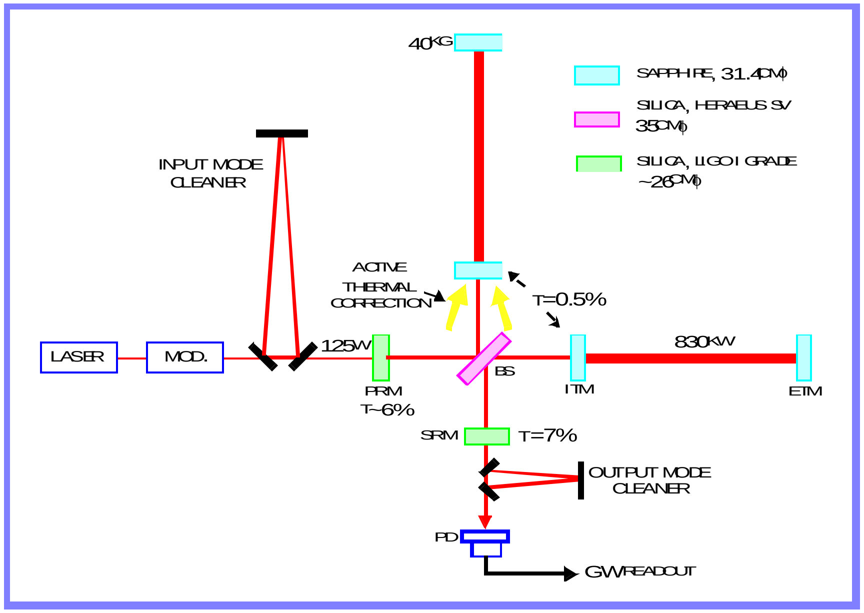
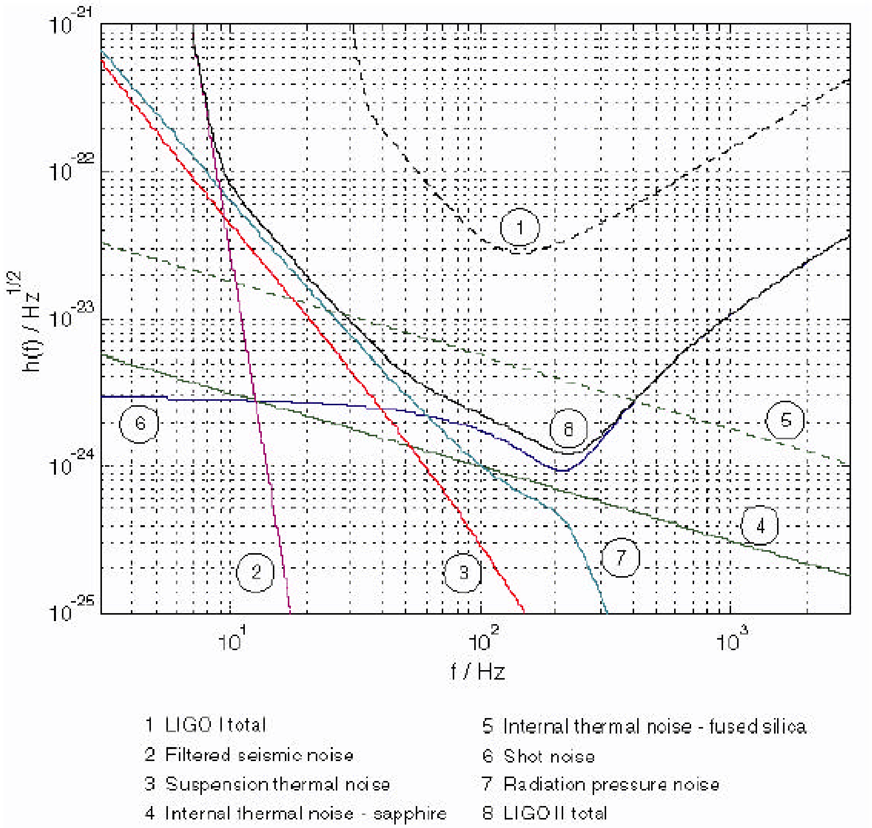
Advanced LIGO Optical Configuration Prototyping and modeling at Caltech

- **Advanced LIGO Optical Config**
  - » **Dual recycling**
  - » **Control scheme**
  - » **output mode cleaner, DC readout**
- **Caltech 40 Meter Prototype**
  - » **Objectives and scope**
  - » **Trade-offs and compromises**
  - » **Accomplishments, plans and milestones**
  - » **LSC involvement**
- **Some modeling activities**
  - » **Length sensing / control with TWIDDLE**
  - » **Alignment sensing / control with ModalModel**
  - » **Noise modeling with BENCH**
  - » **DRLIGO E2E model for lock acquisition and control**
  - » **Imperfect optics: FFT modeling**
  - » **Thermal effects using Melody**



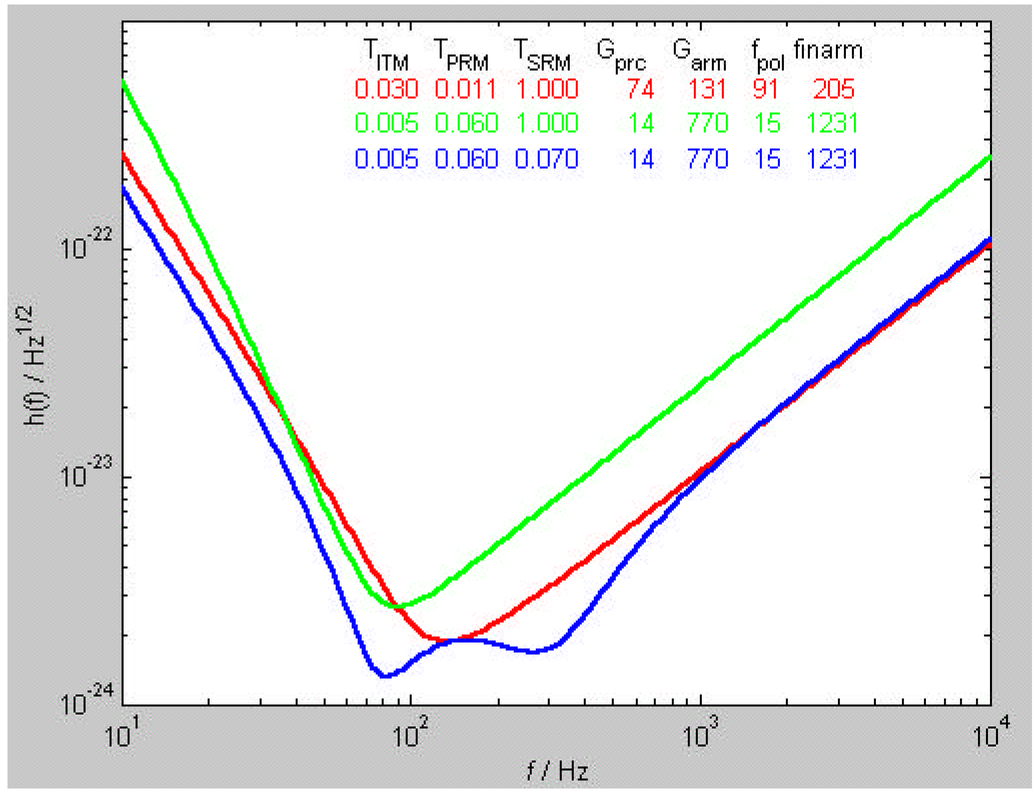
Advanced LIGO Systems

- Active seismic isolation system to reduce low-f seismic / environmental noise
- Multiple-pendulum suspensions and F-Si ribbons to reduce low-f, mid-f suspension noise
- High-Q mirror material to reduce mid-f thermal noise
- High mass (~30 kg) test-mass mirrors to reduce radiation pressure noise
- High-power (~200 W) stabilized IR laser to reduce high-f shot noise
- Dual-recycled optical configuration to tune shot-noise response vs frequency; potentially beat SQL



Dual-recycled optical configuration

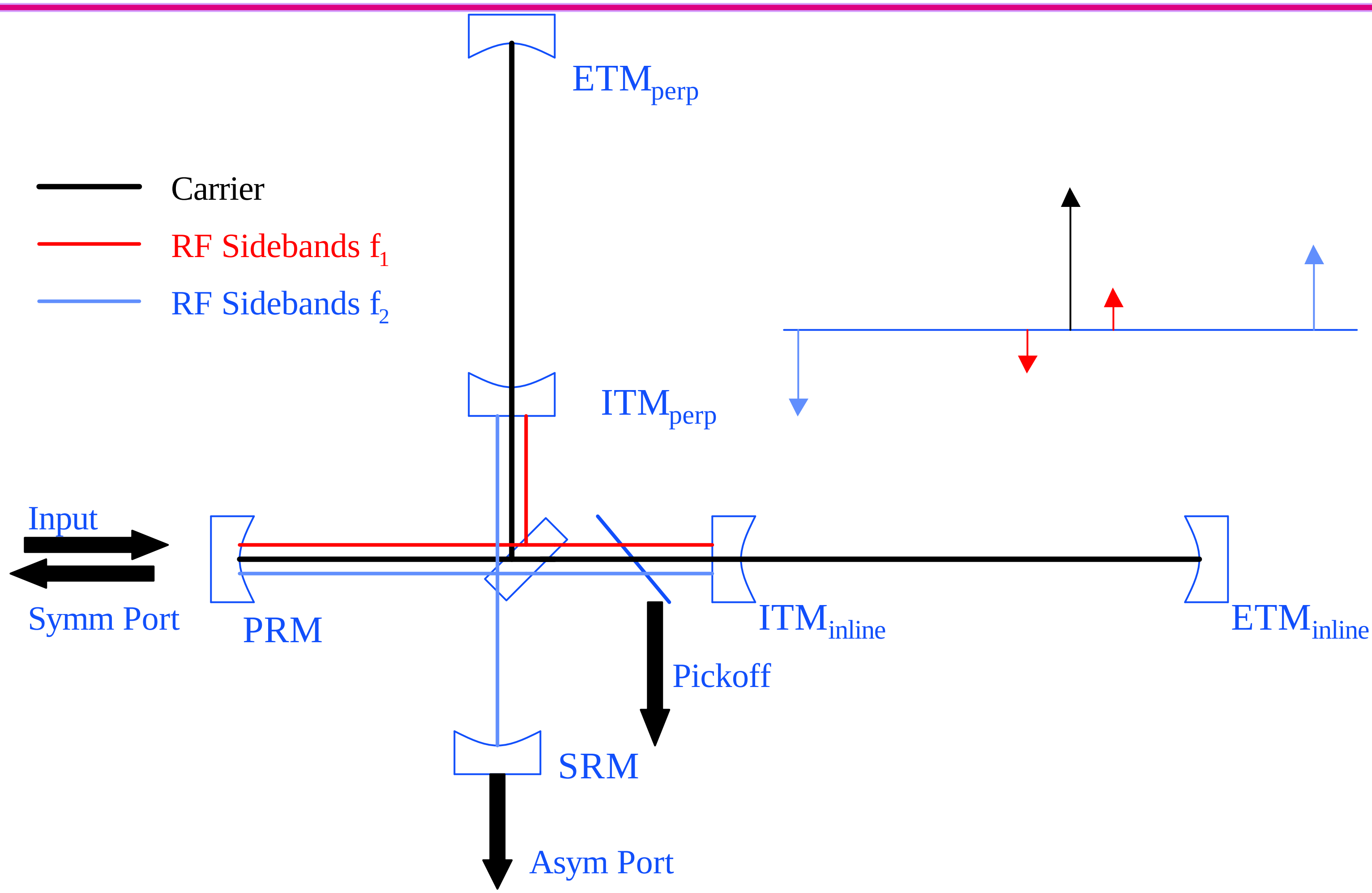
- **Fabry-Perot arms, with higher finesse than for Initial LIGO**
  - » **higher arm gain, narrowing shot noise limited bandwidth at high-f**
- **Power recycling mirror, lower PRC finesse than for Initial LIGO**
  - » **lower power recycling gain, to reduce absorption in BS, ITMs, thus reducing thermal effects in presence of higher power laser**
- **Signal recycling mirror, operating in Resonant Signal Extraction (RSE) mode, to extend bandwidth of IFO response to GW.**
  - » **Compensate for reduction in bandwidth due to higher finesse arms**
- **SRC is detuned to optimize response for GW's of ~ 300 Hz**



AdvLIGO control scheme

- **Scheme agreed upon in Aug 2000, drawing on best features of table-top prototypes, with clearer goals**
- **Must control 7 suspended optics**
  - » **forming 4 coupled cavities (2 arms, PRC, SRC)**
  - » **5 cavity lengths DOF's (L_{CM}, L_{DM}, l_{PRC}, l_{SRC}, l_{mich})**
  - » **6 pairs of angular DOF's (pitch & yaw)**
- **The SRC (nominally) does not see carrier light,**
  - » **can't use carrier light to control SRM**
- **Initial LIGO uses one pair of RF sidebands (~ 30 MHz)**
  - » **Applied before input mode cleaner**
  - » **using both sidebands in a pair in a balanced way**
  - » **Schnupp asymmetry to send RF out the dark port**
- **AdvLIGO will use two pairs of RF sidebands (~9/180 MHz)**
  - » **Applied before input mode cleaner**
  - » **9 MHz mainly reflected back to symmetric port, sensing PRM**
  - » **180 MHz transmitted to asymmetric port, sensing SRM**
  - » **Demod at 171/189 MHz to sense l_{PRC}, l_{SRC}, l_{mich}, insensitive to arms**
  - » **Because of detuned SRC, only one sideband in a pair is resonant in SRC/PRC**

Control topology for Advanced LIGO



Output mode cleaner, DC demodulation

- An output mode cleaner is desired to remove "junk" light from the asymmetric port GW signal
  - » Carrier light leaking out due to imperfect Michelson contrast
  - » RF-modulated light for heterodyne GW detection
  - » Must limit power at asym port to level manageable by available photodiodes, given the much higher power levels in AdvLIGO
- Can be a short, monolithic device like PSL pre-mode-cleaner.
- Only carrier light and GW signal sidebands exit the output MC
- Use DC (homodyne) demodulation to sense GW signal beating against carrier light local oscillator.
- The carrier light is very stable and pure TEM_{00} since it is filtered by the high-finesse arms
- Use offset-locked arms to allow a small, controlled amount of carrier light out the arms to exit the asym port to act as a local oscillator for homodyne (DC) GW detection.
- DC readout seems favored in current modeling; further work required to determine whether traditional RF readout has better quantum-limited sensitivity. RF readout remains available as a fall-back.

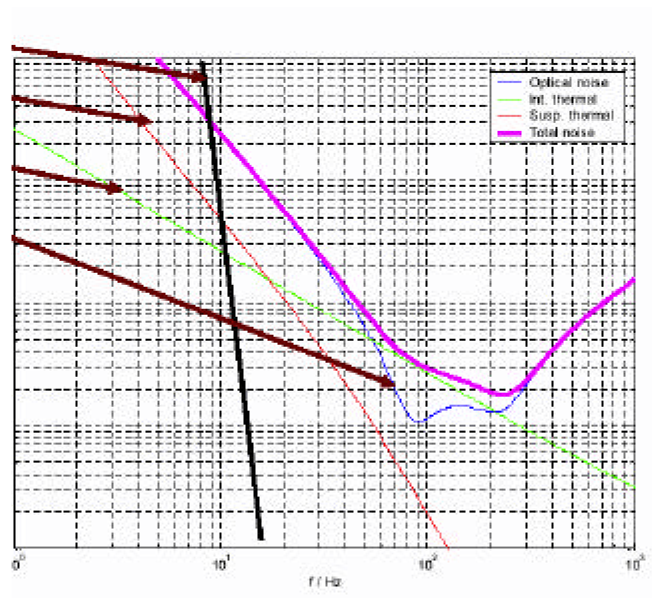
Need for prototyping optical configuration and control

- **The Advanced LIGO optical configuration and control scheme is *extremely* complex, with many innovations.**
- **A high-fidelity prototype of the system should make the transition from Initial -> Advanced LIGO far less painful**
- **LIGO observatories must remain undisturbed during initial science run, and transition between Initial -> Advanced LIGO must proceed as quickly and efficiently as possible**
- **Full engineering prototype is essential for minimizing downtime between Initial -> Advanced LIGO.**
- **The Glasgow 10m IFO will test many elements of the optical and control scheme. Results will inform the 40m program, to refine the full engineering prototyping and reduce the technical risk (K. Strain, LSC AIC chair, Glasgow).**

40m Laboratory Upgrade - Objectives

- Primary objective: full engineering prototype of optics control scheme for a dual recycling suspended mass IFO
  - » Table-top IFOs at Caltech, Florida, Australia, Japan (~ complete!)
  - » These lead to decision on control scheme by LSC/AIC (August 2000 LSC)
  - » Glasgow 10m DR prototype with multiple pendulum suspensions
  - » Then, full LIGO engineering prototype of ISC, CDS at 40m
  - » First look at DR shot noise response (*high-f*)

- Other key elements of AdvLIGO are prototyped elsewhere:
  - »**LASTI, MIT**: full-scale prototyping of Adv.LIGO SEI, SUS (*low-f*)
  - »**TNI, Caltech** : measure thermal noise in Adv.LIGO test masses (*mid-f*)
  - » **AIGO, Gingin** : high powered laser, thermal effects, control stability
  - »**ETF, Stanford:** advanced IFO configs (Sagnac), lasers, etc



Advanced LIGO technical innovations tested at 40m

- **a seventh mirror for signal recycling**
  - » **(length control goes from 4x4 to 5x5 MIMO)**
- **detuned signal cavity (carrier off resonance)**
- **pair of phase-modulated RF sidebands**
  - » **frequencies made as low and as high as is practically possible**
  - » **unbalanced: only one sideband in a pair is used**
  - » **double demodulation to produce error signals**
- **short output mode cleaner**
  - » **filter out all RF sidebands and higher-order transverse modes**
- **offset-locked arms**
  - » **controlled amount of arm-filtered carrier light exits asym port of BS**
- **DC readout of the gravitational wave signal**

Much effort to ensure high fidelity between 40m and Adv.LIGO!

Differences between AdvLIGO and 40m prototype

- **Initially, LIGO-I single pendulum suspensions will be used**
  - » **Full-scale AdvLIGO multiple pendulums will not fit in vacuum chambers**
  - » **to be tested at LASTI**
  - » **Scaled-down versions can fit, to test controls hierarchy – in 2004?**
- **Only commercial active seismic isolation**
  - » **STACIS isolators already in use on all 4 test chambers**
  - » **providing ~30 dB of isolation in 1-100 Hz range**
  - » **No room for anything like full AdvLIGO design – to be tested at LASTI**
- **LIGO-I 10-watt laser, negligible thermal effects**
  - » **Other facilities will test high-power laser: LASTI, Gingin, …**
  - » **Thermal compensation also tested elsewhere**
- **Small (5 mm) beam spot at TM's; stable arm cavities**
  - » **AdvLIGO will have 6 cm beam spots, using less stable cavities**
  - » **40m can move to less stable arm cavities if deemed useful**
- **Arm cavity finesse at 40m chosen to be = to AdvLIGO**
  - » **Storage time is x100 shorter**
  - » **significant differences in lock acquisition dynamics, in predictable ways**
- **Due to shorter PRC length, control RF sidebands are 36/180 MHz instead of 9/180 MHz; less contrast between PRC and SRC signals**

40m Laboratory Upgrade – More Objectives

- Expose shot noise curve, dip at tuned frequency
- Multiple pendulum suspensions
  - » this may be necessary, to extrapolate experience gained at 40m on control of optics, to LIGO-II
  - » For testing of mult-suspension controllers, mult-suspension mechanical prototypes, interaction with control system
  - » Not full scale. Insufficient head room in chambers.
  - » Won't replace full-scale LASTI tests.
- thermal noise measurements
  - » Mirror Brownian noise will dominate above 100 Hz.
- Facility for testing/staging small LIGO innovations
- Hands-on training of new IFO physicists!
- Public tours (SURF/REU students, DNC media, princes, etc)

40m Infrastructure

- **Dismantling of old IFO, distribution of surplus equipment to LIGO and LSC colleagues**
- **Major building rehab:**
  - » **IFO hall enlarged for optics tables and electronics racks**
  - » **roof repaired, leaks sealed**
  - » **new electrical feeds and conditioners, 12" cable trays, etc**
  - » **new control room and physicist work/lab space**
  - » **New entrance room/changing area**
  - » **rehab of cranes, safety equipment, etc**
- **Active seismic isolation system (STACIS) procured, installed, and commissioned on all four test mass chambers**

STACIS Active seismic isolation

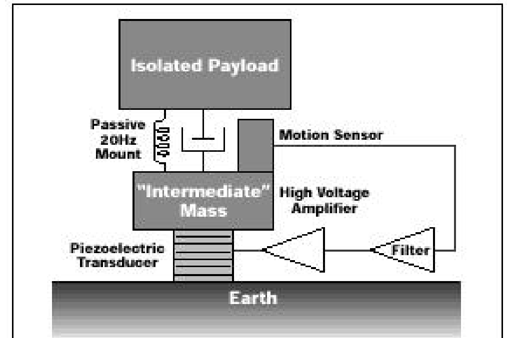
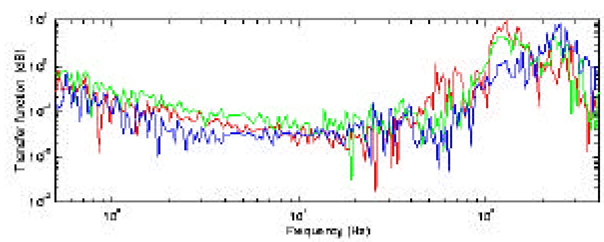
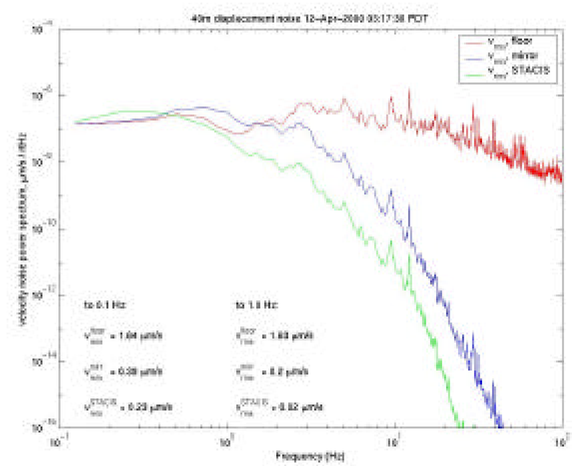


Figure 18

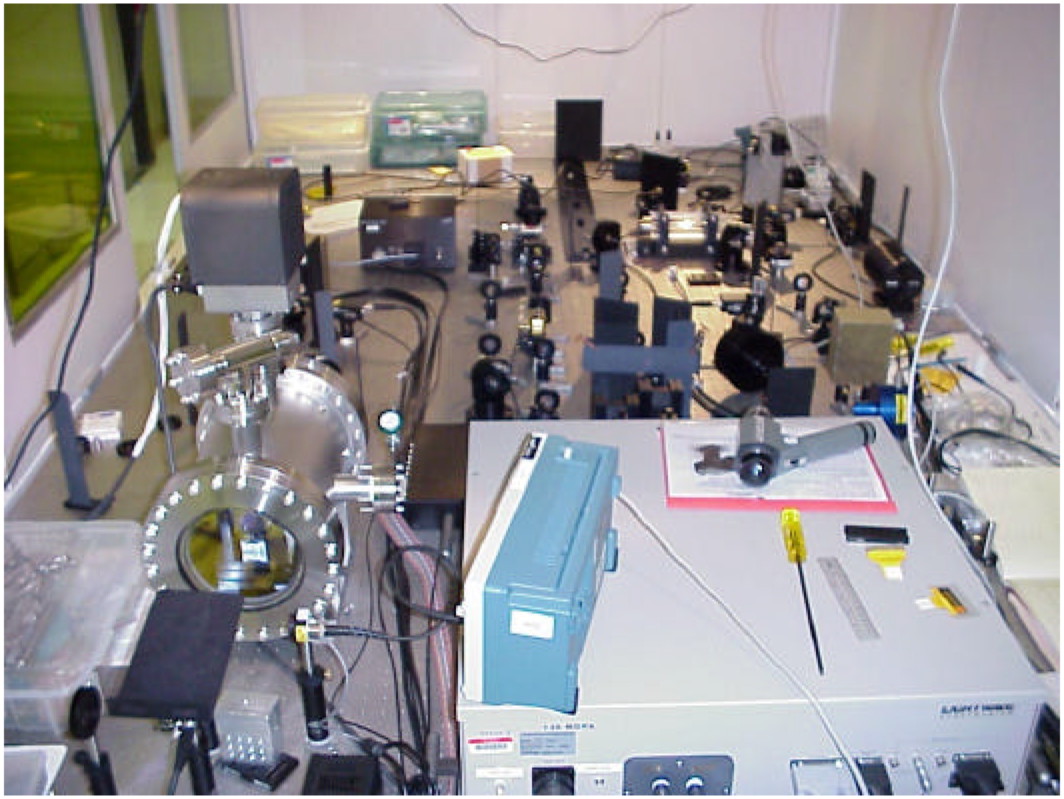
- One set of 3 for each of 4 test chambers
- 6-dof stiff PZT stack
- Active bandwidth of 0.3-100 Hz,
- 20-30dB of isolation
- passive isolation above 15 Hz.



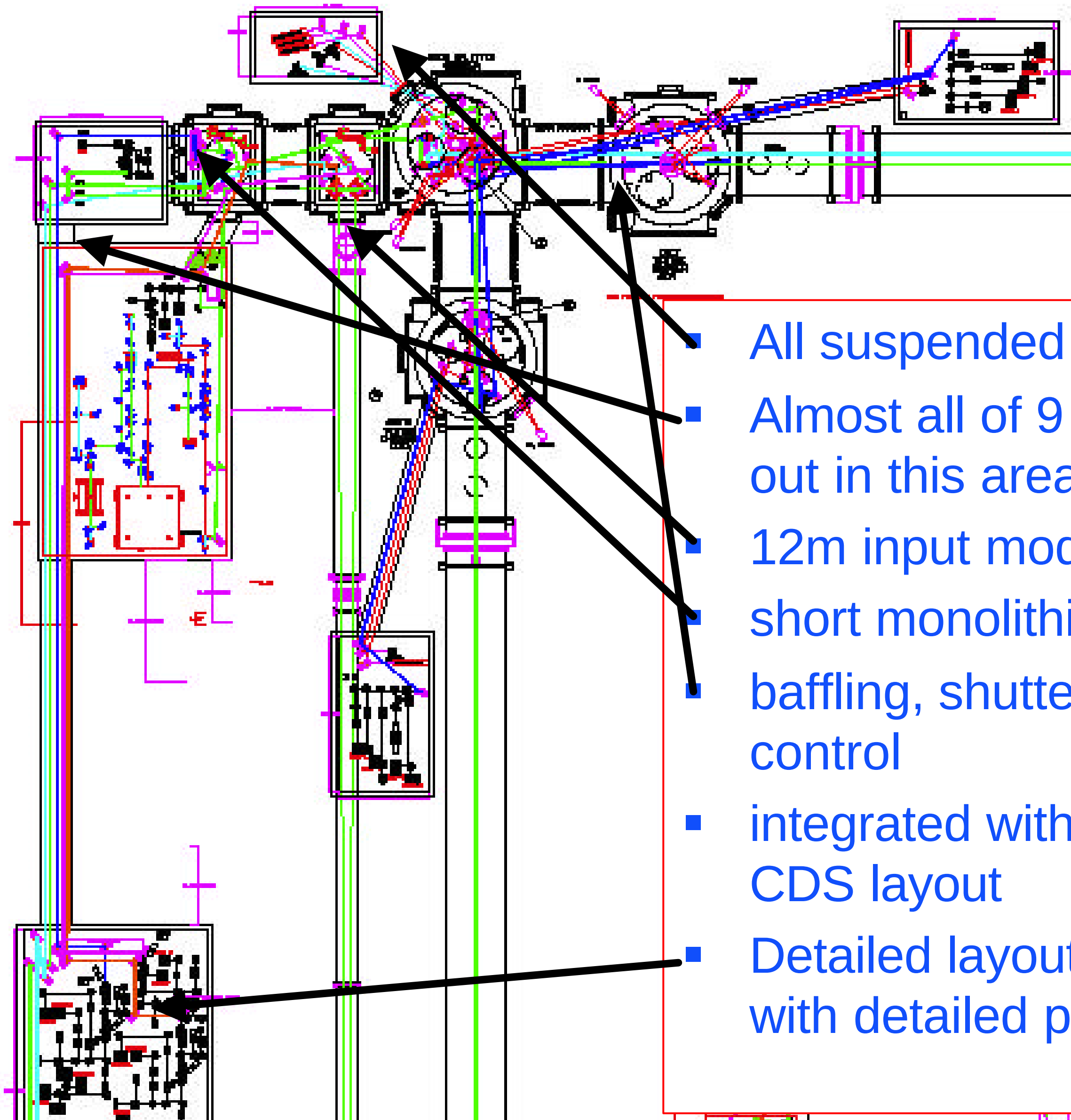


40m Infrastructure, continued

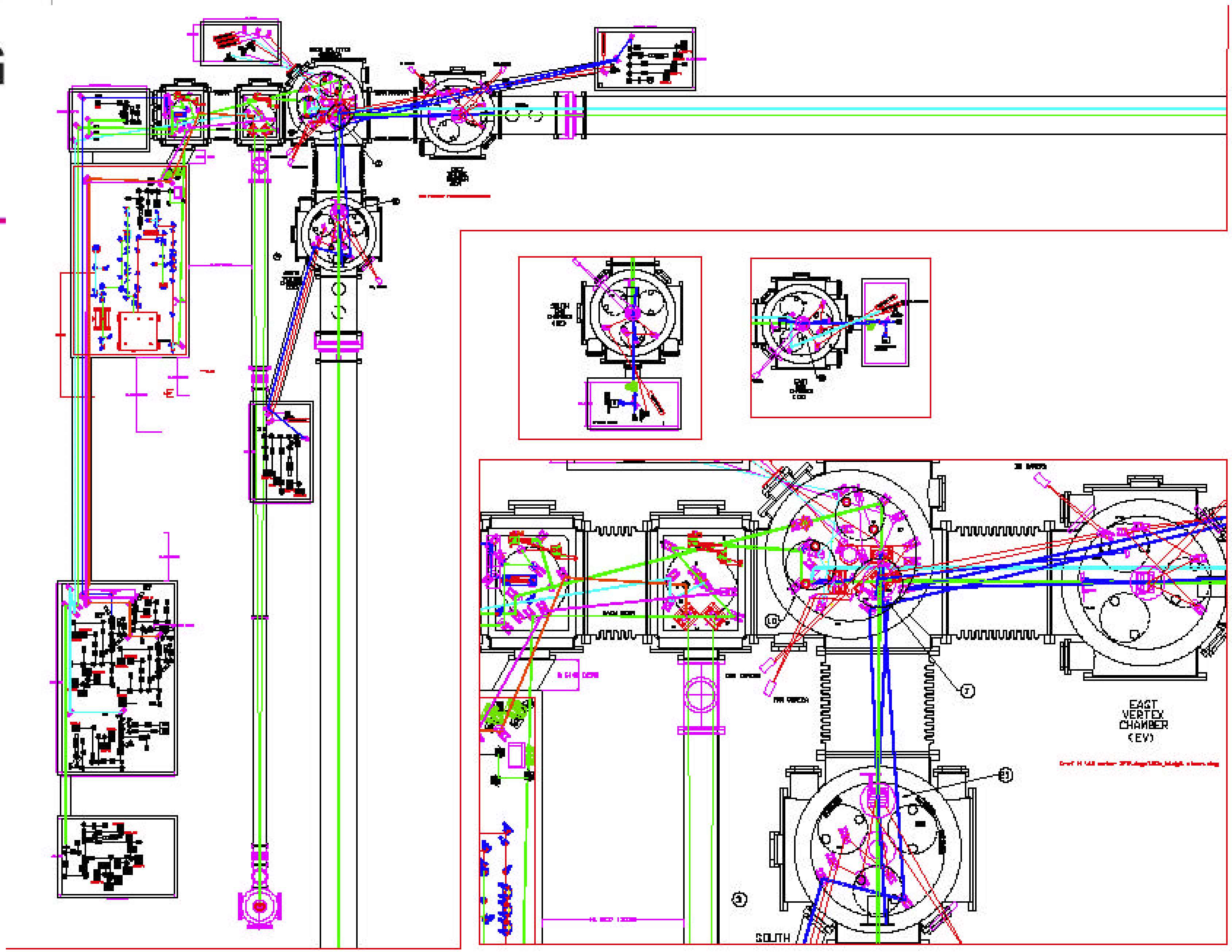
- **New vacuum control system and vacuum equipment**
  - » **Installed and commissioned**
- **New output optic chamber, seismic stack fabricated**
  - » **To be installed in summer 2001**
- **Vacuum envelope for 12 m input mode cleaner fabricated**
  - » **To be installed in summer 2001**
- **Electronics racks, crates, computers, network… procured and installed**
- **LIGO PSL installed and commissioned**
  - » **Full characterization in summer 2001**



Optical Layout



- All suspended optics have OpLevs
- Almost all of 9 output beams come out in this area
- 12m input mode cleaner
- short monolithic output MC
- baffling, shutters, scattered light control
- integrated with building, electrical, CDS layout
- Detailed layout of all ISC tables, with detailed parts lists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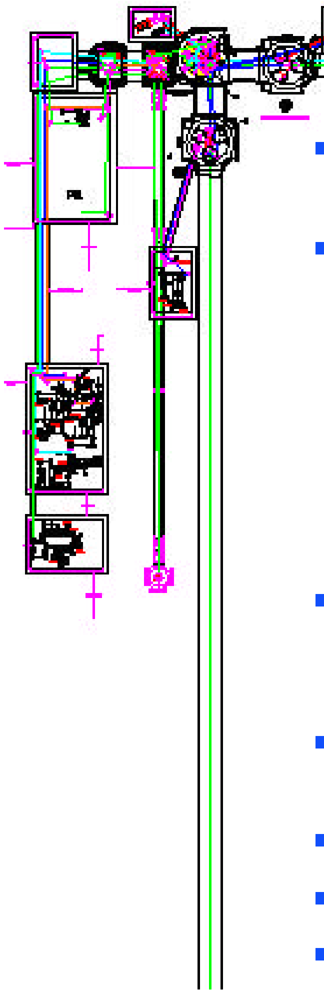
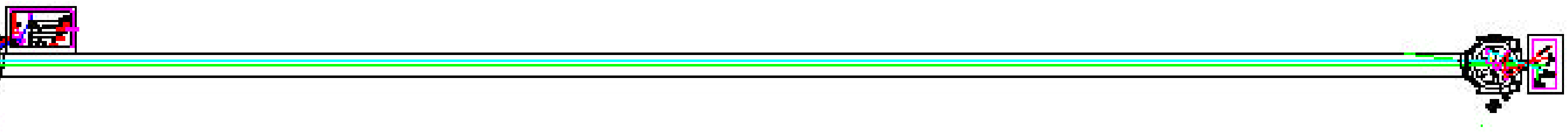
Accomplishments in last year: IFO planning





- **New 12 meter input mode cleaner design finalized**
  - » vacuum envelope assembly in summer/fall 2001
- **Detailed optical layout in advanced stages**
  - » all in-vacuum components laid out
  - » optical levers for all suspended masses
  - » baffling, scattered light suppression, shutters, etc
  - » Nine output beams routed to optical tables near electronics racks
  - » Detailed layout and parts list for all ISC tables
  - » input mode cleaner, output mode cleaner, mode-matching telescopes laid out
  - » integrated with building, electrical, CDS layout
- **Suspended optic glass blanks received**
  - » MC optics currently being polished
  - » MC optics coating, core optics polishing and coating in coming year
- **Initial-LIGO SOS suspensions for MC, BS, RM, SM machined**
  - » Assembly and hanging of optics, in early 2002
- **Scaled SOS suspensions for ITMs, ETMs under design**
- **Detailed WBS for construction**
- **Detailed WBS for experiment is in progress**

Milestones through 2004

- **4Q 2001: Infrastructure complete**
  - » **PSL, 12m MC, vacuum controls, DAQS, PEM**
- **4Q 2002:**
  - » **Core optics and suspensions ready. Suspension controllers. Some ISC.**
  - » **Glasgow 10m experiment informs 40m program**
  - » **Control system finalized**
- **2Q 2003:**
  - » **auxiliary optics, IFO sensing and control systems assembled**
- **3Q 2003: Core subsystems commissioned, begin experiments**
  - » **Lock acquisition with all 5 length dof's, 2x6 angular dof's**
  - » **measure transfer functions, noise**
  - » **Inform CDS of required modifications**
- **3Q 2004: Next round of experiments.**
  - » **DC readout. Multiple pendulum suspensions?**
  - » **Final report to LIGO Lab.**

LSC involvement

- At March 2001 LSC meeting, issued a CALL FOR INTEREST in forming an Advanced LIGO Optical Control Configuration experimental group focused on the prototyping activities at the 40m.
- There will be many meaty tasks ripe for LSC involvement.
- A draft Conceptual Design Document will be available for review by that time.
- We expect that the Optical Control Configuration will evolve and maybe depart from the scheme outlined at the August 2000 LSC meeting; we must remain flexible for as long as possible to ensure high fidelity between the 40m prototype and what will be realized in Advanced LIGO!

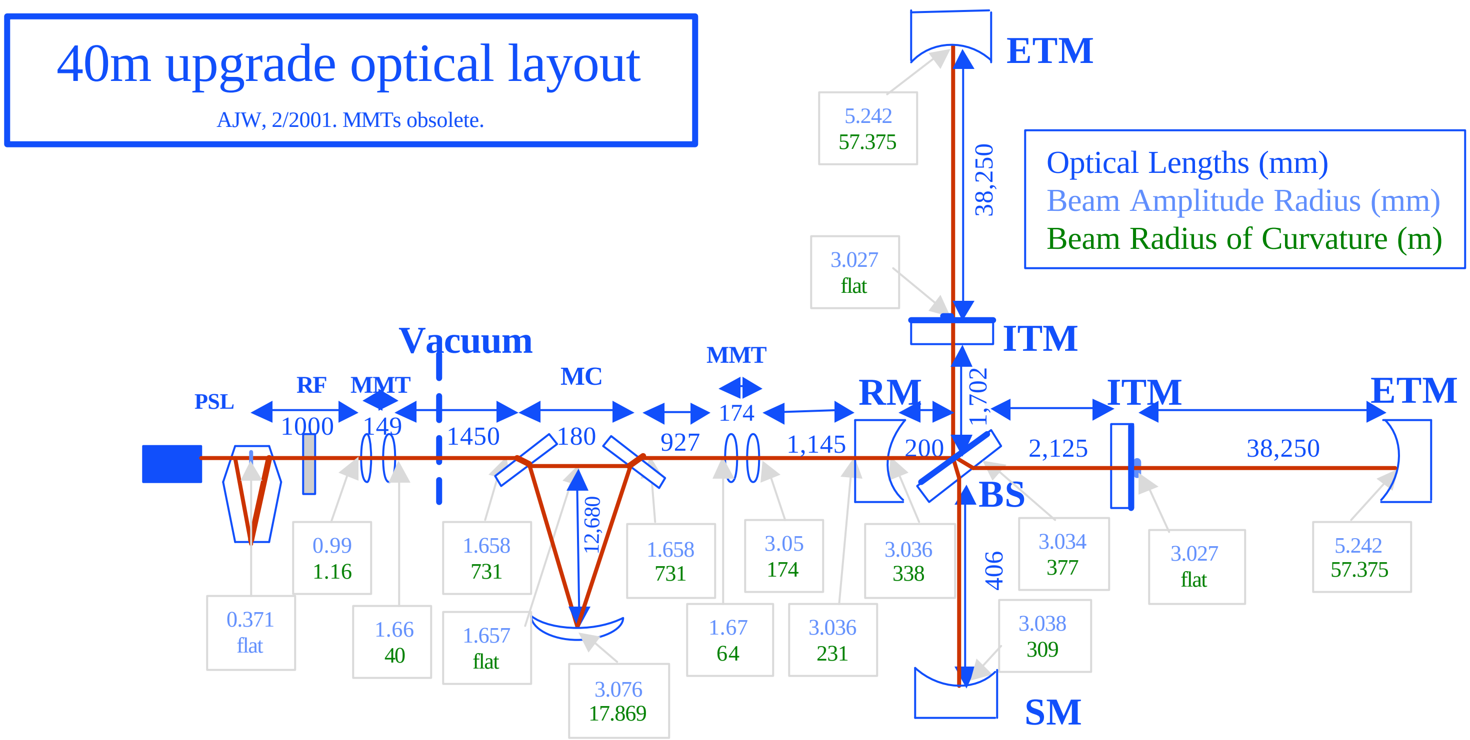
Experimental Tasks/challenges

- develop and refine the length and alignment control schemes.
- develop models of the interferometer response.
- develop lock acquisition strategies and establish lock acquisition.
- assemble and commission the dual-recycled IFO.
- measure transfer functions for all degrees of freedom.
- study noise in L- and GW-DC signals.
- characterize detector (lock acquisition, noise, etc).
- make needed modifications to the control scheme.
- study DC readout.
- multiple pendulum suspensions.
- prepare a final report with recommendations to the Lab (probably sometime in 2004).
- prepare one or more papers for publication.

Modeling of AdvLIGO and 40m

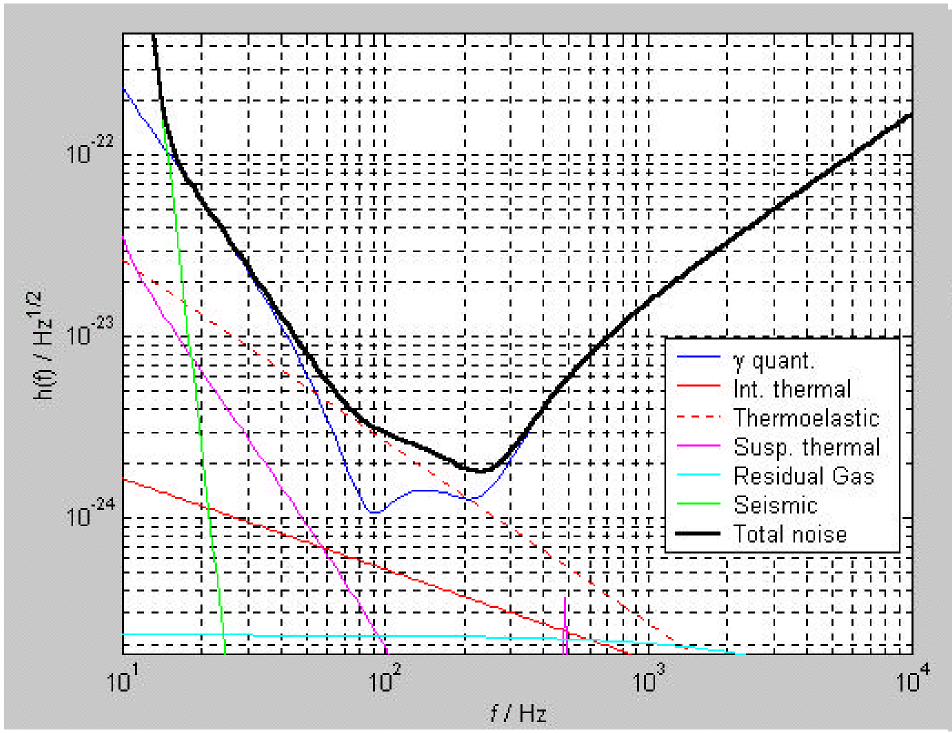
- **Specification of all optical parameters**
  - » **Cavity lengths, RF sideband frequencies and resonance conditions**
  - » **mirror trans., dimensions, ROC, optical quality, tolerances…**
- **Detailed length-control model scheme using Twiddle**
  - » **Adv.LIGO and 40m following parallel paths**
- **Alignment sensing & control modeled using ModalModel (SURF student)**
- **Suspensions for 5" test masses modeled using Simulink (SURF student)**
- **Noise in GW channel modeled in Matlab (BENCH)**
- **Model of IFO DC response with imperfect optics using FFT program (CSUDH group) (in progress)**
- **Model of lock acquisition dynamics using E2E (in progress)**
- **Thermal effects modeled with Melody (in progress)**

Optics Parameters

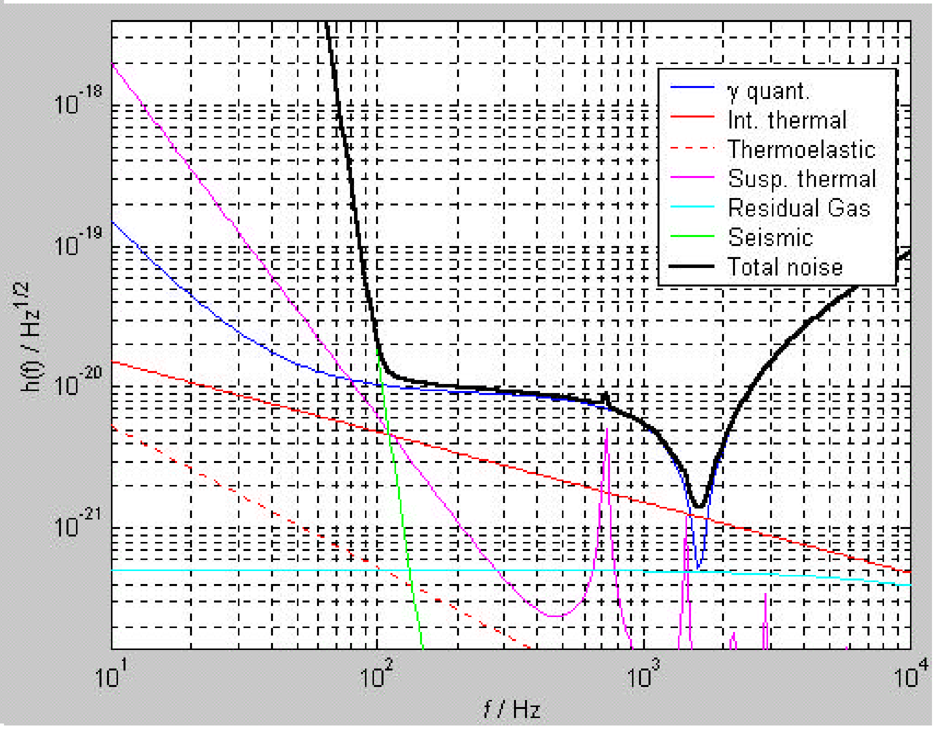


LIGO II and 40m noise curves using BENCH

LIGO II



40m



Length sensing signals from Twiddle

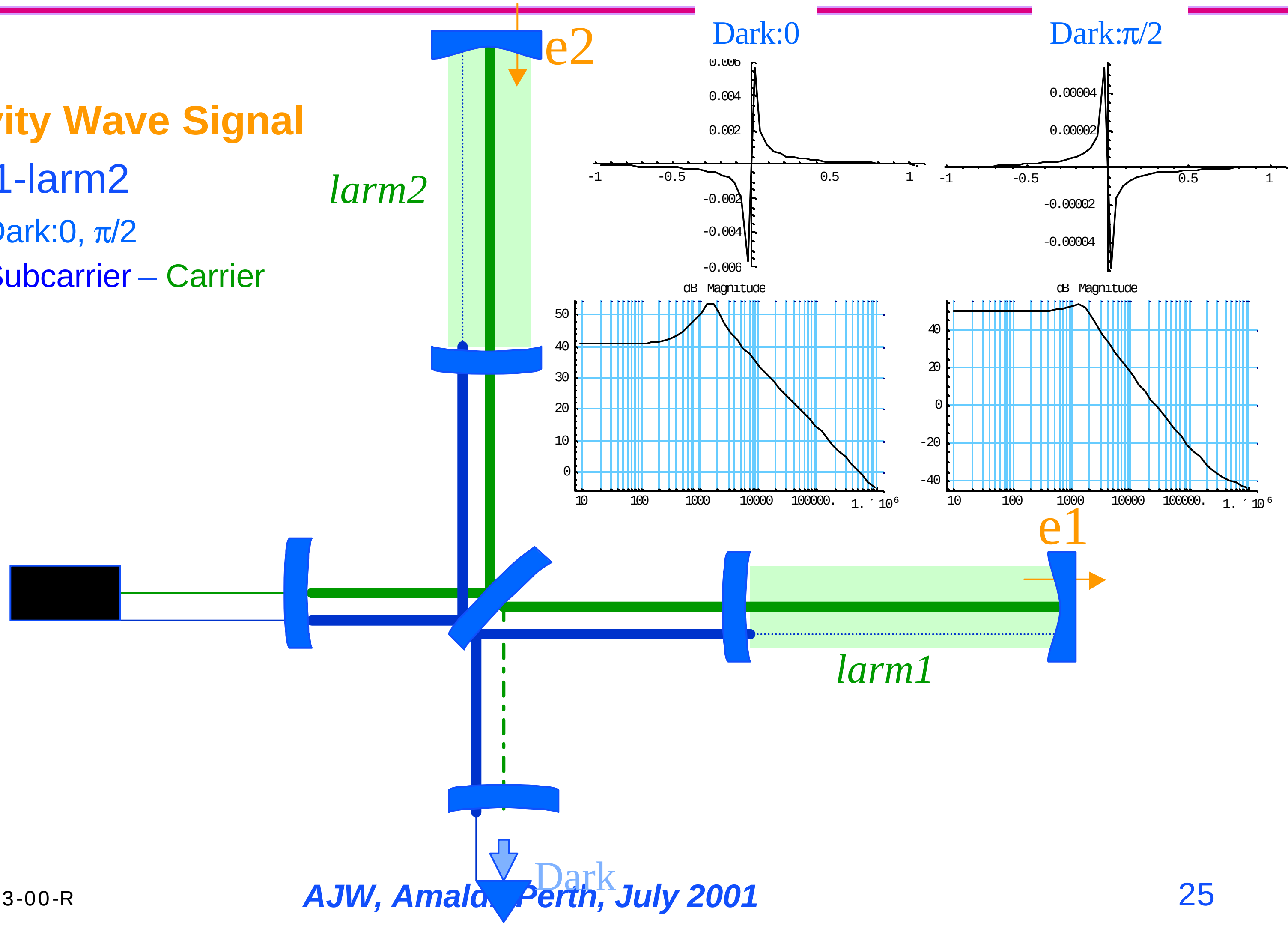
Table 4: LSC signals. $\otimes$ means double demodulation.

Signal	L_+	L_-	l_+	l_-	l_s
SP, f_1	**18.4**	0.01	-0.03	0.12	0.006
AP, f_2	0	**-42.8**	0	-0.05	0
SP, $f_2 - f_1$	0.004	0.002	**-0.155**	0.045	0.088
AP, $f_2 \otimes f_1$	0.0001	0.0002	0.0002	**0.0036**	-0.0019
PO, $f_2 - f_1$	-0.041	0.012	-0.363	0.225	**1.22**

- **Twiddle** is a Mathematica program to numerically calculate response of RF demodulation of IFO signals in response to motion of mirrors away from locked configuration.
- Can construct MIMO length sensing and control matrix.
- AdvLIGO control matrix much more diagonal than LIGO I!
- Mainly due to the availability of 2 pairs of RF sidebands
- Use double demodulation at asym port for the Michelson (l_-) signal

Control signals from Twiddle Differential Arm (L-)

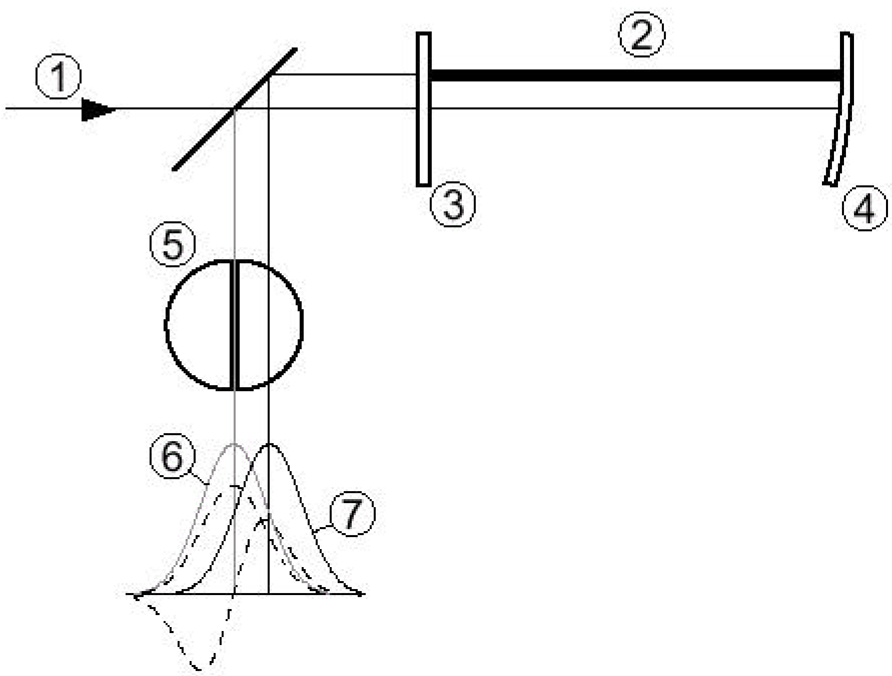
- **Gravity Wave Signal**
- larm1-larm2
  - » Dark:0, π/2
  - » Subcarrier – Carrier



Alignment sensing and control modeling using ModalModel

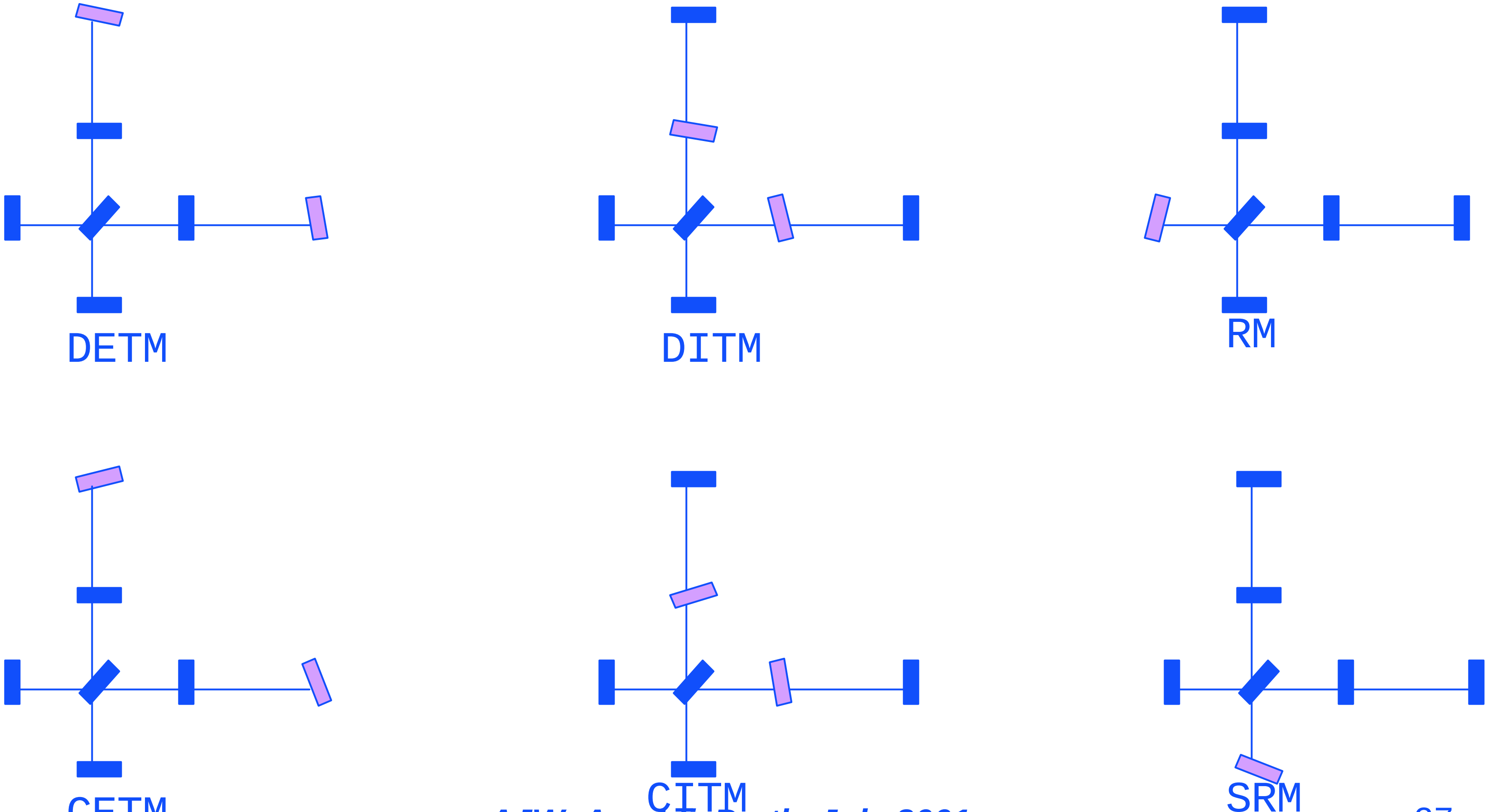
Wavefront sensing:
Alignment Signals for all suspended optics can be obtained by RF-demodulating reflected light on a segmented photodetector --
Only sensitive to TEM01 modes.

ModalModel is a Mathematica program to calculate response of WFS to misalignments;
Used to design WFS layout and control system.



Wavefront Sensing

Degrees of Freedom - yaw (pitch equivalent)

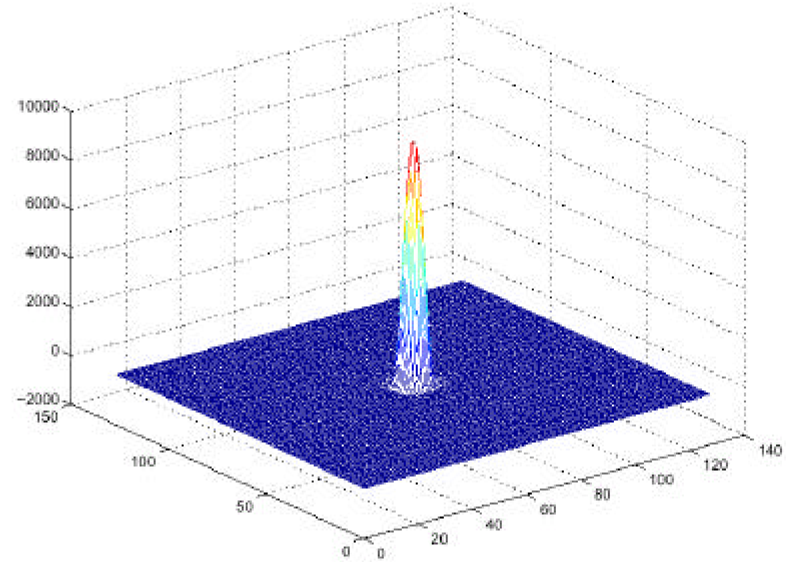


Alignment Control Matrix
LIGO 4km with Signal Recycling (tune of .9)

	DETM	DITM	CETM	CITM	RM	SRM
Dark - Cr-SB	-2.37628	-1.08382	-9.40779×10^{-7}	-4.29089×10^{-7}	-0.000116507	2.2692×10^{-16}
RF Phase	112.4	112.4	112.4	112.4	112.4	121.2
Guoy Phase	90.	90.3	156.1	156.4	90.	15.8
Bright - Cr-SB	0.0419013	-2.51001	-1.82156	-8.14058	8.91718	0.407523
RF Phase	62.6	62.6	40.2	64.3	72.9	59.7
Guoy Phase	153.8	153.8	86.7	147.1	153.6	153.7
Pick - Cr-SB	11.2559	-674.163	-60.8787	-2145.11	2897.32	109.457
RF Phase	62.6	62.6	131.	69.2	68.6	59.7
Guoy Phase	153.8	153.8	66.8	153.5	153.9	153.7
Dark - SB-SC	-0.0312238	1.87011	0.263947	-15.8088	21.2272	-0.705959
RF Phase	74.4	74.4	166.7	166.7	167.	11.4
Guoy Phase	139.	139.	56.8	56.8	57.3	27.8
Bright - SB-SC	0.123516	-7.39785	0.493503	-29.5578	40.1068	2.40455
RF Phase	98.9	98.9	168.6	168.6	168.	166.3
Guoy Phase	50.1	50.1	108.2	108.2	107.7	123.
Pick - SB-SC	-1.37894	82.5899	23.2389	-1391.87	1835.79	111.127
RF Phase	63.	63.	169.8	169.8	170.1	165.5
Guoy Phase	130.1	130.1	53.8	53.8	54.1	53.8
Dark - Cr-SC	8.67135×10^{-7}	-2.06755×10^{-6}	-7.43631×10^{-11}	-2.129×10^{-10}	9.4874×10^{-8}	-8.85897×10^{-16}
RF Phase	57.6	147.1	161.6	158.	58.3	58.4
Guoy Phase	94.5	4.3	84.6	81.2	95.2	5.3
Bright - Cr-SC	0.000427078	0.00223217	0.75704	3.95676	5.29618	0.
RF Phase	115.2	25.	58.4	148.3	12.9	0
Guoy Phase	148.1	58.2	4.	94.2	48.3	0
Pick - Cr-SC	-0.0381109	-0.199191	67.5556	353.087	556.522	0.
RF Phase	69.8	159.6	13.	102.9	58.4	0
Guoy Phase	13.5	103.6	49.4	139.6	5.	0

Modeling of Imperfect Optics with "FFT" program

- "FFT" is a (poorly-named) Fortran program that simulates static response of Initial LIGO and Advanced LIGO with imperfect optics, using pixelized 2D maps of beam profile.
- Can input pixelized reflection and transmission mirror maps, with arbitrary deformations
  - » Imperfect radius of curvature, astigmatism, etc
  - » Index of refraction inhomogeneity
  - » Surface roughness with mm-sized spatial wavelength
  - » Misalignments, limited apertures, etc
- FFT solves for relaxed fields, determining HOM components, contrast defect, mode mismatch, etc.
- Information used to determine degradation of strain sensitivity, set tolerances on polishing specs, misalignments, inhomogeneity, allowable thermal distortions, etc.

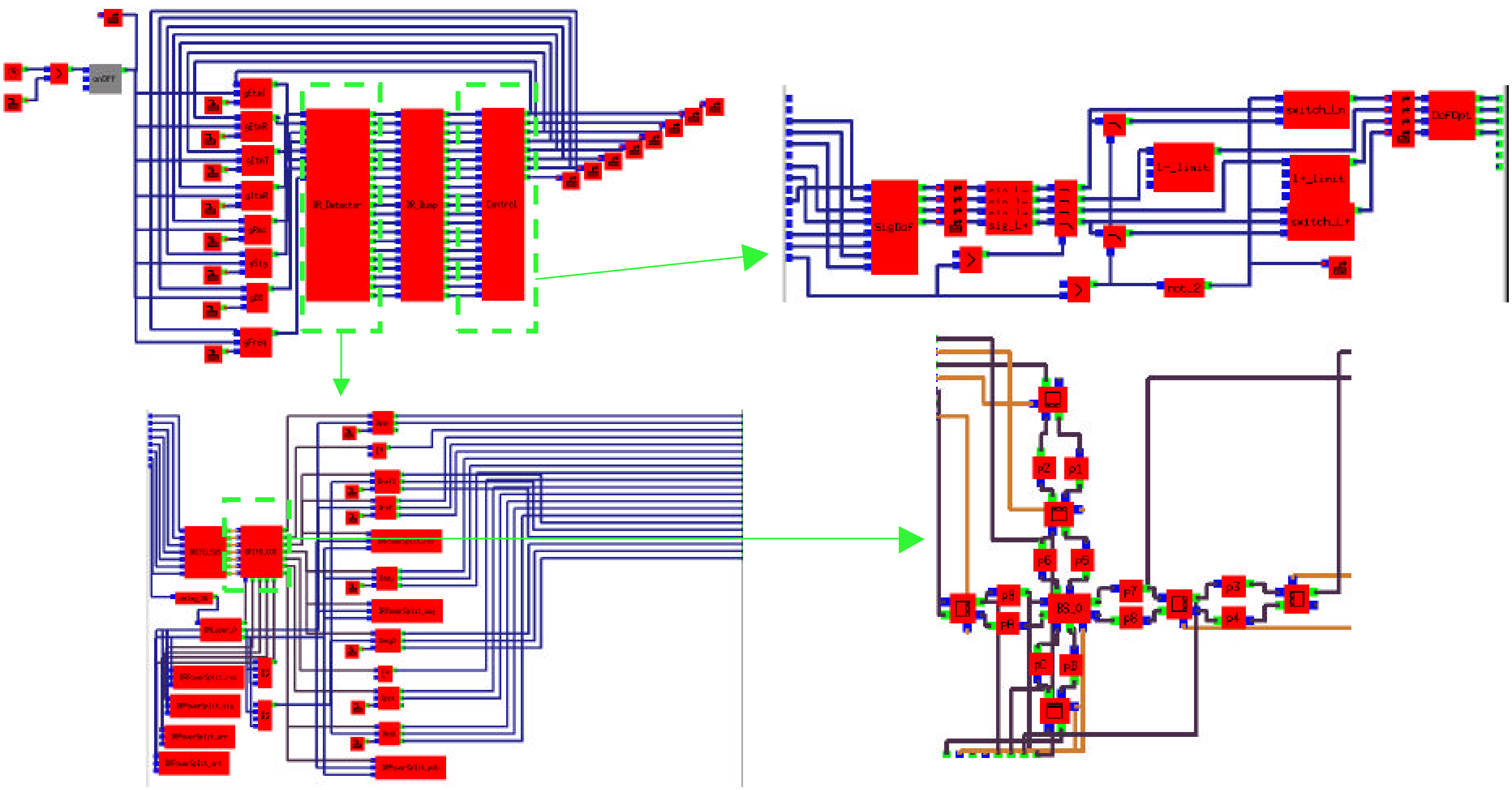


FFT relaxed beam spot on a FP arm end mirror. The mirror aperture extends almost to the edge of the mesh area.

E2E modeling

- E2E performs a time-simulation of response of arbitrarily configured IFO, including various noise sources, suspensions, control electronics, etc
- The Han2K E2E model has been extremely useful in designing and implementing lock acquisition control algorithms
- This model has been extended to simulate a dual-recycled AdvLIGO IFO (length degrees of freedom only)
- Work is beginning to generalize the length control and lock acquisition scheme from Initial LIGO to AdvLIGO
- With 4 interlocking FP cavities, the IFO could fall into many undesired states on the path towards full lock; to be explored.

E2E GUI for constructing a dual-recycled AdvLIGO IFO



Summary

- Much prototyping and modeling activity in progress.
- Goal is to understand and test all the techniques and engineering required to build a dual-recycled suspended-mass IFO for AdvLIGO, *before* construction begins, to minimize down-time between Initial LIGO and AdvLIGO.
- At Caltech, 40m prototype will be ready for detailed engineering tests of AdvLIGO optical configuration, control and readout schemes during 2003-2004 (after Glasgow 10m tests).