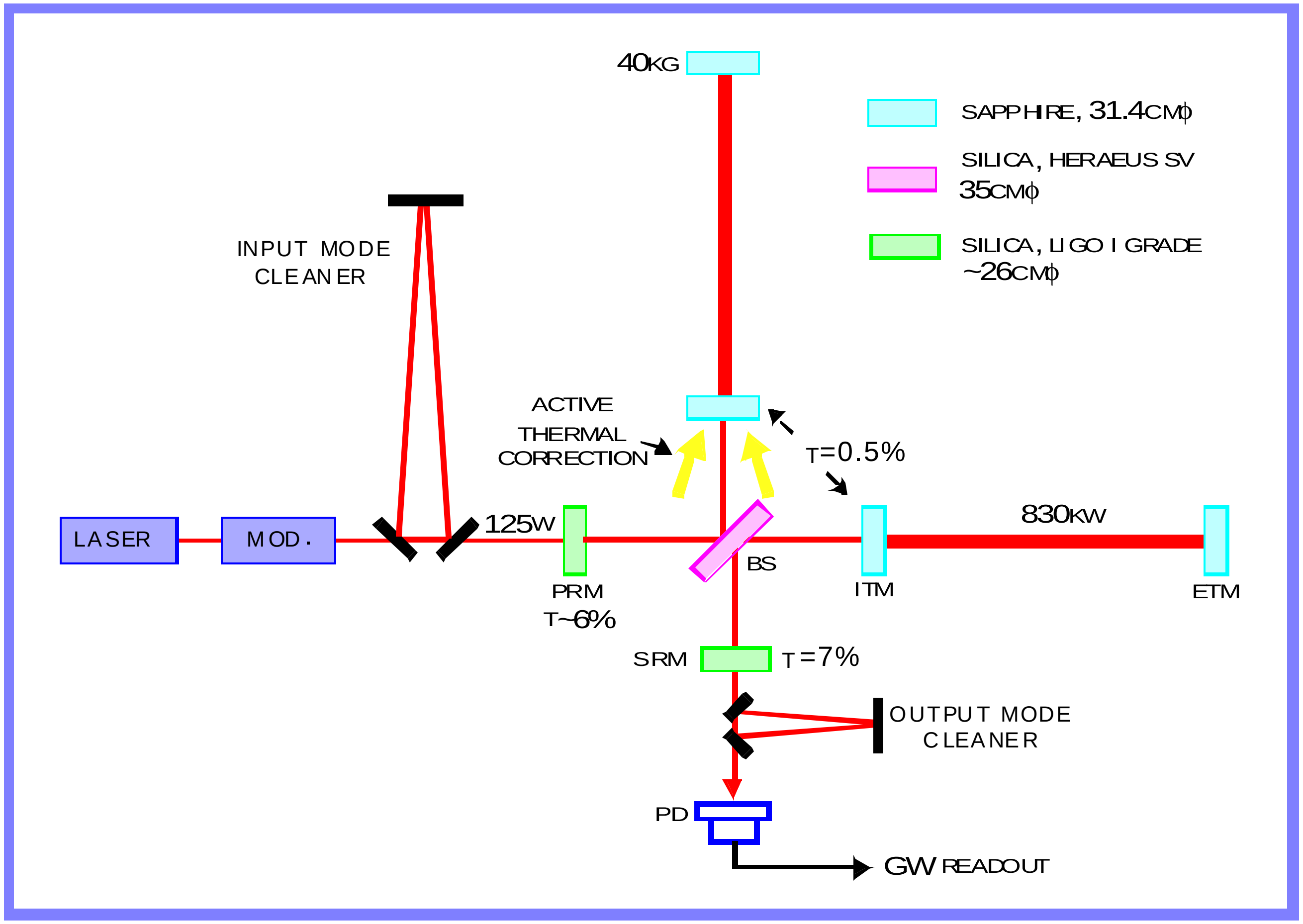
Comparison with 40 kg fused silica test masses, Pin = 80 W



System level requirements

- Non-gaussian noise
  - » Difficult to establish quantitative requirements
  - » Subsystems should be designed to avoid potential generation of non-gaussian noise
- Availability – as for initial LIGO:
  - » 90% for a single interferometer (40 hrs min continuous operation)
  - » 85% for two in coincidence
  - » 75% for three in coincidence
- Environmental sensing
  - » Initial PEM system basically adequate, some sensor upgrades possible
- Infrastructure constraints
  - » Designs must fit with existing LIGO facilities, with two possible changes:
    - – Larger diameter mode cleaner tube
    - – mid-station BSCs moved to the ends, for 4km length 3rd ifo
- Data acquisition
  - » Same sample rate and timing requirements as for initial LIGOb
  - » Each subsystem must be designed with appropriate data acquisition channels

System level design – basic layout



What we've left out

- Internal thermal noise
  - » Flat-topped beams to reduce thermo-elastic noise
  - » Cooling of the test masses
  - » Independent readout of test mass thermal motion
- Quantum noise
  - » Quantum non-demolition techniques
  - » Very high power levels, coupled with all-reflective configurations
- Seismic noise
  - » Independent measurements of gravitational gradient noise

Systems level design: signal recycling

- Provides ability to do some shaping of the response, but principal advantage is in power handling:
  - » Signal recycled interferometer: 200 Mpc NBI range, 2.1 kW beamsplitter power
  - » Non-signal recycled, same input power: 180 Mpc range, 36 kW beamsplitter power
- Limit to signal vs power recycling comes from losses in the signal recycling cavity
  - » Arm cavity finesse of ~1000 probably OK
  - » Arm cavity finesse of ~10,000 probably too high
- Not requiring a tunable or selectable signal recycling mirror
  - » Not necessary for the ‘broadband performance’ goal

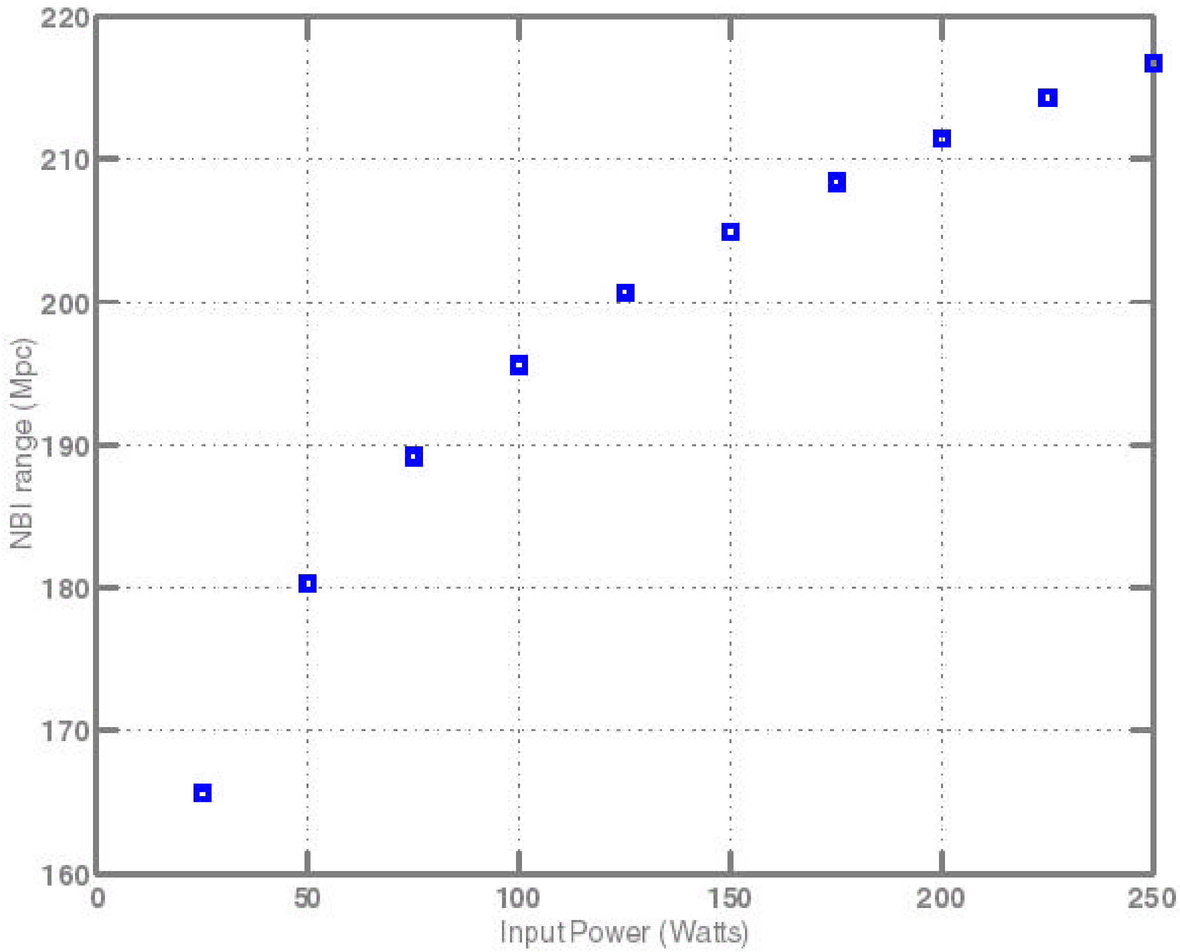
Output mode cleaner

- Reduce the output power to a manageable level
  - » 20x higher input power (compared to initial LIGO) leads to 2-3x higher output power
    - – 1-3 watts total power w/out a mode cleaner
  - » Output mode cleaner leaves only the TEM00 component of the contrast defect, plus local oscillator
    - – ~100 mW total power w/ mode cleaner
- Necessary for dc readout scheme
  - » Technical laser intensity noise must be controlled
  - » Even with rf readout, detecting and getting shot noise in several Watts is tough
- Two possible designs:
  - » Dc readout: short (~0.5 m) rigid cavity, modest isolation needs
  - » RF readout: essentially a copy of the input mode cleaner (isolation requirements probably much more lax)

Active thermal compensation

- Thermal loading comparison, total absorbed power:
  - » Initial LIGO: 20 mW
  - » AdLIGO, sapphire: 350–1600 mW, silica: 60-340 mW
  - » Sapphire has lower thermal lensing by a factor of 25, lower thermo-elastic distortion by a factor of 2
  - » AdLIGO must also operate at low power
- Required compensation: roughly a factor of 10 in opd
- Two compensation methods
  - » Radiative ring heater, close to optic
  - » External heating laser beam, scanned over the optic
- Compensation plate
  - » Several advantages for active compensation actuation: limit temperature rise in TM; avoid noise of laser actuator; easier to interface

Input power



40kg sapphire test masses

180 W from laser

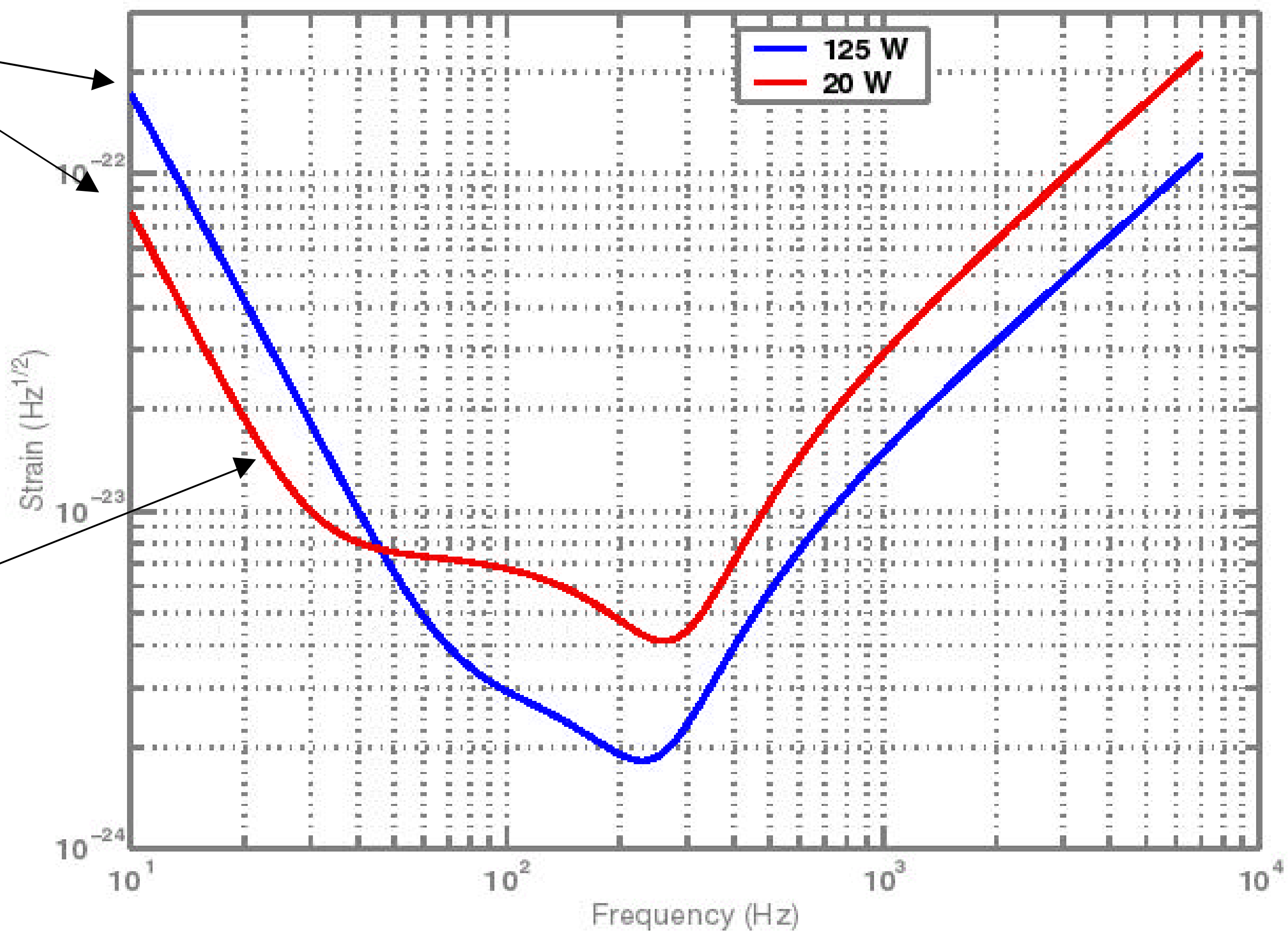
165 W from PSL

125 W from MC

Low & High power modes

Factor of 3 difference at low frequencies

Quantum radiation pressure roughly equal to suspension thermal noise

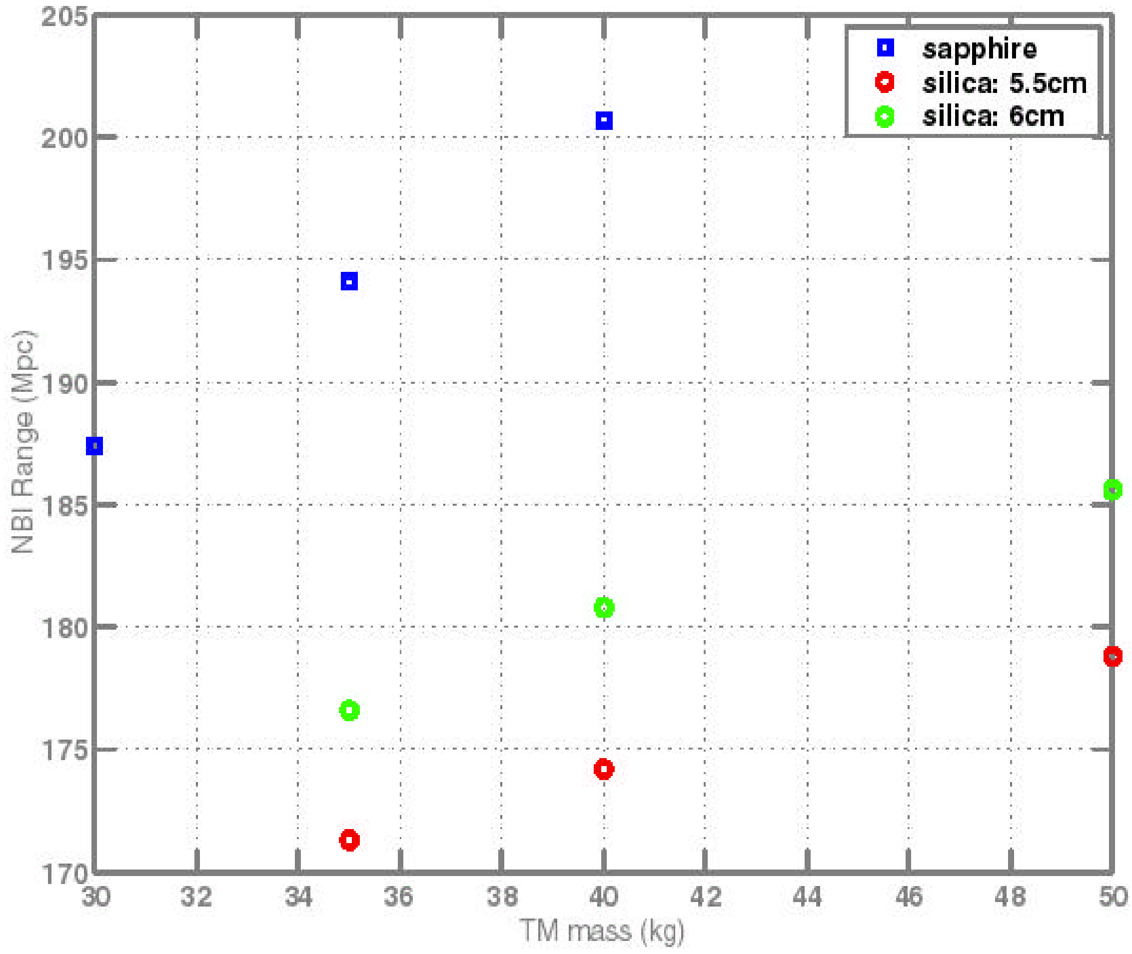


Test mass material: sapphire vs fused silica

- Sapphire is baseline design:
  - » 20% larger NBI range
  - » Potential for thermal loading advantage
  - » Still under development:
    - – Size
    - – Absorption
    - – Homogeneity
    - – Scattering
- Silica
  - » Better understood materials properties
  - » Size available, but expensive

Test mass size and mass

Bigger is better!



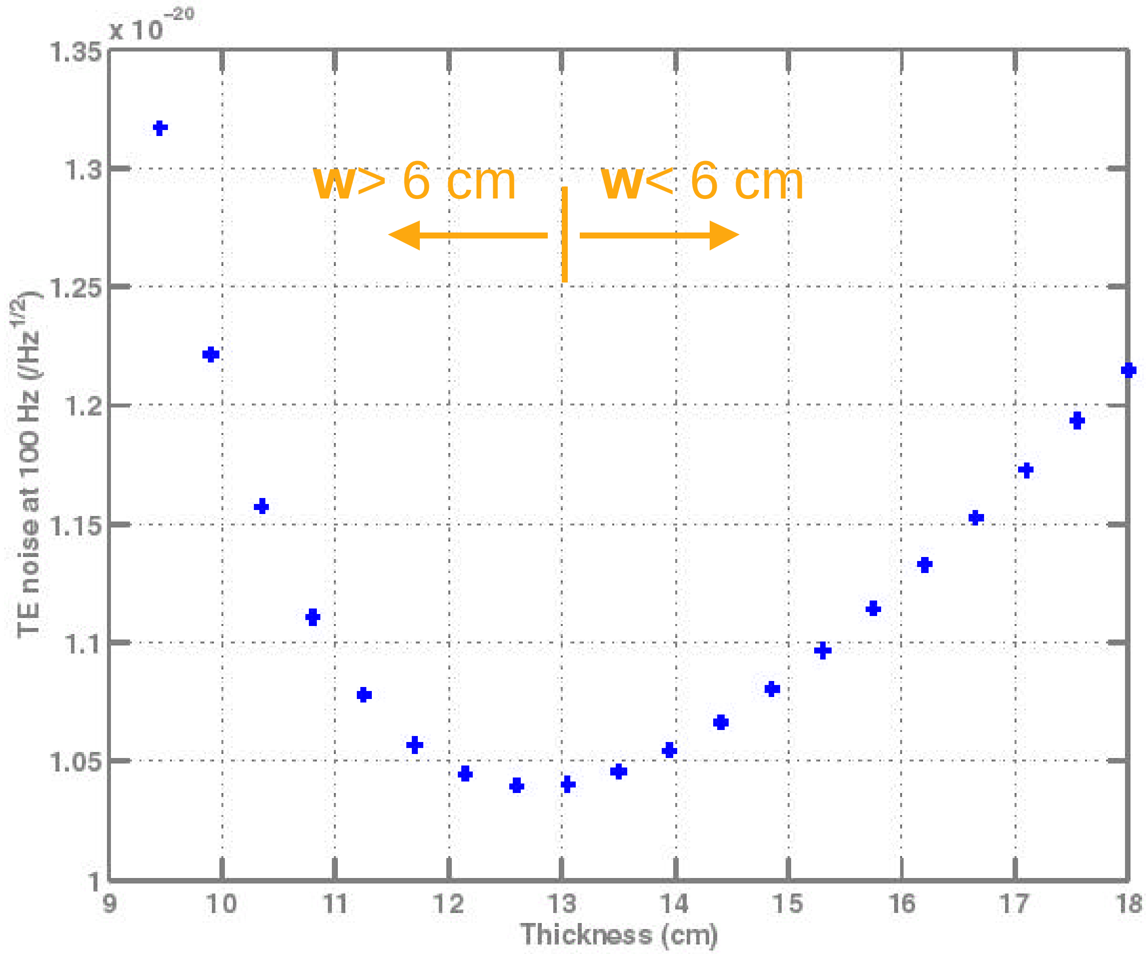
40 kg a practical maximum for sapphire (for AdL timescale)

Fused silica: choice not so clear

Beam size

- Win quickly with sapphire, $\mathbf{w}^{-3/2}$, more slowly with fused silica, $\mathbf{w}^{-1/2}$
- Limits imposed by:
  - » Aperture loss in arm cavities
  - » Polishing very long radii of curvature
  - » Attaining polishing uniformity over a larger area
  - » Stability of arm cavities in the presence of mirror distortions and misalignments
- Sapphire
  - » With an upper limit of 15 ppm aperture loss, beam radius of 6.0 cm minimizes thermo-elastic noise, for a 40 kg piece
- Silica
  - » Probably limited more by thermal distortions; using 5.5 cm for now

40 kg sapphire optimization



Aperture loss kept constant at 15 ppm

Seismic wall frequency: 10 Hz

- Specific source detection
  - » Sensitivity to NBIs or stochastic background doesn't significantly change for cutoff frequencies less than 15 Hz
  - » Somewhat more sensitive for intermediate mass BH-BH mergers; still probably no significant loss for any cutoff less than 12-13 Hz
- Technology threshold
  - » Horizontal ground motion (isolated by seismic + suspension) crosses quantum radiation pressure & suspension thermal noise below 10 Hz
  - » Vertical isolation not so large, since last stage of suspension is relatively stiff; couples to beam path at a level of ~0.001
  - » Fiber cross section also driven by minimizing thermal noise: smallest diameter fiber is not the best
  - » By using a dense penultimate mass material, it appears feasible to keep the vertical mode under 10 Hz

GW channel readout: 2 candidates

- RF readout, as in initial LIGO
  - » Phase modulate at interferometer input
  - » Arrange parameters for high transmission of RF sidebands (one anyway) to output port
- DC readout
  - » Small offset from carrier dark fringe
  - » GW signal produces linear baseband intensity changes
  - » Advantages compared to rf readout:
    - – Output mode cleaner simpler
    - – Photodetector easier, works at DC
    - – Lower sensitivity to laser AM & FM
    - – Laser/modulator noise at RF frequencies not critical
- Comparison of quantum-limited sensitivity still in progress

System level noise sources: control of fundamental noise sources

- Quantum noise
  - » Photodetector quantum efficiency: > 90%
  - » Readout scheme: must not significantly compromise ideal sensitivity
- Internal thermal noise
  - » Make beam as big as possible (optimized given sapphire size constraint)
  - » Don't spoil Q of substrate material, BUT …
    - – Mirror coatings and possibly polishing have a significant effect, that we may not be able to mitigate
- Suspension thermal noise
  - » Under control: stress and shape of fiber
  - » Ribbons (10:1 aspect) give about 2x lower noise
    - – ~10% improvement in stochastic sensitivity in low-power mode
  - » Ribbons not required – too risky for the payoff – though R&D should continue, and they're not ruled out if development goes well

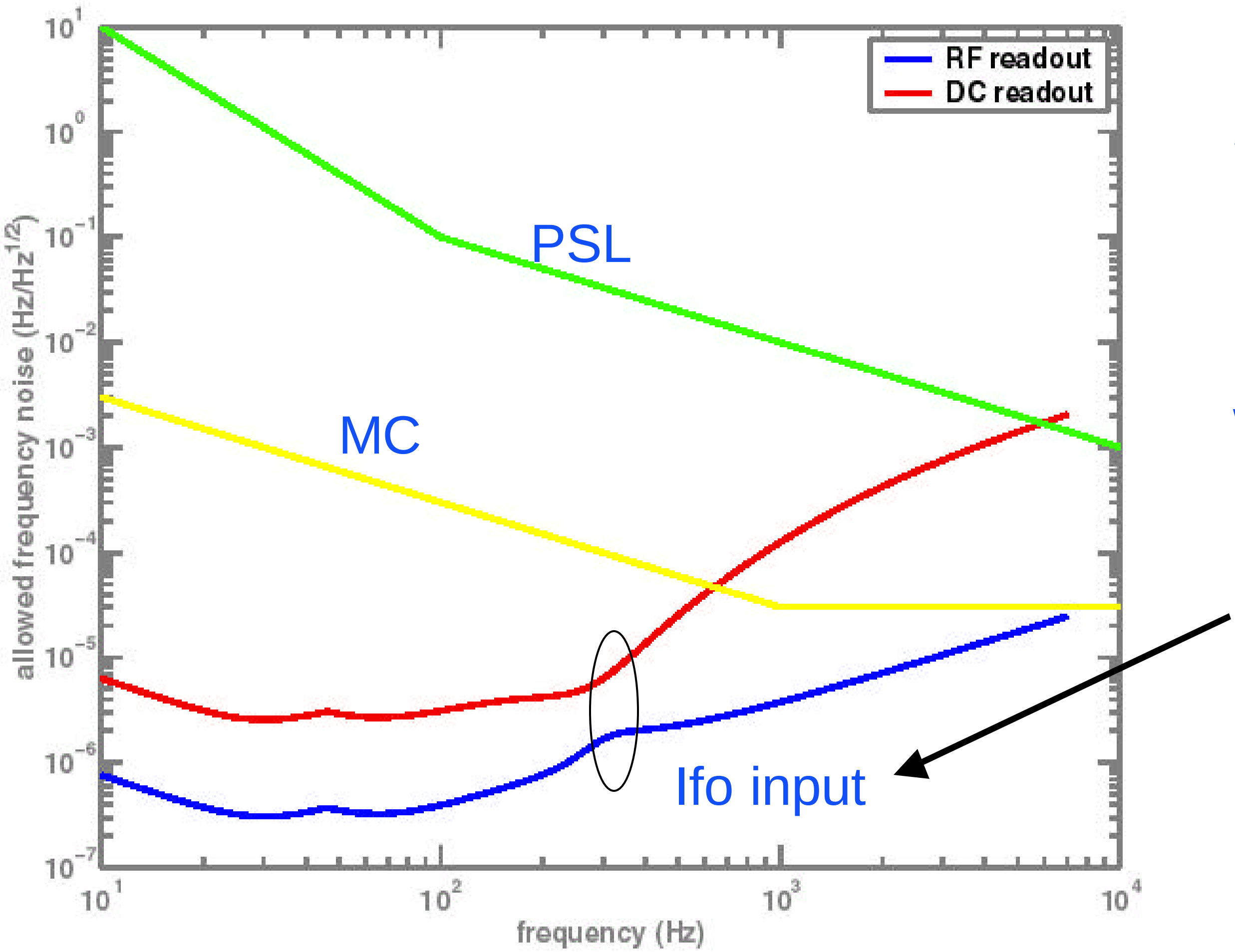
Technical noise

- Each technical noise source must be held below 10% of the target strain sensitivity
  - » Applies to each noise source over the entire GW band
  - » A single noise source degrades the strain sensitivity by a factor of 1.005
  - » ~10 such noise sources in a given frequency region, 5% strain degradation
- Composite technical noise curve formed
  - » Minimum of the sapphire low-power & high-power strain curves
  - » Applies to noise sources independent of the input power
  - » Don’t need major revision if we switch to fused silica test masses
    - – Sapphire low-power curve covers the silica case

Ground noise

- Displacement noise for each seismic platform:
  - » 2×10^{-13} m/rtHz at 10 Hz
- Test masses: 10^{-19} m/rtHz at 10 Hz
  - » Strain noise: 5×10^{-23} /rtHz, 30% & 60% of the target for high-power and low-power operation, respectively
  - » Suspensions to provide the required isolation
  - » Applies with local damping not active (longitudinal, pitch & yaw)
    - – Control comes from global feedback
  - » Must be satisfied with vertical-horizontal coupling of (no smaller than) 0.001
- Beamsplitter: < 2×10^{-17} m/rtHz at 10 Hz
  - » 10x below test mass effect
  - » Vert-horiz coupling: 1.4%

Laser frequency noise

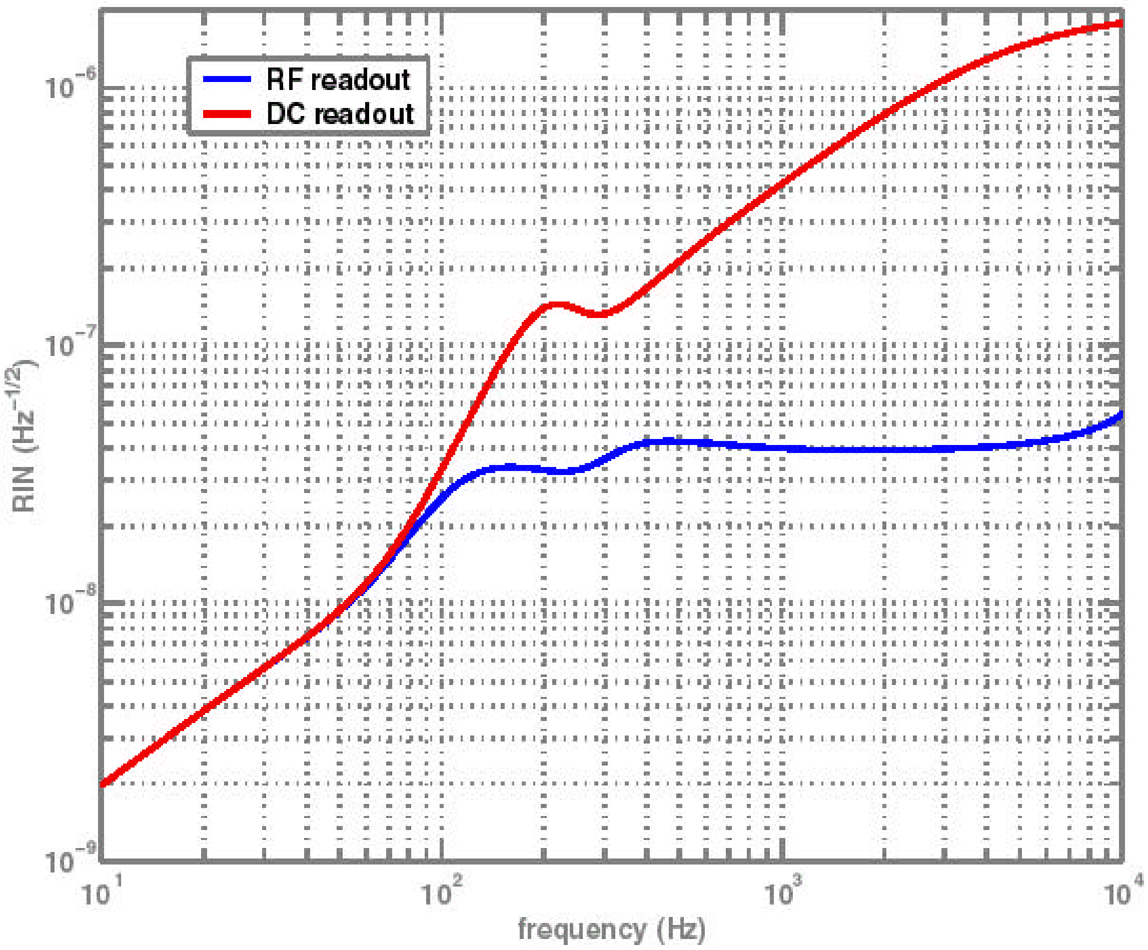


Same three-level stabilization hierarchy as in initial LIGO

PSL & MC specified with more strict RF readout req. in mind

ITM T's matched to 1%; round trip arm loss difference, 20 ppm

Laser intensity noise



Arm cavity power levels matched to 1% (feasible?)

Dominated by technical radiation pressure below 100Hz

RIN: 2 x 10^{-9}/rtHz at 10 Hz – requires about 100 ma of stabilization photocurrent

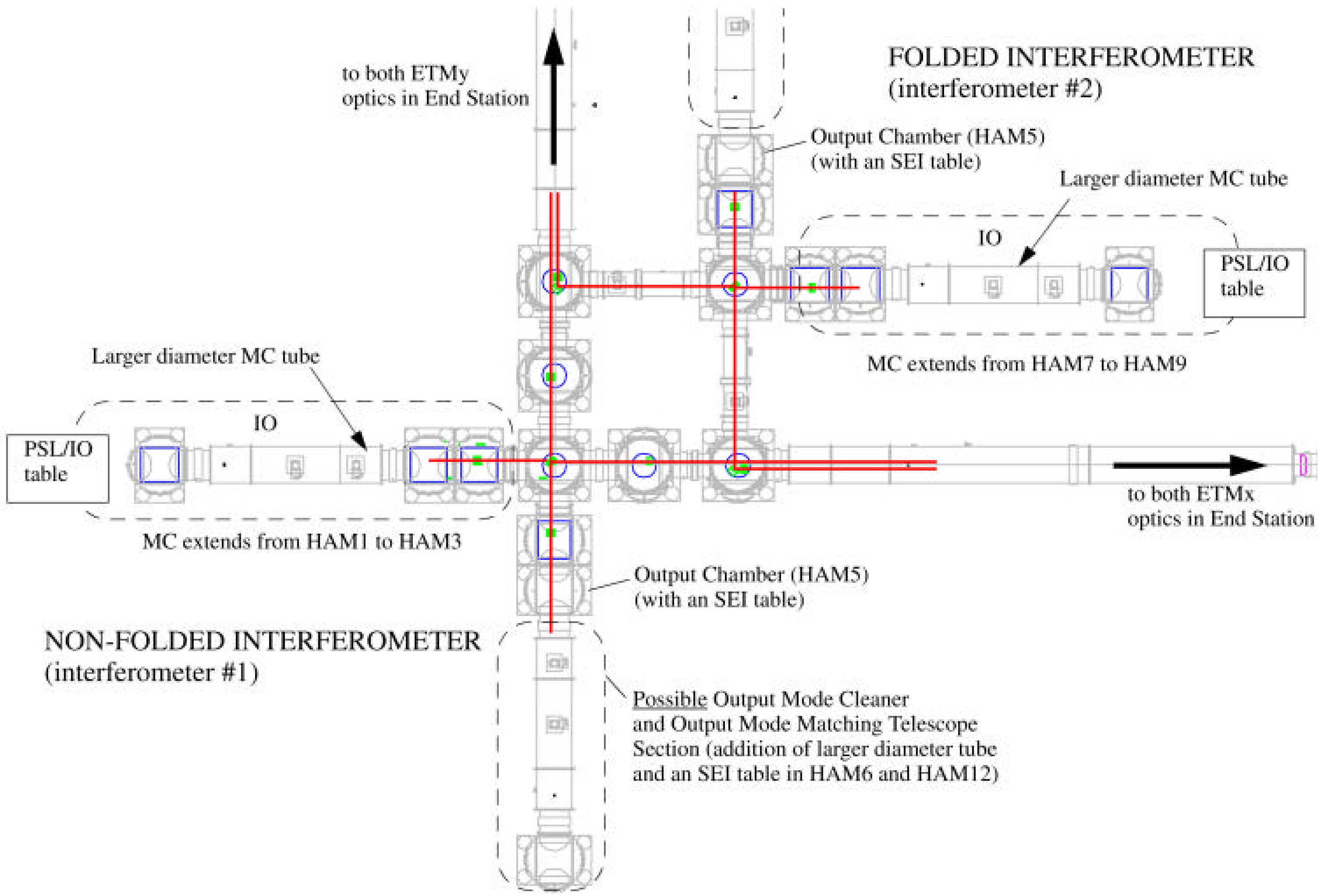
Subsystem requirements

- Primary requirements set as a result of, or to support, the systems requirements & design
- For example, PSL requirements are set for:
  - » Output power (TEM_{00} mode; higher order modes; stability)
  - » Intensity stability (gw band; control band; rf modulation freq)
  - » Frequency stability (gw band; control band)
  - » Modulation inputs (power; frequency)
- Subsystem requirements will be refined and reviewed at each subsystem's design requirements review

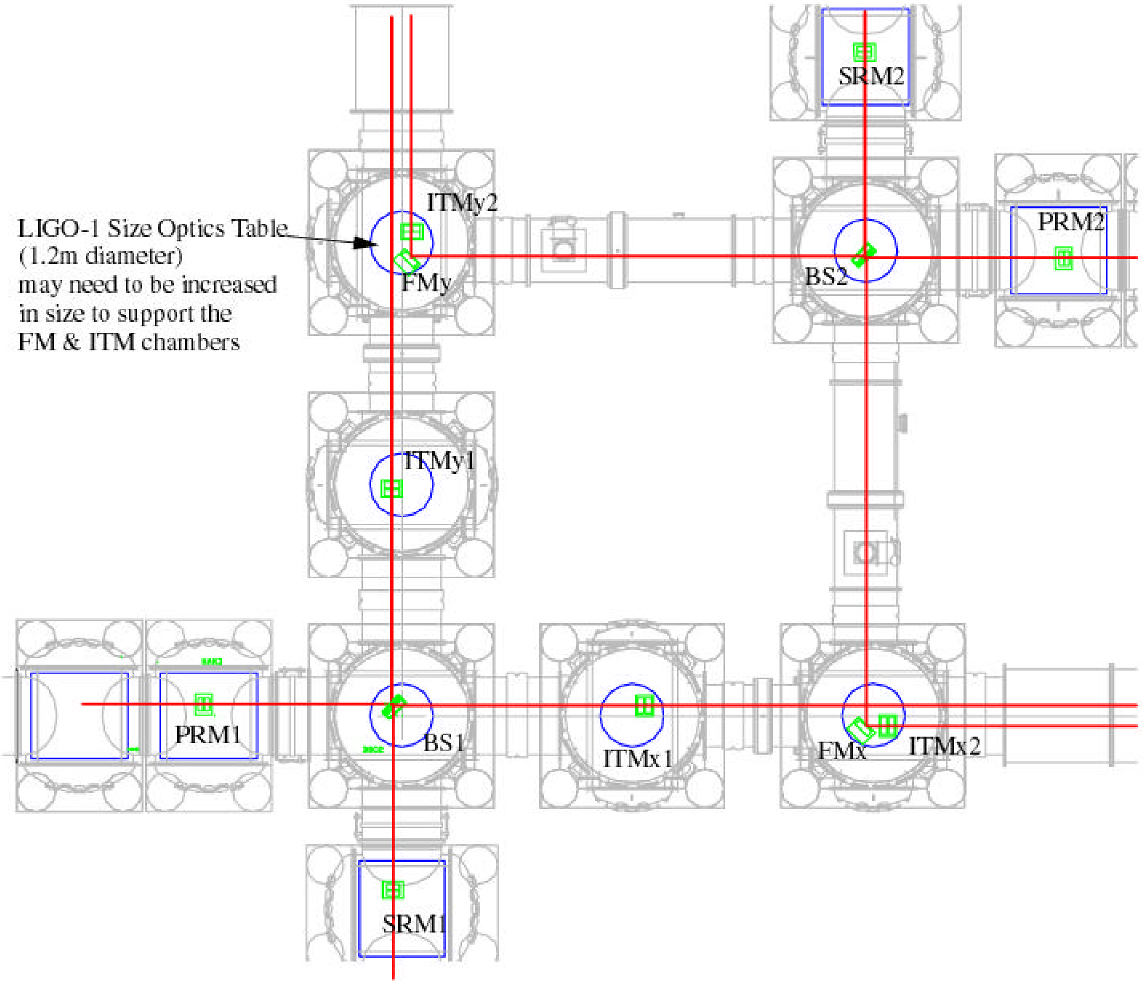
Optical Layout
Cavity Lengths

- Input Mode Cleaner (IMC)
  - » IMC FSR = ~9 MHz
  - » Length = ~16.6 m = ~HAM1 to HAM3 separation
- Power Recycling Cavity (PRC)
  - » PRC FSR = 2 x IMC FSR = ~18 MHz
  - » Length = ~8.3 m = ~HAM3 to BSC2 separation
  - » Asymmetry = 0.2 m
- Signal Recycling Cavity (SRC)
  - » f = 180 MHz
  - » Length = ~8.4 m = ~HAM4 to BSC2 separation
- Fabry-Perot (FP) Arm Cavities
  - » Length = ~4 km
- Precise frequencies and lengths in the optical layout document
  - » T010076-01
  - » Folded interferometer layout pending

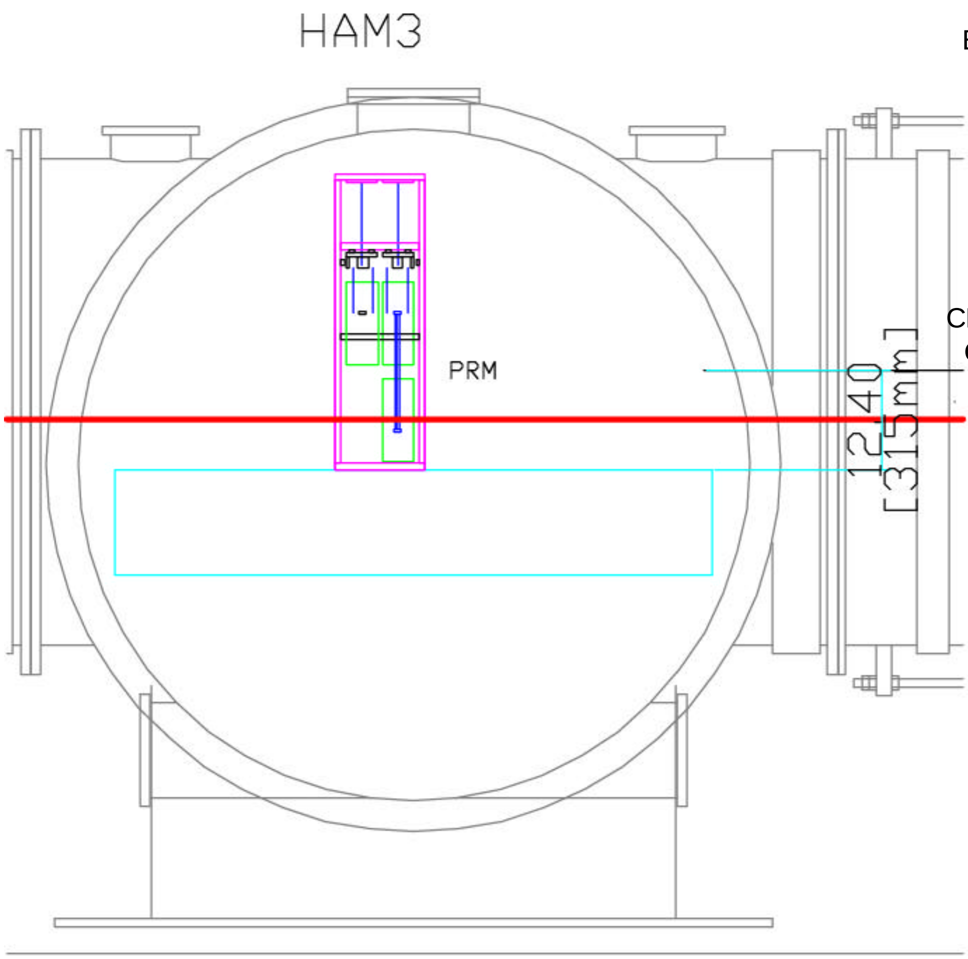
Optical Layout
Plan View

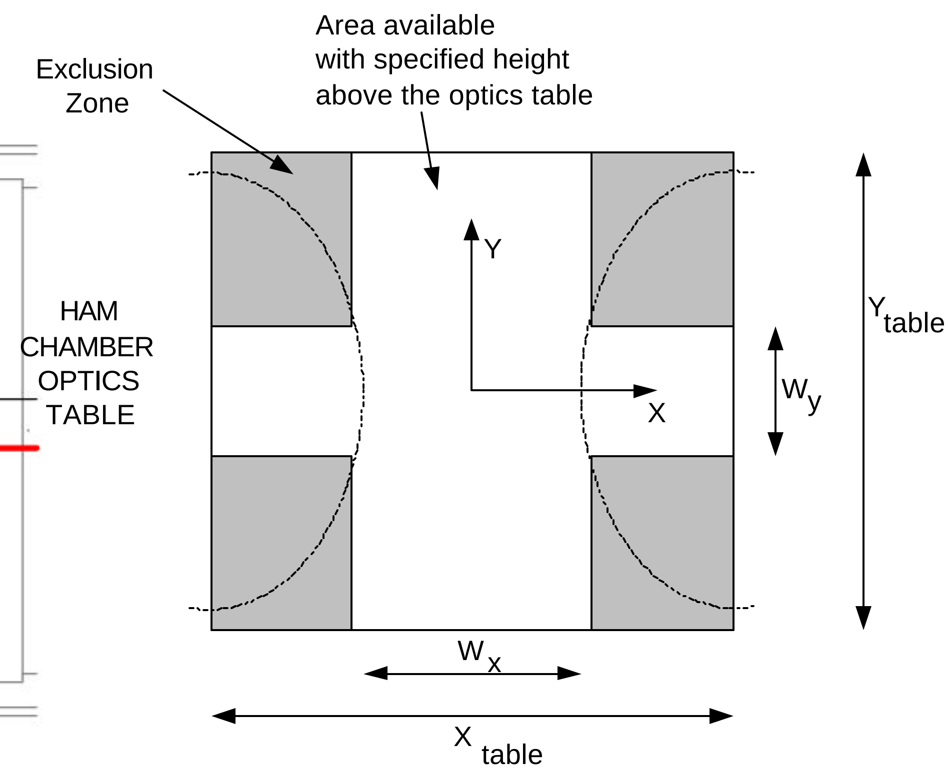


Optical Layout
Recycling Cavities



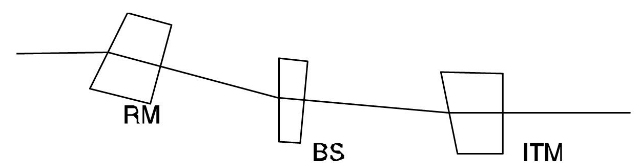
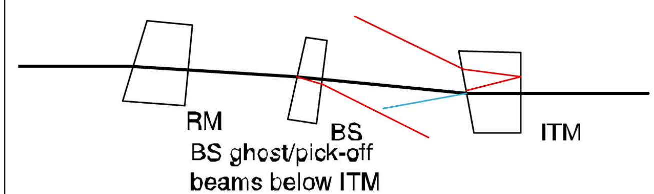
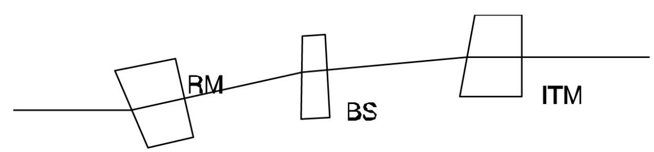
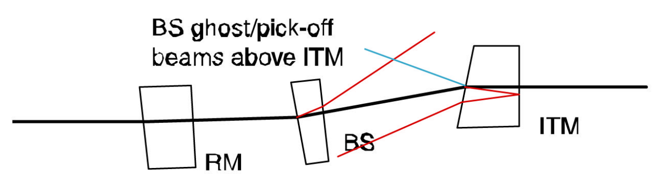
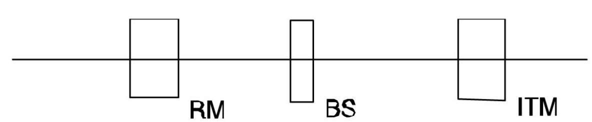
Headroom in HAM Chamber constrains MC, RM placement



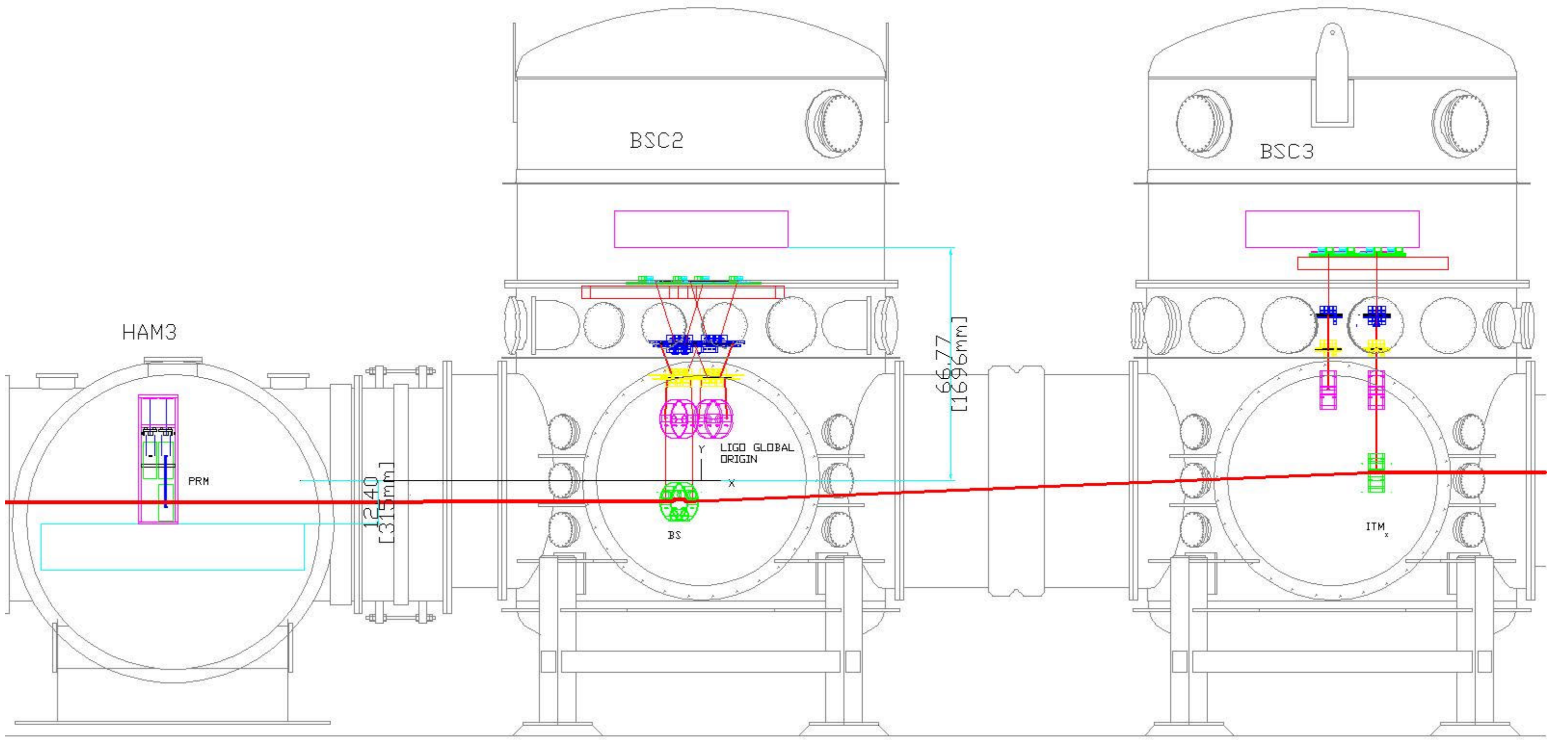


- Available area dimensions as a function of table & suspension heights are defined in T000087-01

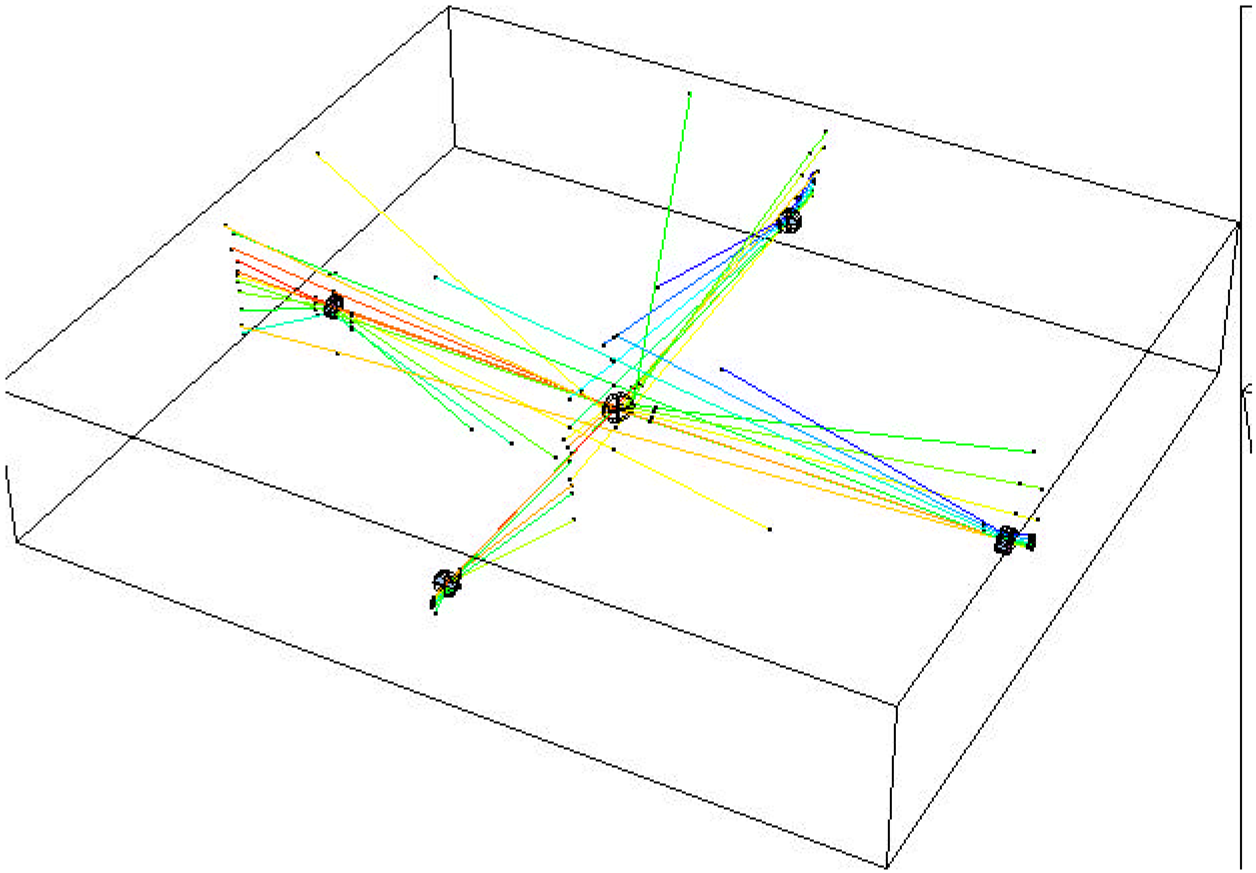
Optical Layout
Wedge Options

#	*Case*	*Refracted Path Schematic, elevation view (BS rotated into the plane and angles exaggerated for clarity)*
1	Vertical Wedges: ITM & BS with thick sides up **(like LIGO-1)**	
2	Vertical Wedges: ITM with thick side up, BS with thick side down	
3	Vertical Wedges: ITM and BS with thick sides down	
4	Vertical Wedges: ITM with thick side down, BS with thick side up **(current baseline for advanced LIGO)**	
5	Horizontal Wedges (left/right orientation will matter due to handiness associated with the folded and non-folded interferometers)	

Optical Layout Elevation View



Optical Layout Ghost Beams



Optical Layout Criteria

- Requires BS wedge angle > currently defined manufacturing limit

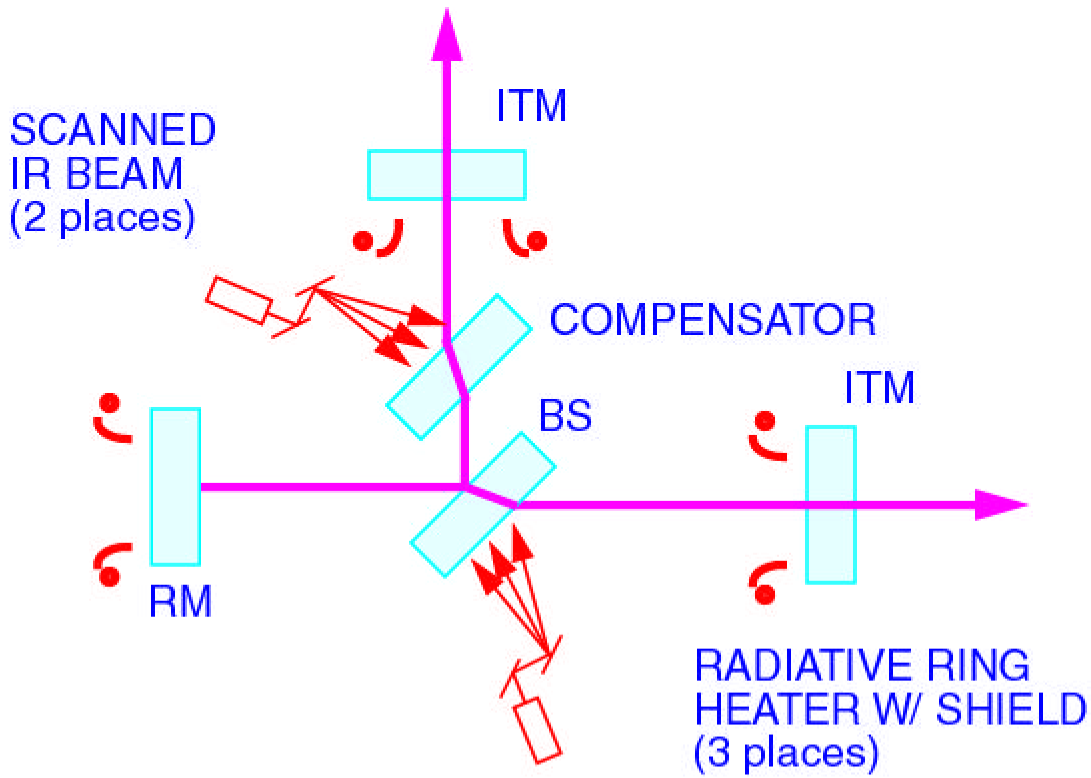
Criteria#	Parameter	IFO#1	IFO #2	Requirement
1	Lateral separation between IFO beams	TBD		>400 mm
2a	Maximum BS wedge angle	1.3 [a]	TBD	1 max
2b	Maximum ITM wedge angle	1.1	TBD	3 max
2c	Maximum PRM wedge angle	0.23	TBD	3 max
2d	Maximum SRM wedge angle	0.23	TBD	3 max
3	Wedge angle tolerance	TBD	TBD	1
4	Beam height in HAM chambers[b]	-157 mm	TBD	-157 mm
5a	BS Pickoff Beam Separation from ITM$_x$ (margin after - $2R_{100ppm}$)	16 mm [a]	TBD	> 30 mm
5b	ITM$_x$ Pickoff Beam Separation from BS (margin after - $2R_{100ppm}$)	65 mm	TBD	> 30 mm
5c	ITM$_y$ Pickoff Beam Separation from BS (margin after - $2R_{100ppm}$)	31 mm	TBD	> 30 mm
6a	BS 1st ghost separation at the ITMs (margin after - $2R_{100ppm}$)	< 0, ITMy [a]	TBD	> 30 mm
6b	ITM$_x$ 1st ghost separation at the BS (margin after - $2R_{100ppm}$)	75 mm	TBD	> 30 mm
6c	ITM$_y$ 1st ghost separation at the BS (margin after - $2R_{100ppm}$)	41 mm	TBD	> 30 mm
6d	RM 1st ghost separation at the BS (margin after - $2R_{100ppm}$)	< 0 [c]	TBD	> 30 mm
7	Beam line to baffle edge separation in the beam tube (backscatter limit)	281	TBD	> 200 mm
8	Length sensing noise due to optic wedge & pitch angle coupling (as a fraction of a FP surface contribution)	0.50, seismic 0.17, thermal	TBD	< 1, seismic < 0.28, thermal
9 to 13	constraints	all are met	TBD	see section 4

a. Need to revisit the BS maximum wedge angle criteria. BS pick-off separation would be increased with a larger BS wedge angle.
b. in the LIGO global coordinate system
c. Requires beam dumps on the BS suspension structure and a beam dump to catch the RM ghost beam reflection off of the BS, as in LIGO-1.

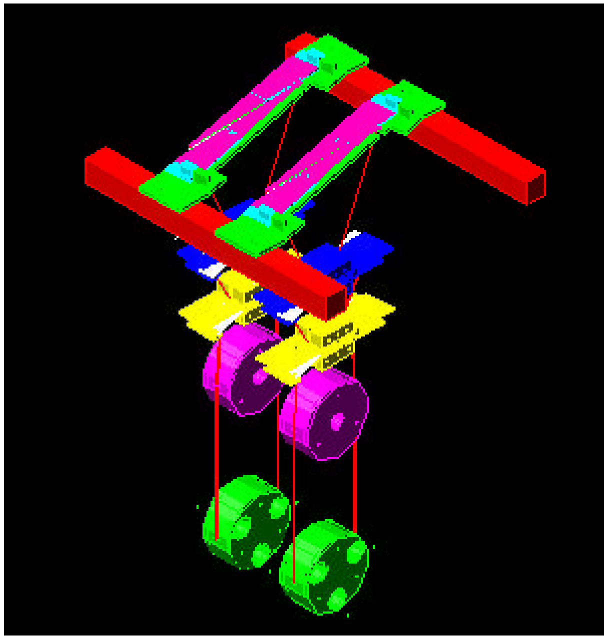
Optical Layout Issues, Limitations

- Folded interferometer layout pending
- Active thermal compensation system?
  - » May require the addition of 1 or 2 phase plates in the PRC
  - » May benefit from putting the AR side of the PRM into the PRC for common mode corrector
- Single recycling cavity pick-off beam?
  - » 3 in initial LIGO: ITMx, ITMy, BS
  - » May require only one in advanced LIGO
- Non-wedged ITMs?
- Horizontal Wedges?
  - » May be possible if a single RC pick-off is sufficient
  - » May require (somewhat) larger SEI BSC tables
    - – In fact, recommend going to maximum size square BSC SEI tables (limited by support tubes)
- Suspension planform dimensions?
  - » Layout is tight, need an estimate of SUS quad & triple base size to resolve

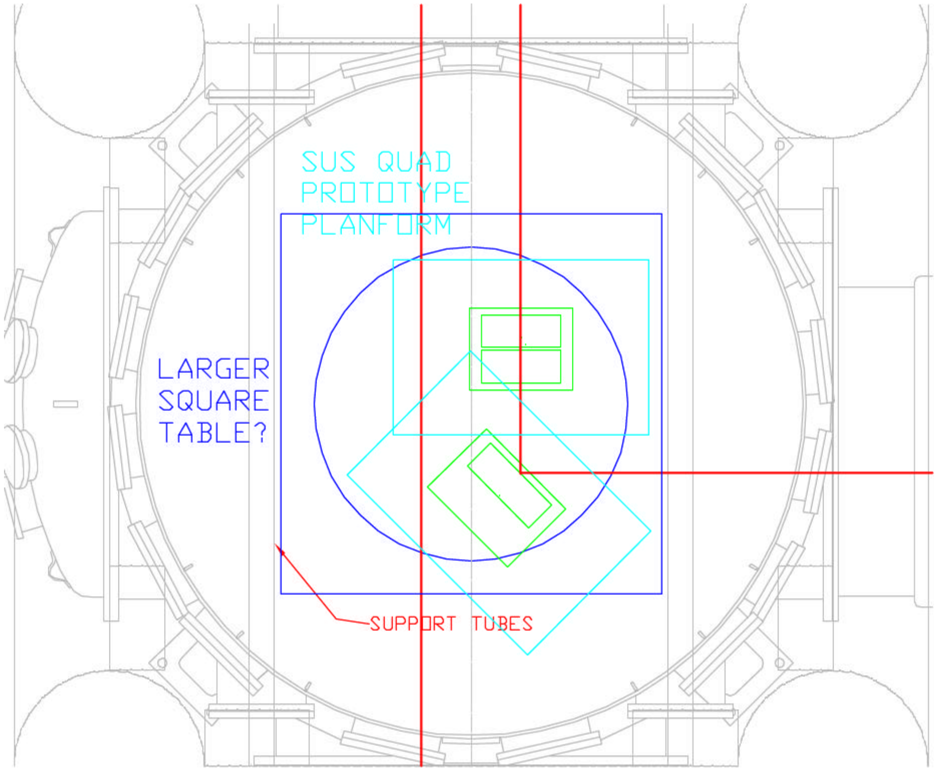
Active Thermal Compensation Potential Implementation



Suspension Table Area?



- Suspension
  - » Quadruple prototype (shown at left)
  - » Apparent planform dimensions: 700 X 1020 (lateral) mm
  - » >> than assumed 330 X 420 (lateral) mm in layout



Generic Requirements & Standards for Subsystems

- Collection of (or pointers to) the general requirements and standards which apply to all (or most) subsystems
  - » Design standards
  - » Review requirements
  - » Documentation requirements
  - » Configuration controls
  - » Test requirements
  - » EMC requirements
  - » Vacuum compatible materials, processing
  - » Etc.

Generic Requirements & Standards for Subsystems

Table of Contents

Generic Requirements & Standards for Subsystems

Generic Requirements & Standards for Subsystems

- Basically the same as initial LIGO
  - » Fill omissions, provide clarifications to initial LIGO requirements
  - » Added requirements:
    - – CAD Standards: SolidWorks & 3D preferred
      - AutoCad & 2D may be deemed acceptable on a case by case basis
    - – Earthquake limit for seismic & suspension survival & alignment retention
    - – For controlled documents: Source file archival required (in addition to Adobe AcroBat format)
    - – All piece parts must be marked with part # (= drawing # - revision S/N)
- Status of LIGO-E010123:
  - » Outline completed
  - » Content growing
  - » Comments & suggestions welcome

LIGObservatory Environment

David Shoemaker

3 July 2001

LIGO-G010242-00-D

Purpose

- An overview of the environment at the LIGO sites relevant to the design and operation of the instruments
  - » Will provides pointers to additional sources of information
- Document is organized by the quantity measured, dealing first with one site (LLO) and then the other (LHO)
- The scope of this document covers those aspects of the environment which directly relate to the instrument design and performance
  - » Criterion: if it changes during operation, the performance of the interferometer might change
  - » Should be complementary to the 'Generic Requirements for Detector Subsystems' and the two should span the space

Long-term goals

Document should

- consist of standard plots for similar measurements at different times and places and between sites
- give pointers to data for the plots to allow quantitative analysis, and give fits and approximations for estimates
- carry references to the measurements
- be updated regularly to indicate the latest information on the measured quantities

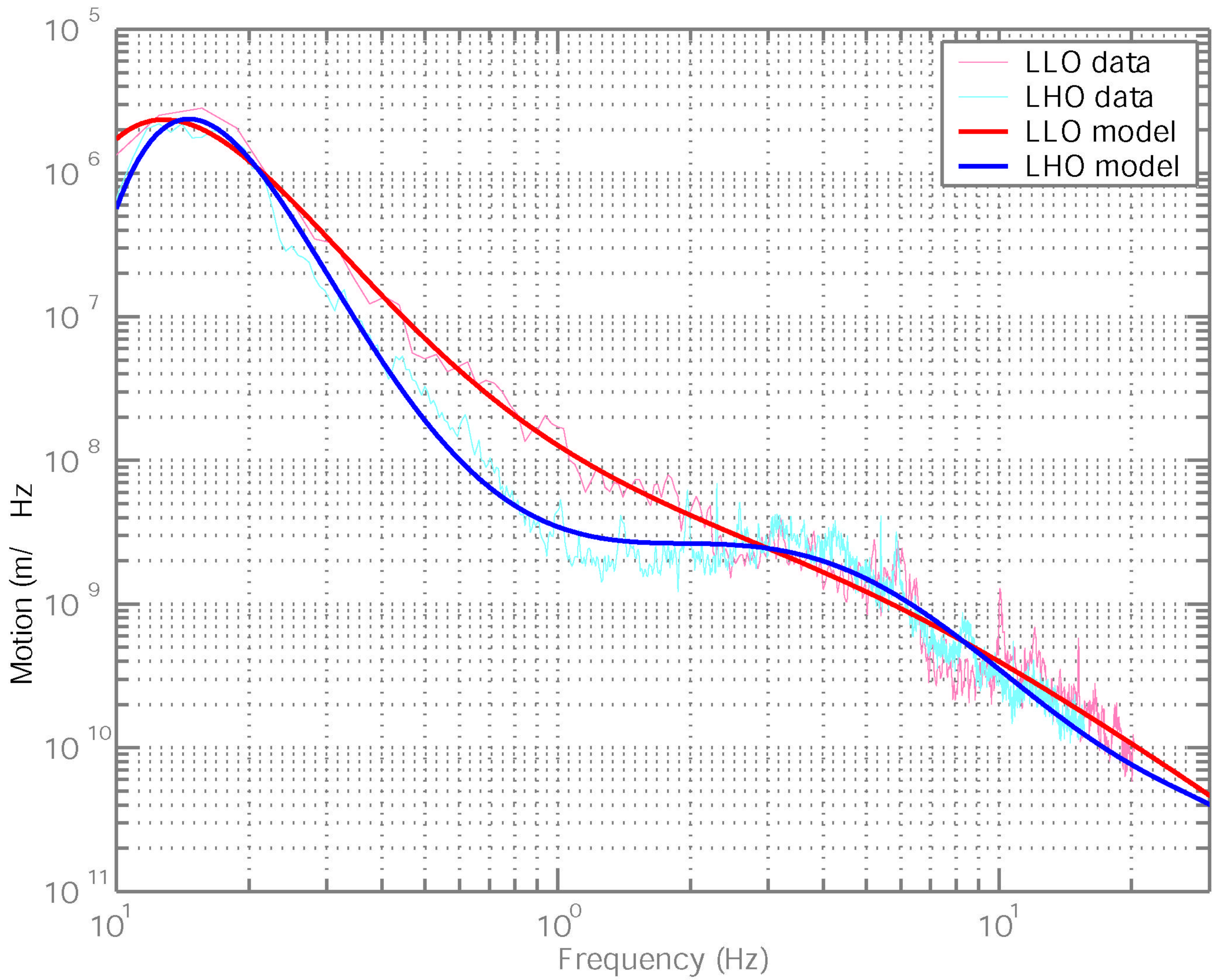
- Notion: create web sites for each observatory to carry data, additional information
  - » Maintain a single ‘paper’ document of top-level current information

…clearly, some work yet to do.

How has, how will this happen?

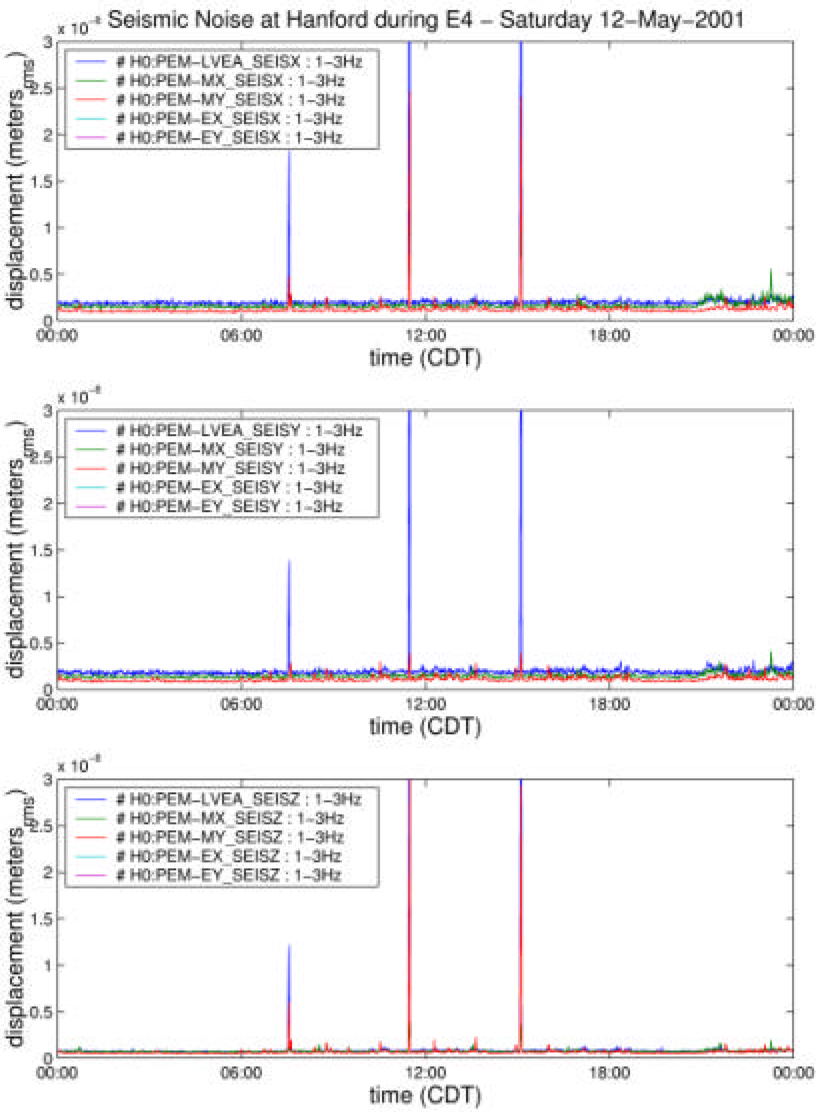
- Growing base of information: Schofield, Giaime, Daw, Johnson, Chatterji, Marka, …
- LSC Detector Characterization group: Riles et alia
- Upper Limit characterization effort
- Continuing attention from the Detector systems group

‘Standard’ seismic spectrum

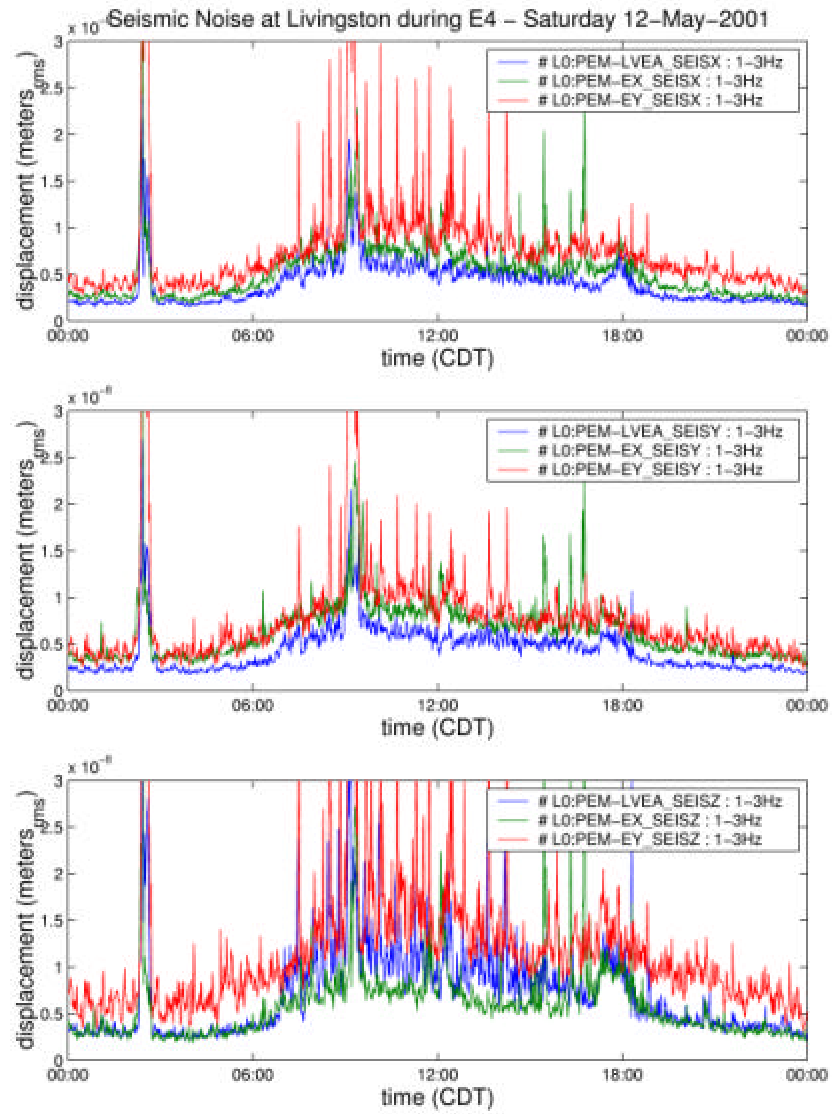


Seismic variability

LHO

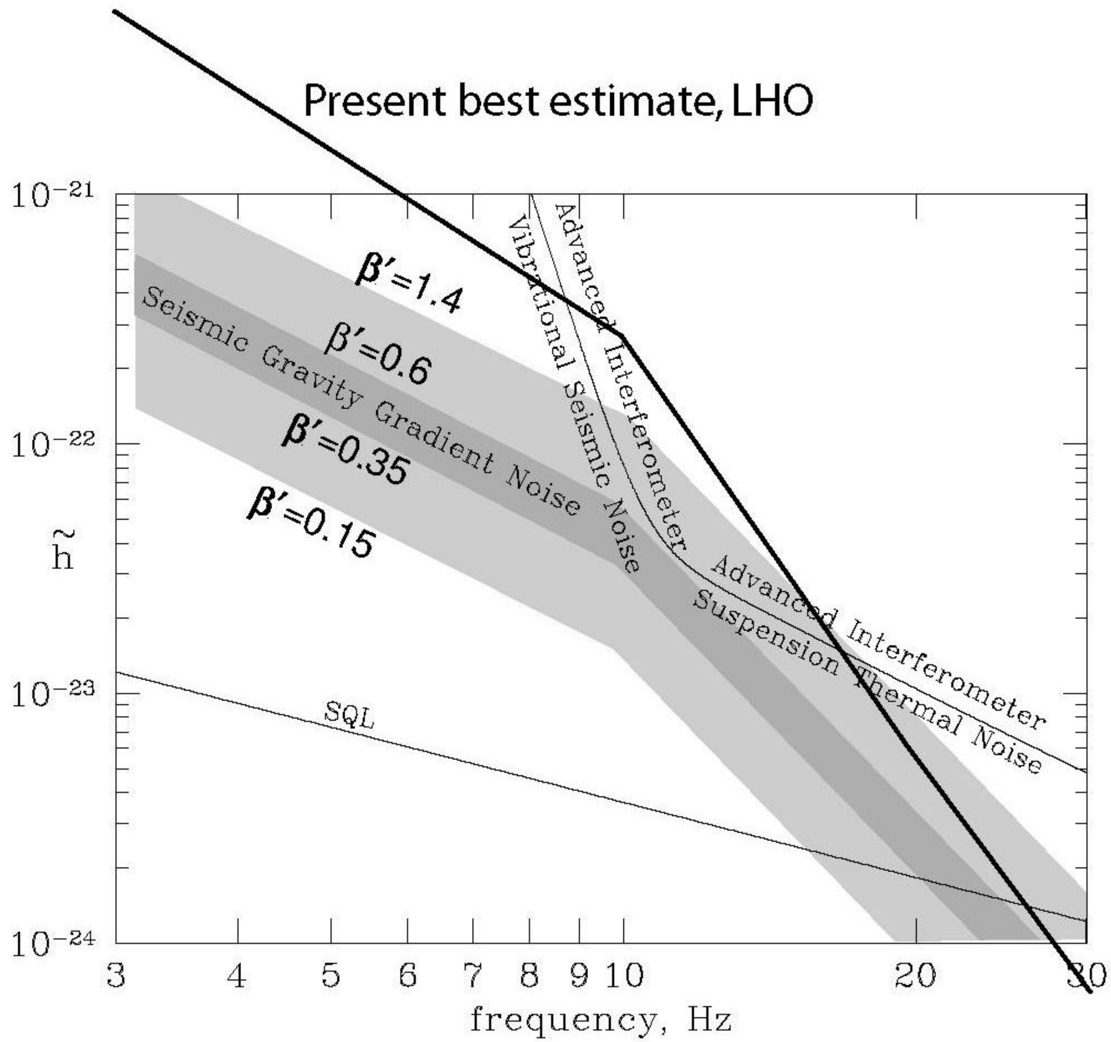


LLO

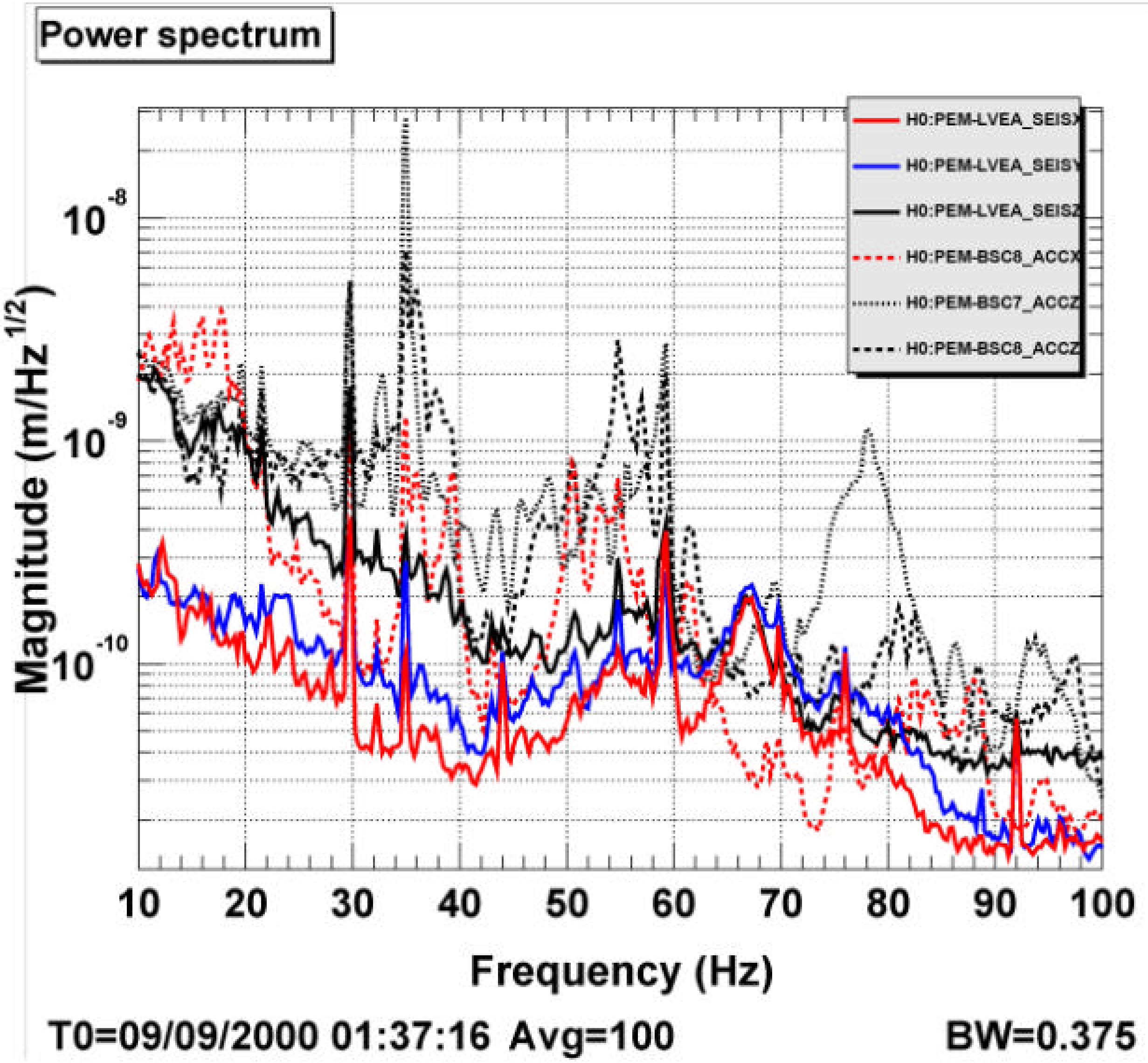


Newtonian background

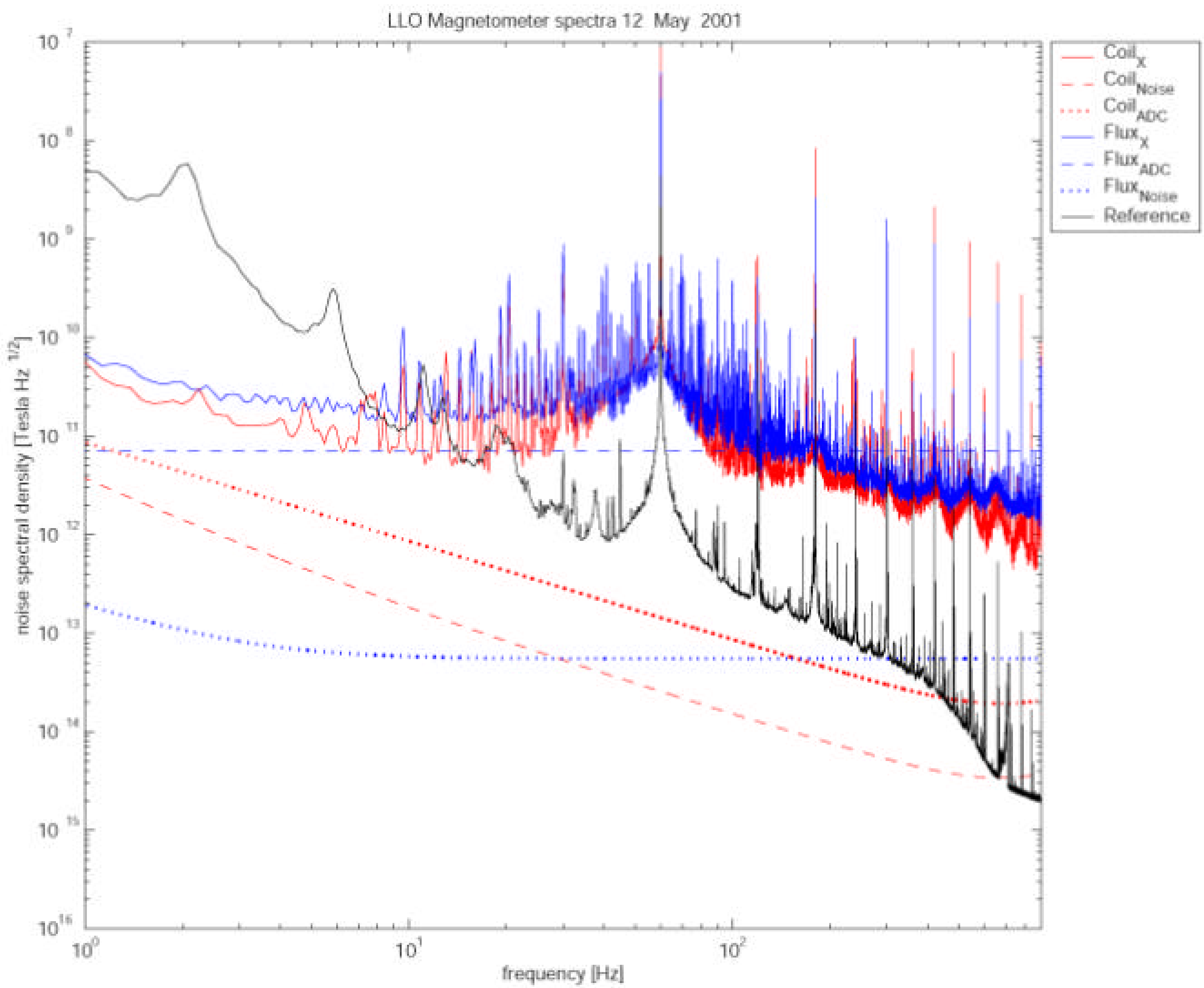
-



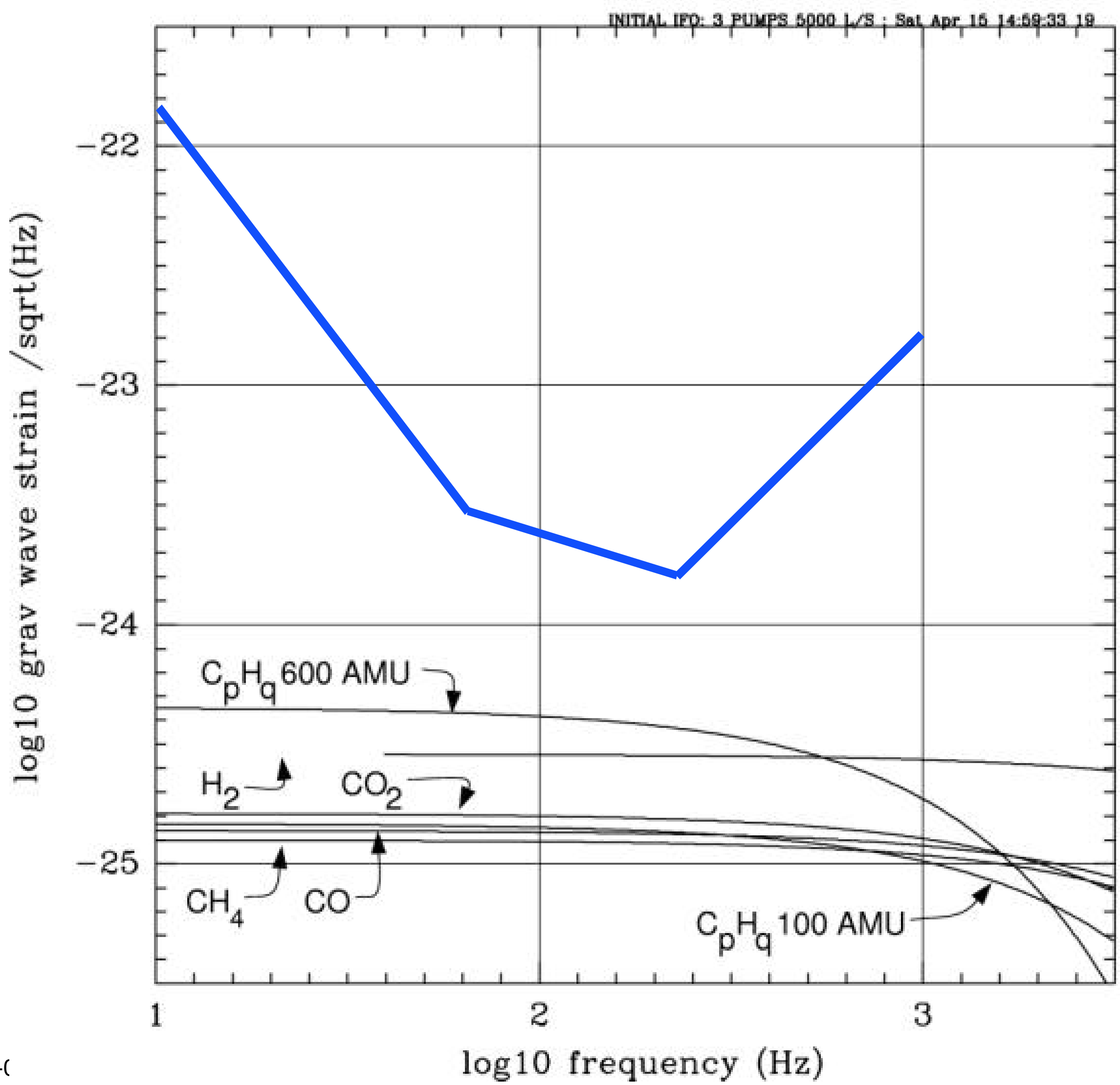
Spectrum at Seismic Supports



Magnetic fields



Residual gas



So…

- Work to do to finish an initial round of collecting existing data
- On-going work to maintain ‘environmental references’ for operation, analysis, design

Summary & Plan

- Systems design: resolution of open issues
  - » Sapphire vs fused silica
    - – Hinges mostly on success of sapphire development
    - – Selection scheduled for mid-20022
  - » Readout scheme
    - – Sensitivity analysis in progress, results are weeks-months away
    - – Bench tests of dc readout
    - – Glasgow, 40m tests
  - » Optics modeling
    - – Need to specify requirements for optics production & active thermal compensation
    - – Meeting held at MIT in May to define modeling needs and start a concentrated effort with the FFT and Melody models
- Data analysis
  - » Begin working with A Lazzarini to to scope AdLIGO data analysis

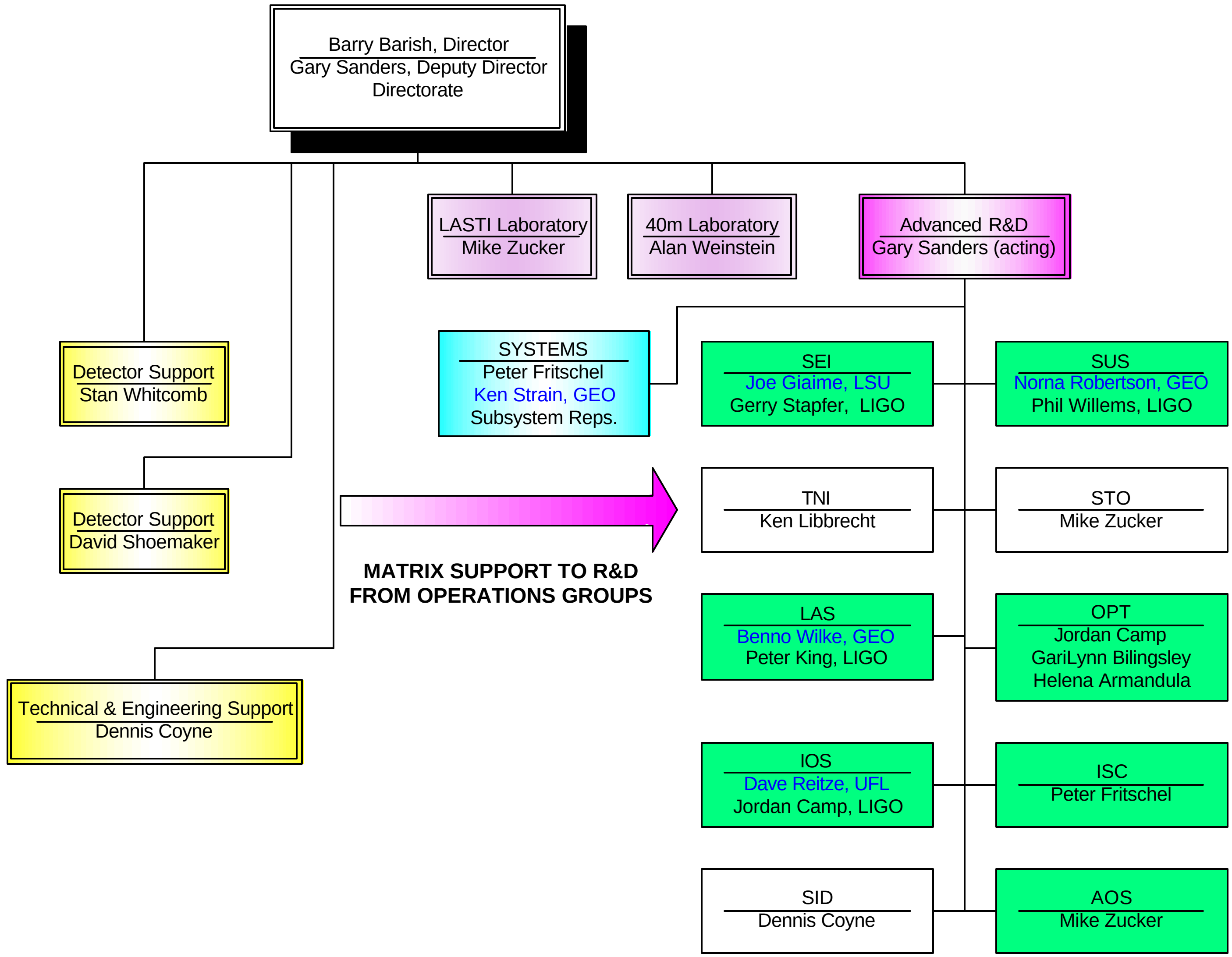
Development Plan

- R&D including Design through Final Design Review
  - » for all long lead or high risk subsystems
  - » LIGO Lab contracts and funds large R&D equipment
  - » Subsystem development plans described at the last LSC meeting (G010082)
- Construction Phase Proposal
  - » Major Research Equipment (MRE) funding
  - » includes 'prosaic' design efforts
  - » Proposal due this fall
- Isolation Test Bed (LASTI)
  - » full scale, integrated suspensions & seismic Isolation testing
  - » in-chamber assembly & installation procedure check-out
  - » possible first article test bed

Development Plan (continued)

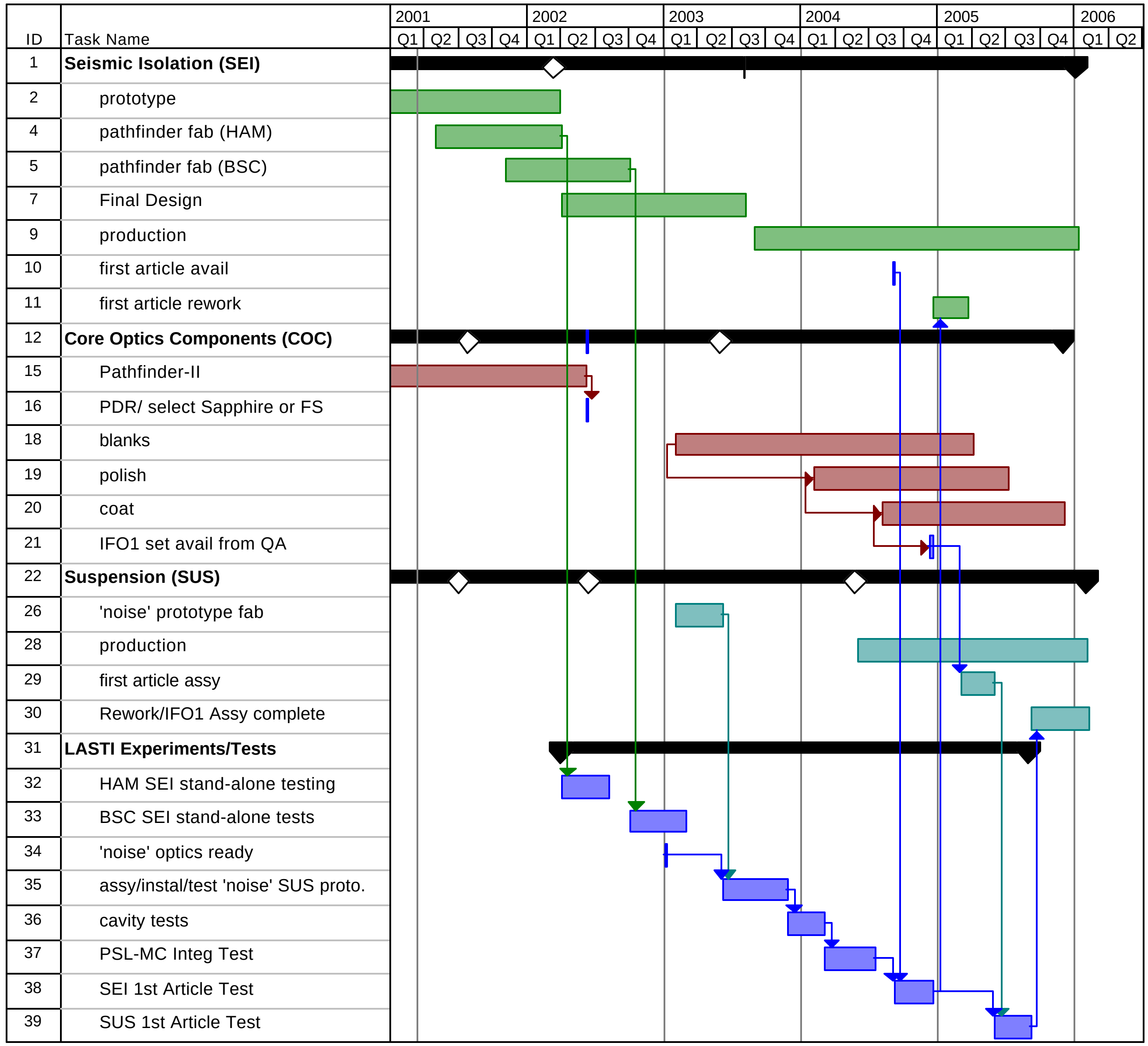
- Controls Test Beds (GEO 10m and LIGO 40m)
- High Power Test Facilities
  - » Component level testing by UFL at LLO
  - » Gingin High Power Interferometer Test Facility
- Integrated Systems Tests
  - » Pre-Stabilized Laser (PSL), Input Mode Cleaner, Suspensions and Seismic Isolation Test at LASTI
  - » Integrated Servo Control Electronics Testing at the LIGO 40m Lab
  - » Possibly early End Test Mass Suspension & Seismic Isolation replacement at a LIGO Observatory

Organization



LASTI & Supporting Subsystem Integrated Schedule

- Subsystem schedules are being integrated into a project plan
- Requirement reviews are already late
- Testbeds (LASTI, 40m, Gingin) are metronomes for the subsystems
- NSF funding limits may defer COC long lead procurement



Installation & Commissioning Plan

- Minimum of a 1 year of Integrated Science Run Before a Major Upgrade
- Schedule to be Coordinated with International GW Observatories to Keep ≥ 2 Detectors Operating
- Start Installation Only When Production & Assembly Pipeline Will Not Limit the Installation Schedule
- Install One Advanced LIGO Interferometer and Incorporate Lessons Leaned into the Subsequent Advanced Interferometers (time lag of ~ 18 months)
- Plan to start installation in early 2006