40m Prototype Upgrade

- Objectives
- Recent activities
- Building modifications
- Optical layout, baffles, pickoffs, ISC tables
- Output chamber, active seismic isolation
- Optics parameters
- Noise
- CDS
- Modeling LSC, ASC

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
  - » These lead to decision on control scheme by LSC/AIC
  - » Then, Glasgow 10m does a “quick” test of the scheme
  - » Then, full LIGO engineering prototype of ISC, CDS at 40m
  - » First look at DR shot noise response (*high-f*)
- Other key elements of LIGO II are prototyped elsewhere:
  - » **TNI, Caltech** : measure thermal noise in LIGO II test masses (*mid-f*)
  - » **LASTI, MIT**: full-scale prototyping of LIGO II SEI, SUS (*low-f*)
  - » **ETF, Stanford:** advanced IFO configs (Sagnac), lasers, etc
- CRITICISM: After Glasgow 10m, DR ISC/CDS is low-risk;
  40m effort is redundant, distracting, unnecessary
- Counter-argument: full engineering prototype of DR control scheme is absolutely essential for success of LIGO II upgrade

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.
- Potentially, thermal noise measurements with maximized beam width (~flat mirrors)
  - » a big, and challenging, diversion.
- Facility for testing/staging small LIGO innovations
- Hands-on training of new IFO physicists!
- Public tours (SURF/REU students, DNC media, etc)

Control Scheme

- Prototyping the control scheme is the primary goal of the 40m upgrade, so want to make it as close to the LIGO II scheme as possible
- Which means waiting until the dust settles on the design. So we don't want to set anything in stone till then.
- Elements of the current design that we should not have any problem in implementing:
  - » PM RF sidebands at low (9MHz) and high (180MHz) frequencies
  - » Smaller PRC length means higher RF: 9->36, keep 180MHz
  - » So, the separation between l_{PRC} and l_{SRC} will be less robust, but adequate.
  - » DC-locked GW signal
  - » Small monolithic output MC.

40m Lab Staff

- Alan Weinstein
- Dennis Ugolini, postdoc
- Steve Vass, Master tech and lab manager
- Rick Karwoski, senior engineer
- Summer 2000: five SURF undergraduates
  - » Lisa Goggin, Cork: Optics – ROC, beam sizes, 12m mode cleaner, MMTs
  - » Brian Kappus, Harvey Mudd: 40m ASC/WFS with ModalModel
  - » Ted Jou, Caltech: 40m LSC with Twiddle
  - » Ivica Stefanovic, Belgrade: Analog and digital suspension controller design
  - » Jitesh Chauhan, Leicester: GDS at 40m

40m Lab recent activity

- Dismantling:
  - » Old PSL, all old electronics crates & racks, all cables (except for vacuum and RF) have been removed.
  - » Old PSL, much electronics and green optics, transferred to Drever's lab
  - » Some electronics transferred to TNI lab.
  - » LIGO-prototype DAQS moved to CDS lab (Wilson house) for DAQ development (Bork)
  - » All optical benches (ISC, Oplevs) disassembled and stored
  - » Test masses and suspensions are still in the vacuum chambers. To be disposed of per decision by Barish & Sanders:
    - – RM will go to Saulson & Harry
    - – EV suspension & controllers, with plastic test mass, will go to Hanford
    - – Remaining test masses and suspensions, to Drever's lab
    - – We keep all useful scopes, analyzers, lasers, oplev optics, SRS amps, etc

40m building modifications

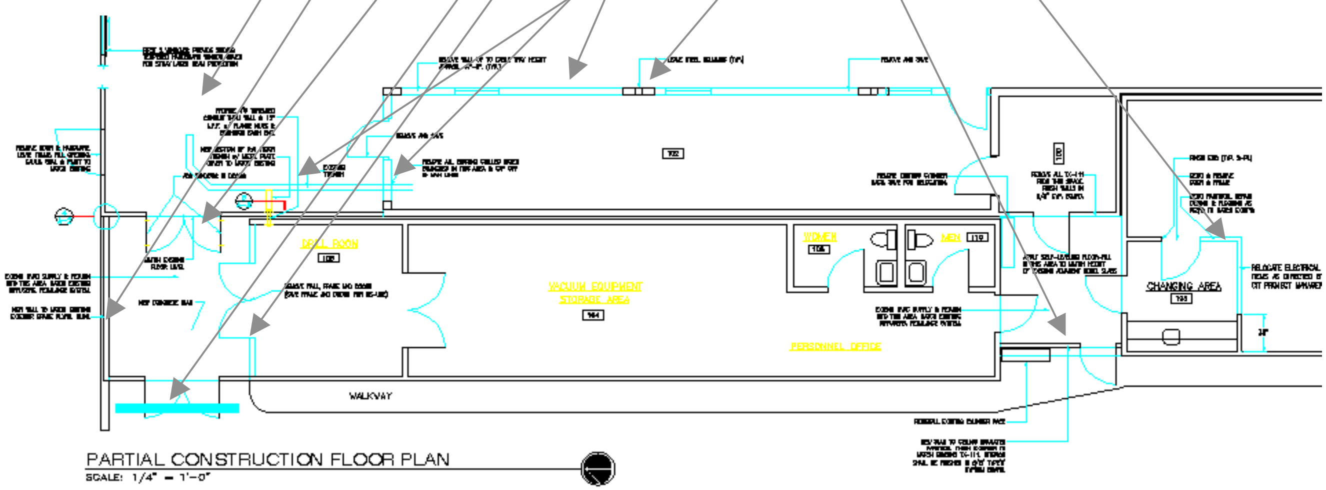
- Remove "doghouse" on roof and patch temporarily. DONE.
- re-roof main IFO hall, and North and South Annexes
  - » Caltech will do this by September, as routine maintenance.
- Need more space for CDS racks, ISC tables; so, remove wall between old control room and IFO hall; North Annex becomes new control room
- Extend the north wall of the North Annex building northward to become flush with the north wall of the main IFO hall.
  - » DONE! And a time capsule was buried under new concrete slab, on 7/31/00
- remove south annex changing area wall
- new enclosed entrance room
- At this point, we will move from old control room to North Annex
- Remove wall between 40 m vacuum system and old control room
- new electrical wiring in North Annex and main IFO hall.
  - » New isolation transformers, breaker panels, and runs to PSL, vertex CDS, end station CDS, and control room outlets.
- Install new 12" cable trays in IFO main hall, for ISC, CDS

40m building modifications

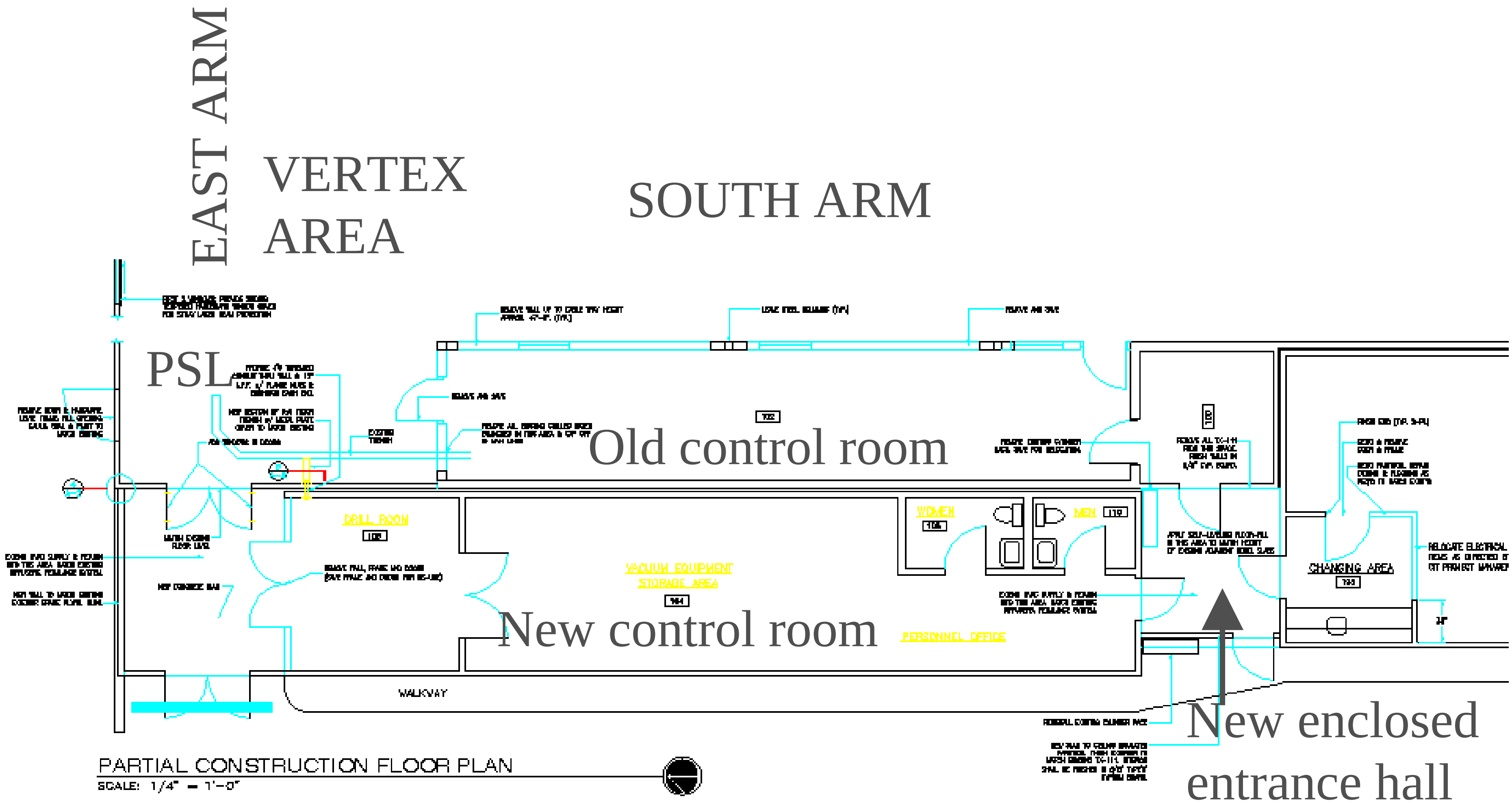
40m Contacts:

- Steve Vass, 395-3980
- Alan Weinstein, 395-6682

- Remove “doghouse” on roof (over the beamsplitter chamber in the vertex area) and patch temporarily
- re-roof main IFO hall, and North and South Annexes (Caltech will do this by September)
- Extend the north wall of the North Annex building northward to become flush with the north wall of the main IFO hall (ie, stretch the North Annex building).
  - This laps over the existing double door entrance at the NW corner of the 40 m lab. Replace this double door with something more suitable (eg, glass doors).
  - Add double door entrance to the west wall at the NW corner of expanded region.
  - Finish North annex (remove old external doors, add flooring, walls, etc)
- new electrical wiring in North Annex and main IFO hall
- remove south annex changing area wall
- new enclosed entrance room
- scientists move from old control room to North Annex
- Remove the partition between 40 m vacuum system and present control room.
  - Remove chilled water plumbing at north wall of control room
  - Leave existing overhead cable trays and electrical conduits; remove partition to highest height possible (7.5'?) without disturbing utilities.
  - Replace partition with posts not closer than 10'.
- Install cable trays in IFO main hall
  - note changes in “drop-downs” with respect to current drawings!



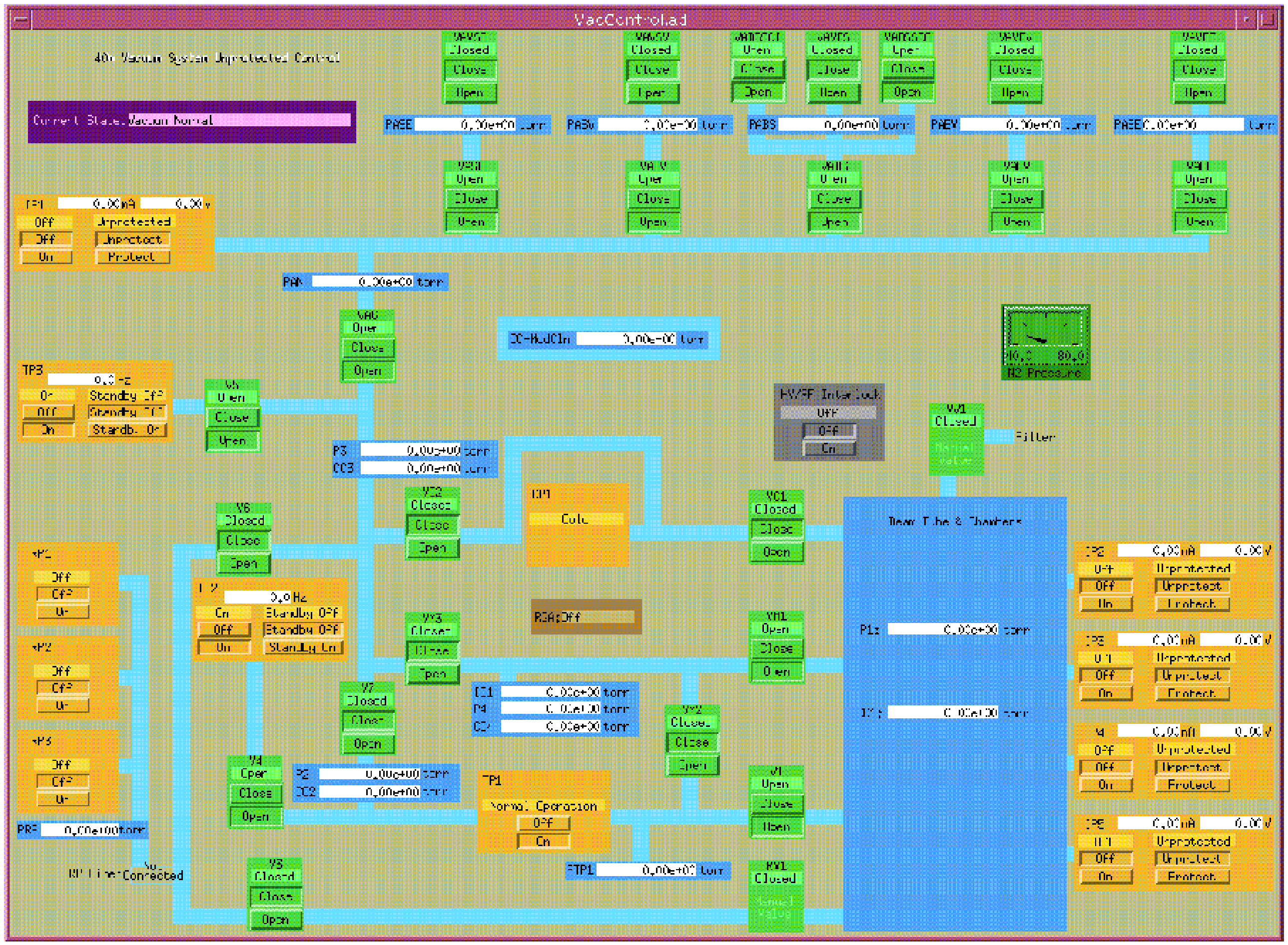
40m building mods



Vacuum control system upgrade

- Vacuum controls: 3 roughing pumps, 3 turbo pumps, 5 ion pumps, one cryopump, 18 vacuum gauges, 26 valves, etc
- Was controlled by old PC-based system, Labview, MetraBus
- Upgrade: keep all devices (plus a few more), control with VME cpu and EPICS controls/displays
  - » Interfaces with DAQS and rest of EPICS control system
  - » EPICS provides archiving, alarms, state transition hooks
  - » Keep essential hardware and software interlocks
  - » Add gate valves to ion pumps, regenerate them, so we can use them!
- Design documented and reviewed (John Worden)
- EPICS code, displays written and tested by Caltech frosh Ted Jou
- Rack/crate/wiring layout by Ugolini and Heefner
- Ugolini has implemented almost all the hardware; expect complete system, software shake-down, by end of summer.

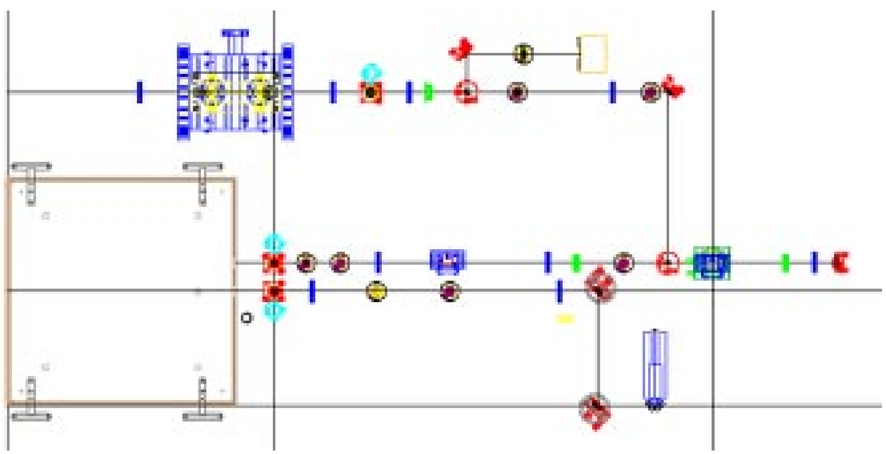
40m Vacuum control EPICS control screen



PSL

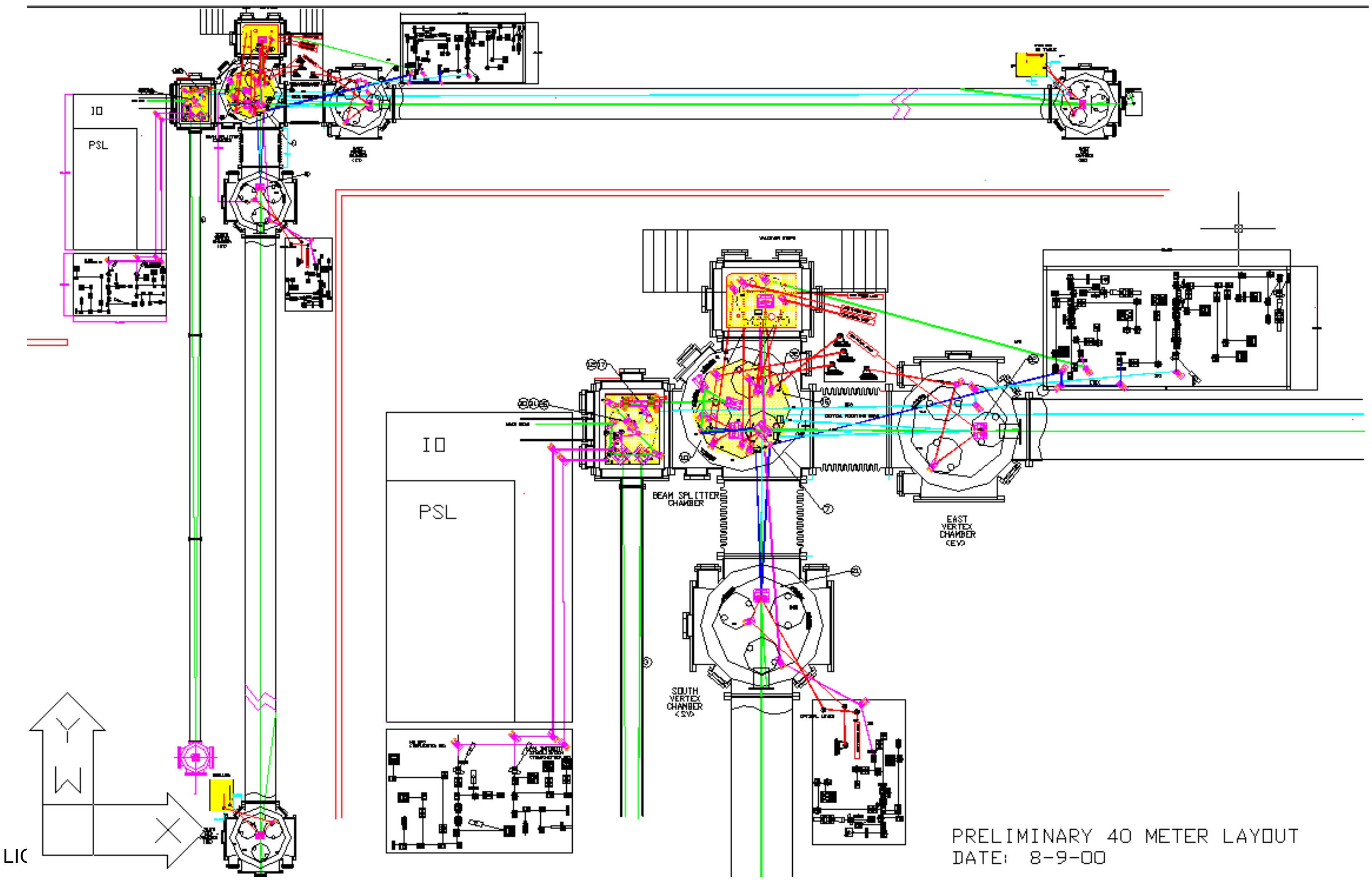
- A LIGO-I clone 6watt PSL (informed by all the experience gained at the sites, so far) is currently under construction by King and Abbott.
- Delivery by winter, maybe early spring.
- Peter is reorganizing the PSL table, to maximize space available for a (potentially) more complex frontal modulation scheme. Additional RF modulation frequencies will be available.

- We may need to use the PSL table for ISC, since table space at the 40m lab is limited (see optical layout).

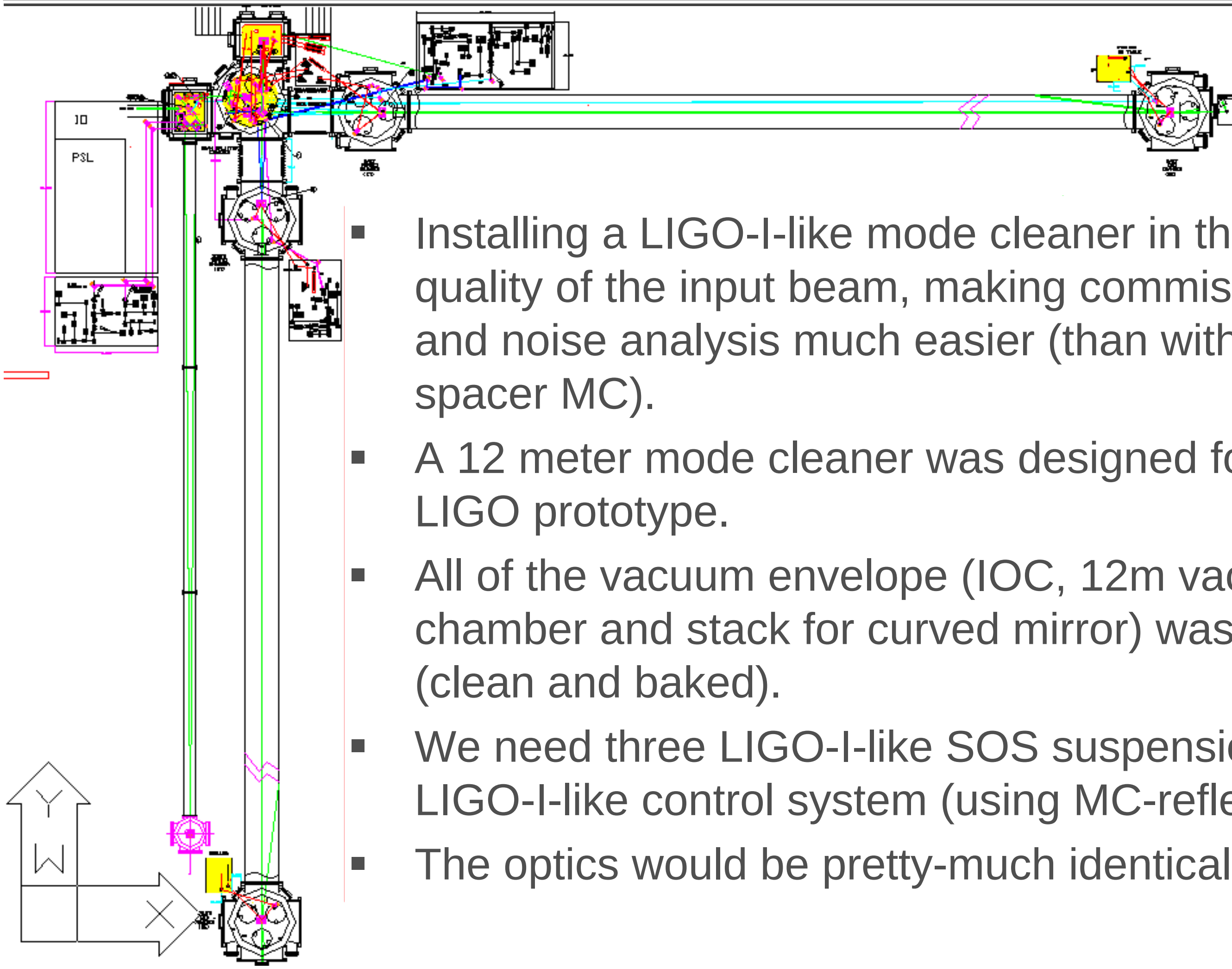


Preliminary Optical Layout

(Dennis Coyne, Mike Smith, Ken Mailand)

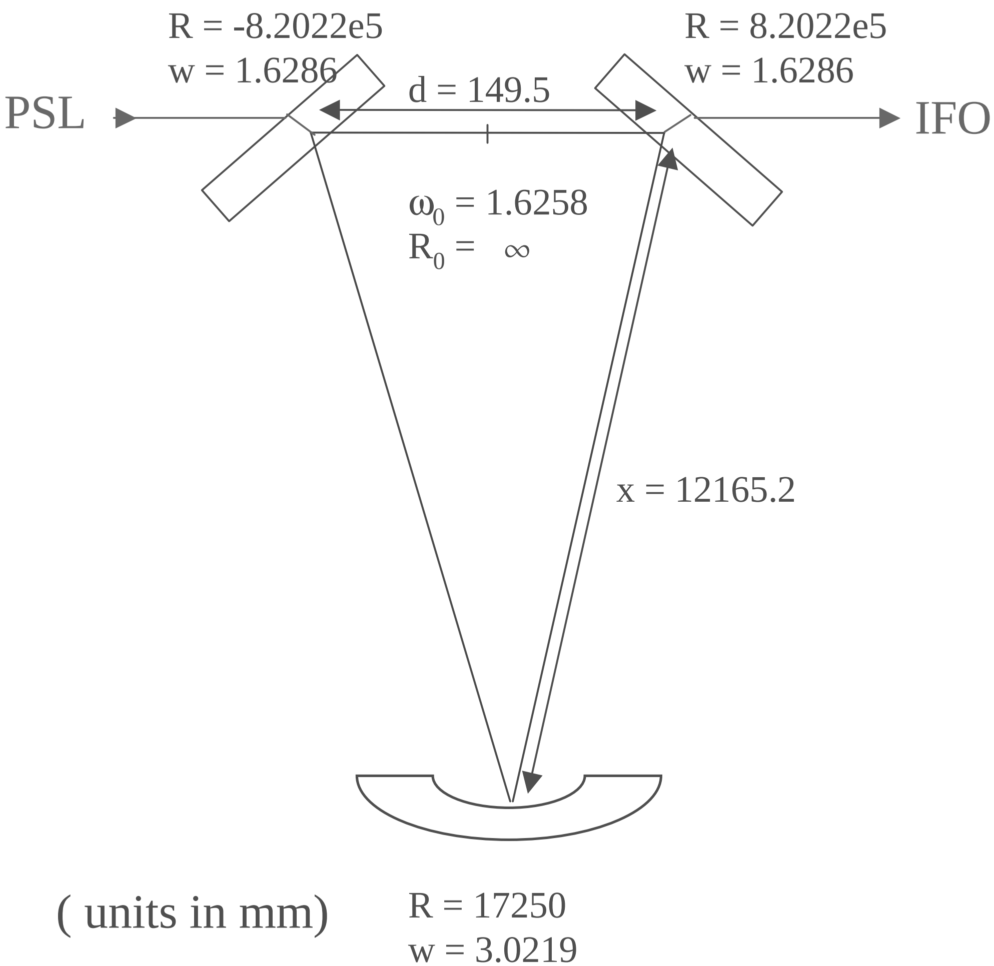


12 meter mode cleaner



- Installing a LIGO-I-like mode cleaner in the 40m will improve the quality of the input beam, making commissioning, lock acquisition, and noise analysis much easier (than with the existing 1m fixed spacer MC).
- A 12 meter mode cleaner was designed for the 40m in 1995, as a LIGO prototype.
- All of the vacuum envelope (IOC, 12m vacuum tube, small chamber and stack for curved mirror) was built and is in hand (clean and baked).
- We need three LIGO-I-like SOS suspensions and 3” optics, and a LIGO-I-like control system (using MC-reflected light).
- The optics would be pretty-much identical to LIGO-I.

12m Mode Cleaner for 40m IFO

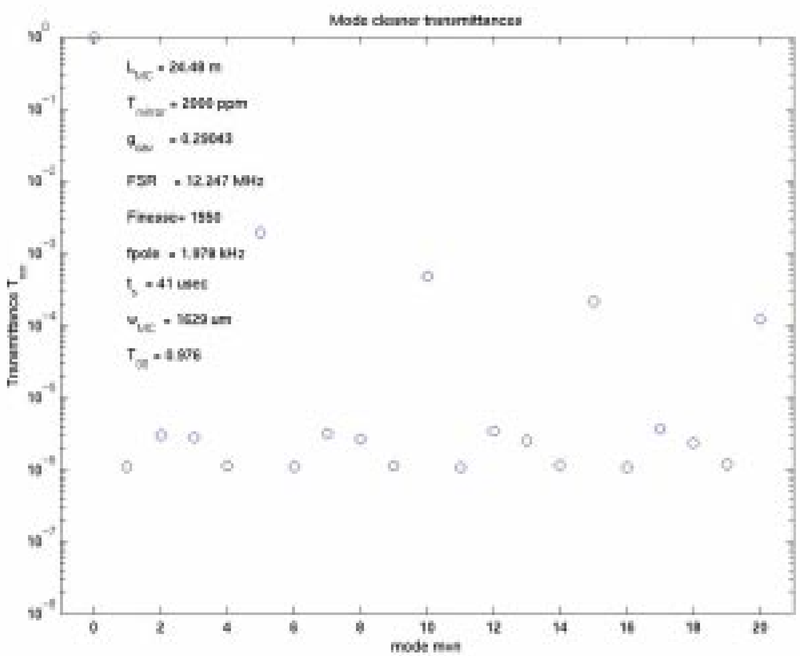


(units in mm)

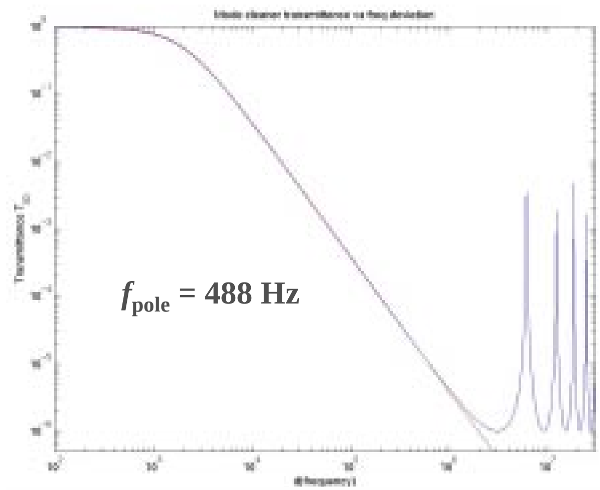
More-or-less identical to the LIGO I Mode Cleaner in design and in dimensions

Mode Cleaner Performance

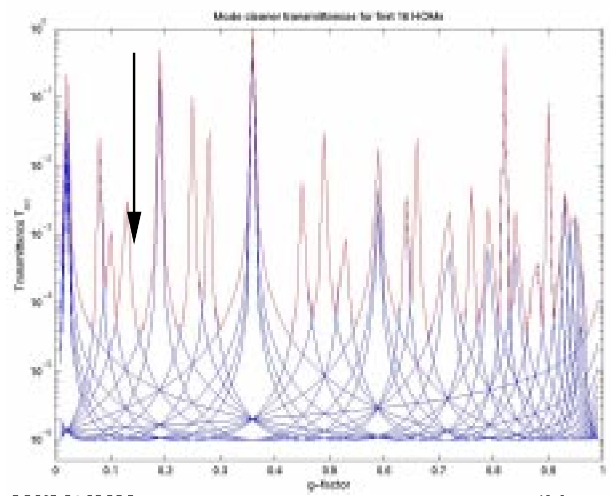
Transmittance of HOMs



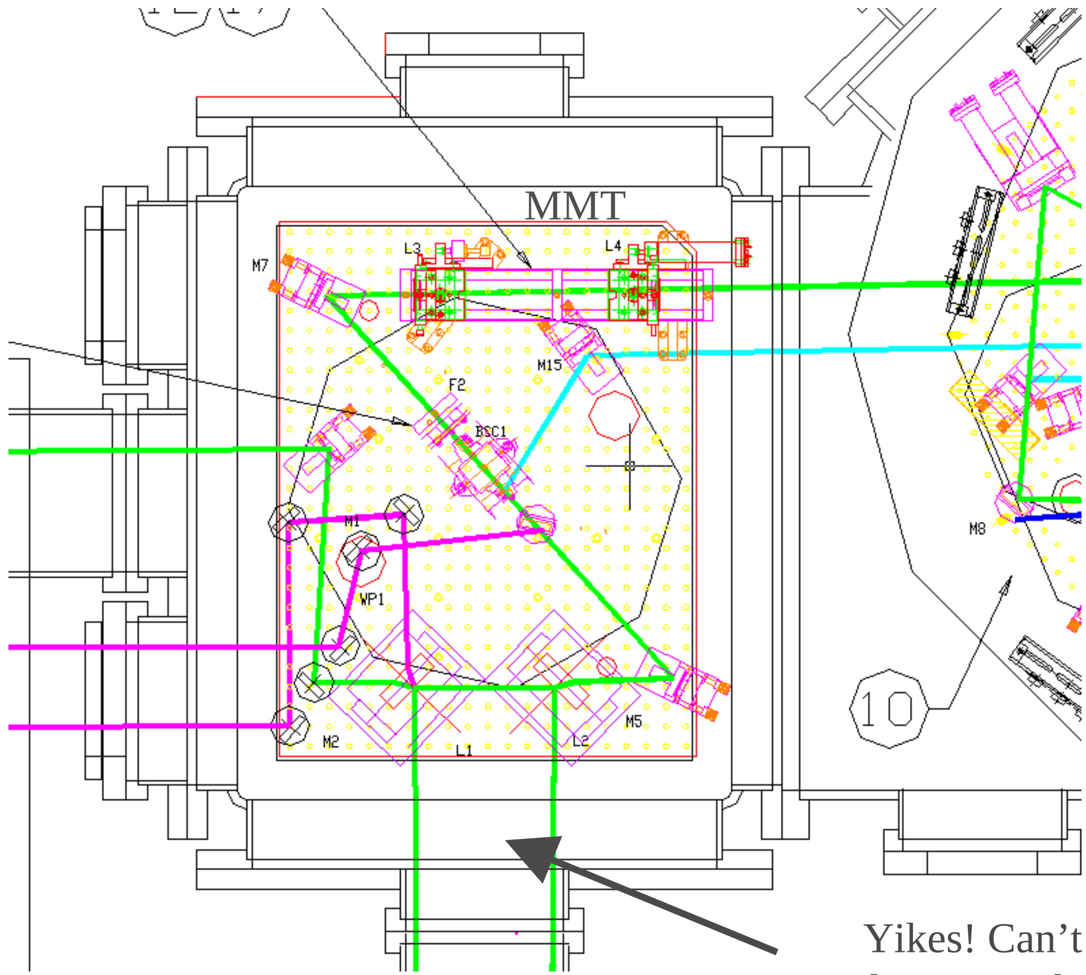
Transmittance of frequency noise



Transmittance of HOM's versus g_1g_2



Crowded Input Chamber!



Main beam from PSL

MC transmitted

MC reflected

Main beam to RM

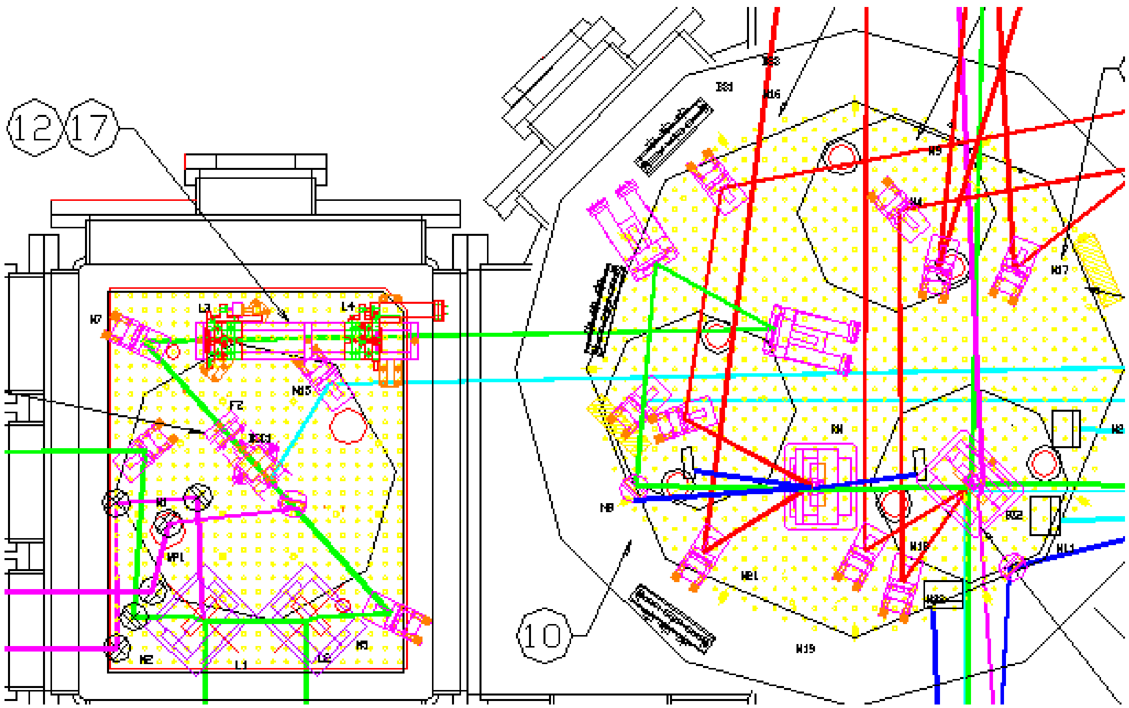
Bright port
to ISC table

12m Mode Cleaner

Yikes! Can't get SOS's
Close enough to fit beams
in 8" tube!!

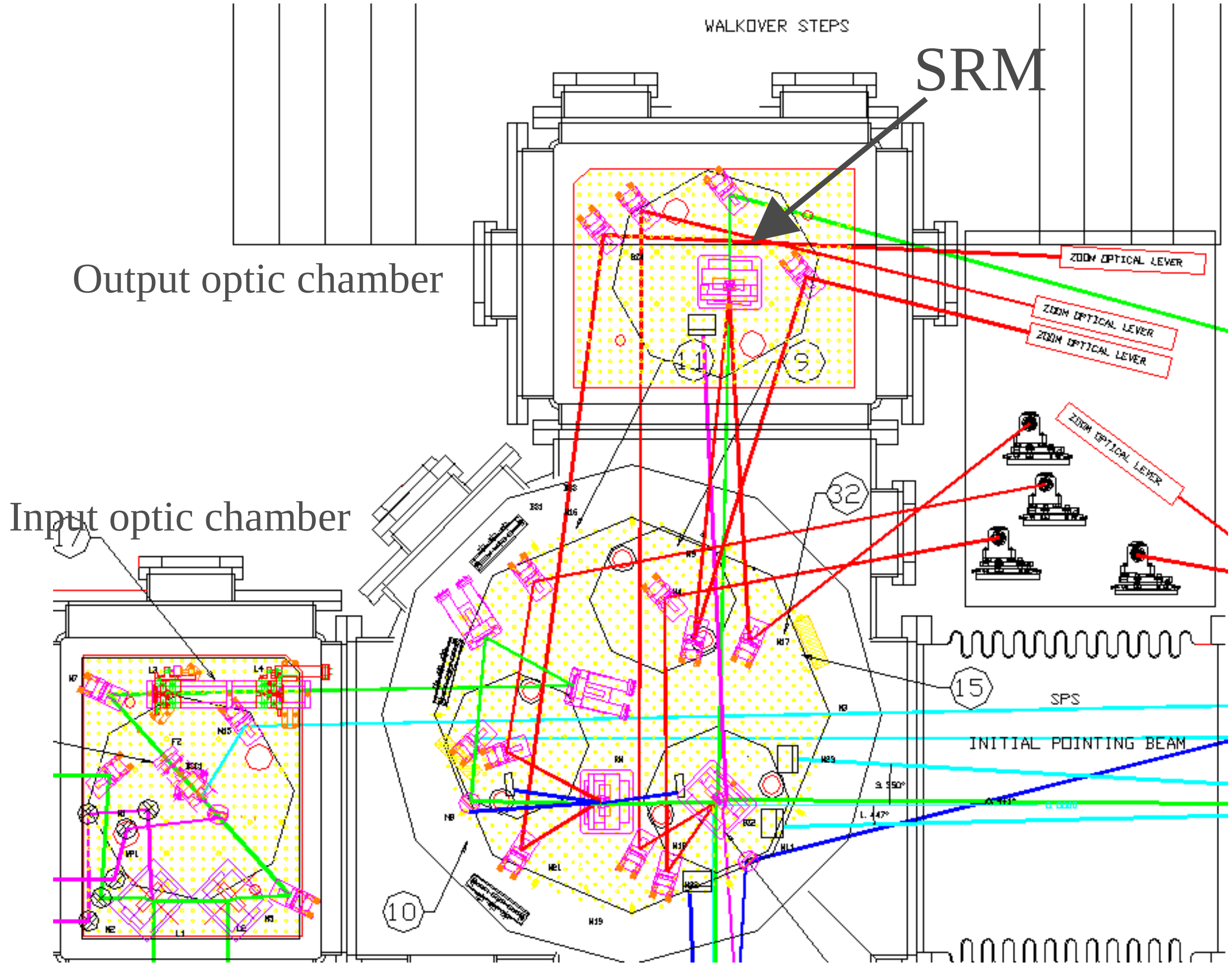
Fixed MMT, steering mirrors

- Fixed, transmissive optics (lenses) for MMT will introduce scattering noise.
- Fixed, reflective optics for folding and steering between MC and RM introduces noise.
- Analysis needed!



Output optic chamber

- Need new chamber to house SRM (7th core optic)
- OOC exists
- It is identical to IOC
- needs new seismic stack / supports
- Too close to wall; need walk-over steps
- Size of SRC is *limited*
- **But, there's room for a small, single-suspension output mode cleaner**

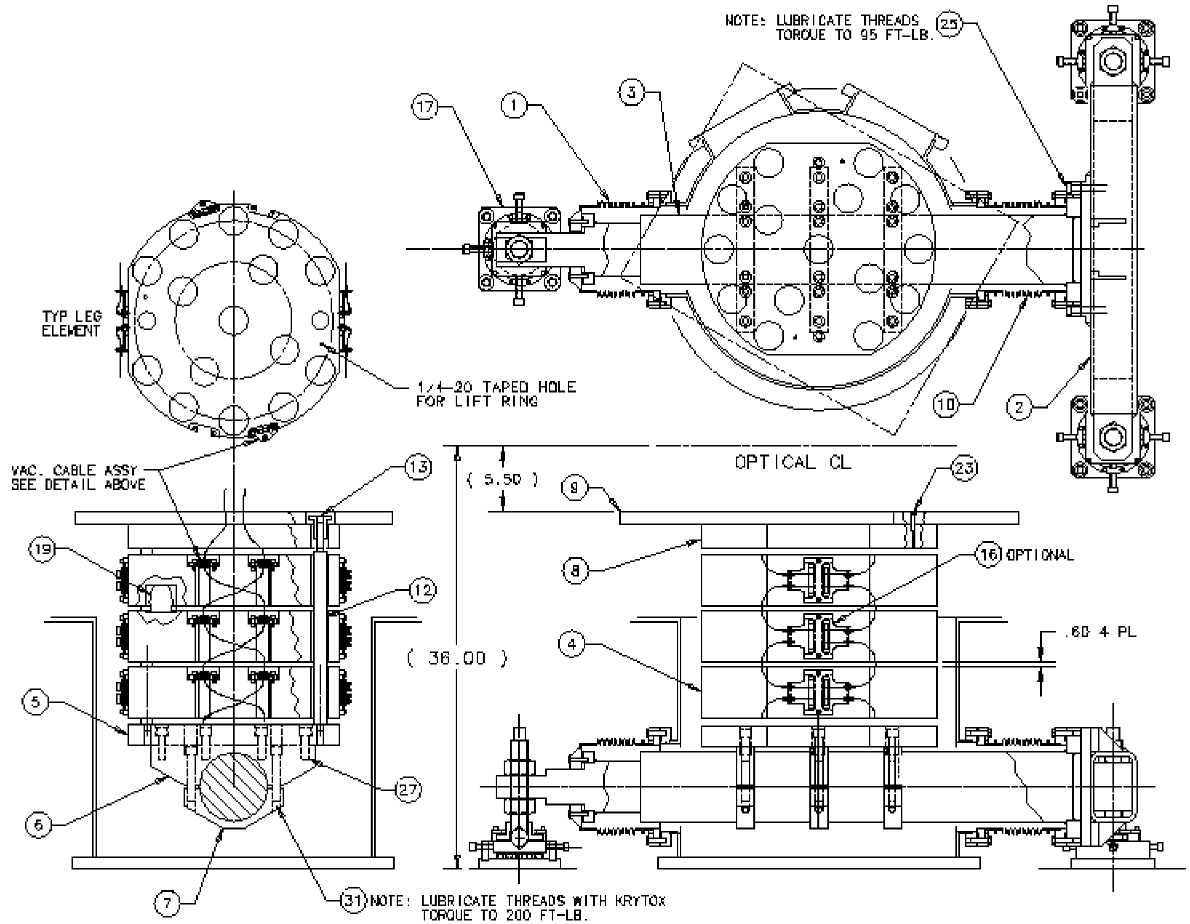


Does the OOC need to be baked?

- OOC is currently being pumped down (empty) with RGA, to determine whether it needs to be baked
- Currently, pressure is
  - p_{tot} ~ 1.7E-7 torr,
  - p_{41} ~ 2.5E-10 torr
- Pumping speed is around 10 ltr/sec.
- advice on how to make this decision is requested!

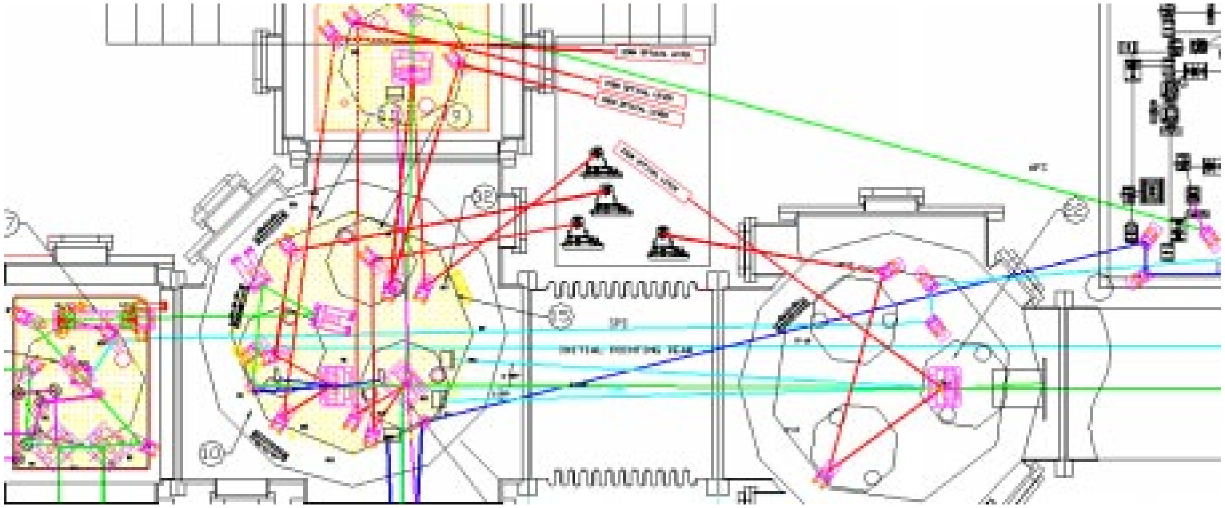
Output chamber seismic stack

- Identical to existing input chamber seismic stack, with a couple of mistakes fixed.
- Machining at Caltech is ~50% complete
- Will need to be cleaned and baked.
- Chamber and vacuum bellows exist at lab.



Baffles, Pickoffs, OpLevs

- Baffling for all 1st-order reflected beams. All wedge angles defined.
- Pickoffs for all output light:
  - » Bright (symmetric) port
  - » Dark port
  - » PRC pickoffs: ITMx, ITMy, BS (only need one of these!).
  - » MC reflected, MC transmitted
- Optical levers on all seven core optics



Do we need active seismic isolation at 40m?

- "seismic wall" at the 40m, with existing stacks (viton springs), is at ~100 Hz
  (LIGO-I with damped-metal springs: < 40 Hz).
- Of course, seismic noise is much worse at 40m than at LIGO!
- For prototyping a LIGO-II control system, we are not concerned with noise in this range
- We *do* need to keep the motion down to be able to acquire and keep lock.
- Mean time to acquire lock (MTTL):
- v_{thr} estimated to be ~ $\lambda/12$ s^{-1}
  (depends on loop gains, etc)
  SO, MTTL ≥ 6 sec

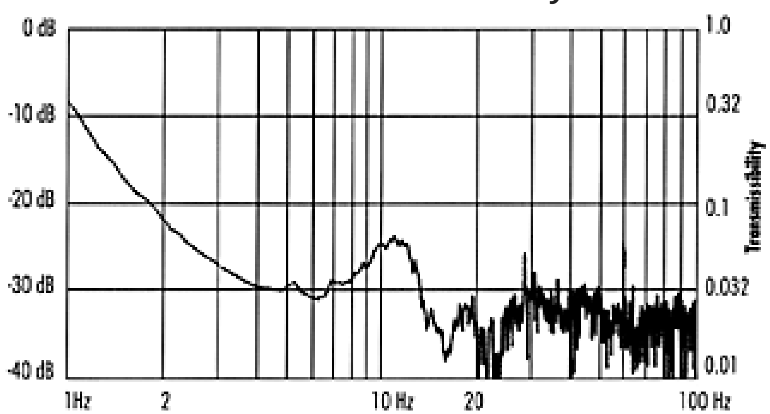
$$\tau_{lock} \sim \frac{\lambda/2}{v_{thr} P(v < v_{thr})}$$

- To estimate $P(v < v_{thr})$, we need to
  - » Measure ground motion *x(f)*
  - » Measure & model stack transfer function, with and w/out active control
  - » Model pendulum transfer function
  - » Integrate *v(f)* spectrum (from, *eg*, 1Hz up), calculate $P(v < v_{thr})$, and MTTL

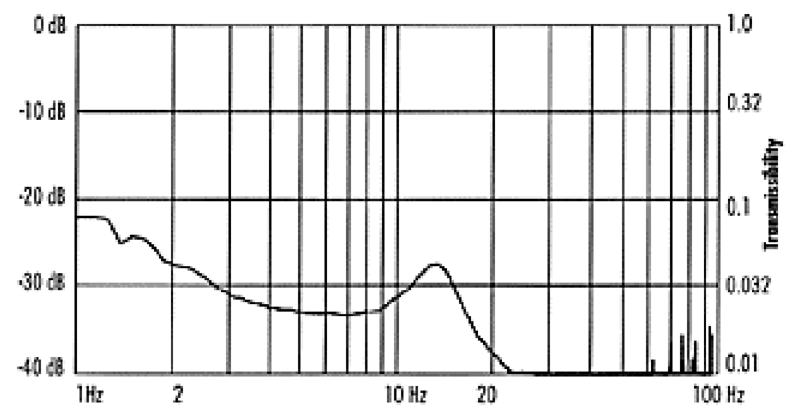
STACIS active isolators

- $3K-$4K for a set of 3 (we'd need one set for each of 4 test mass chambers).
- 6-dof stiff PZT stack
- With active bandwidth of 0.2-1 Hz, passive isolation above 1 Hz.
- TF from 0.1 – 1 Hz is not well known…

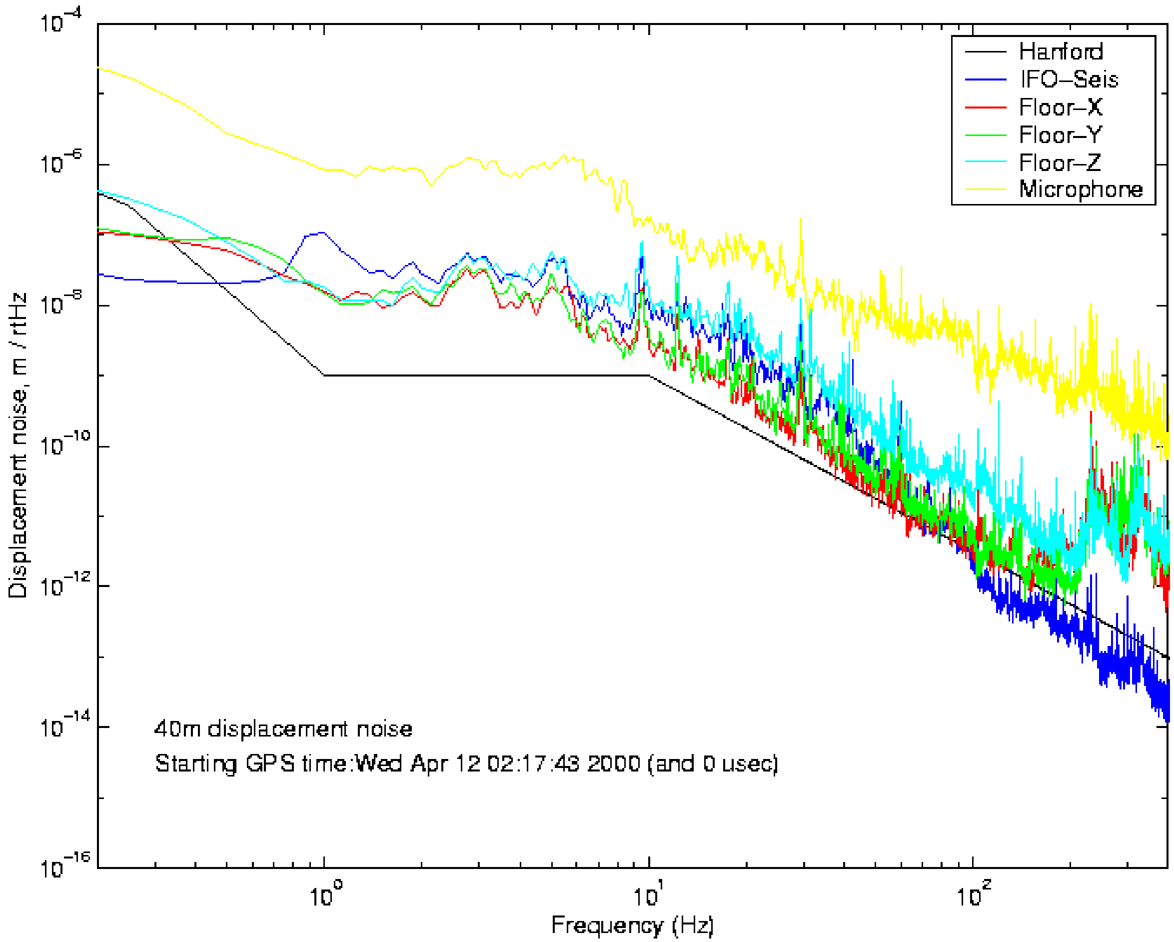
Vertical Transmissibilty



Horizontal Transmissibilty

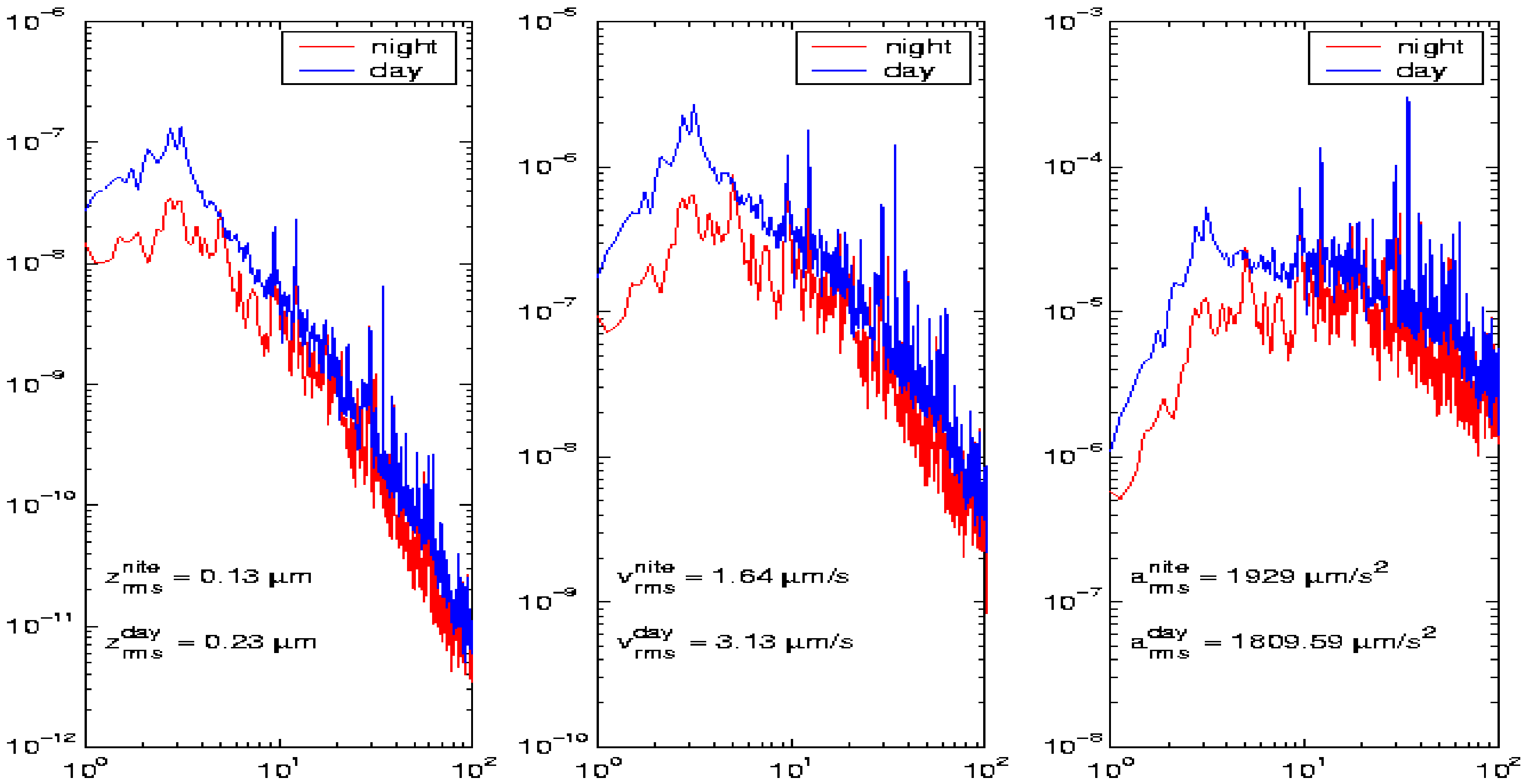


Ground motion at 40m Lab



- Measured with seismometer and 3-axis geophones
- Yellow trace is microphone
- Rms position is ~10x larger than Hanford, from .5 – 10 Hz.

Day vs night at 40m

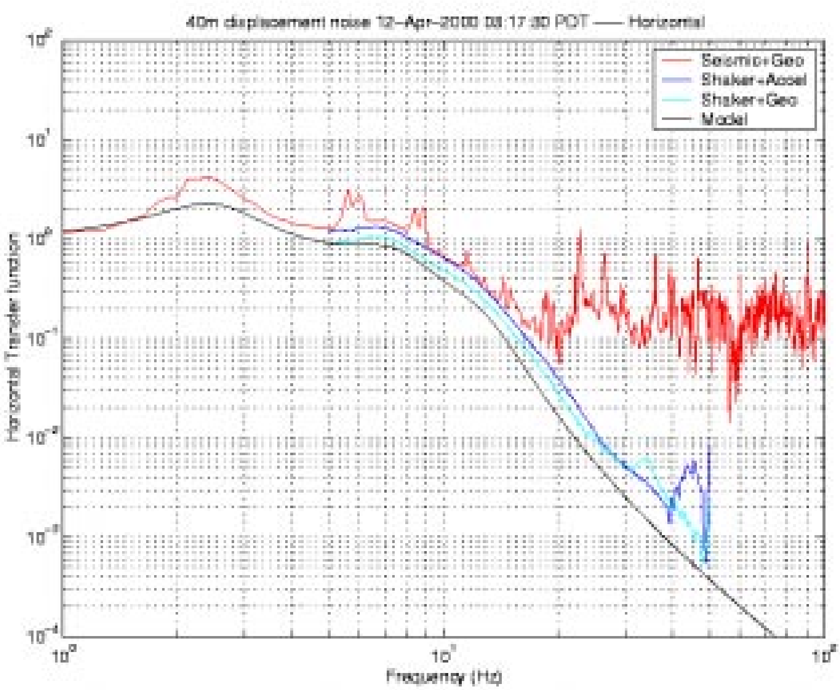


In the past at the 40m, day/night made all the difference for bringing the IFO into lock!

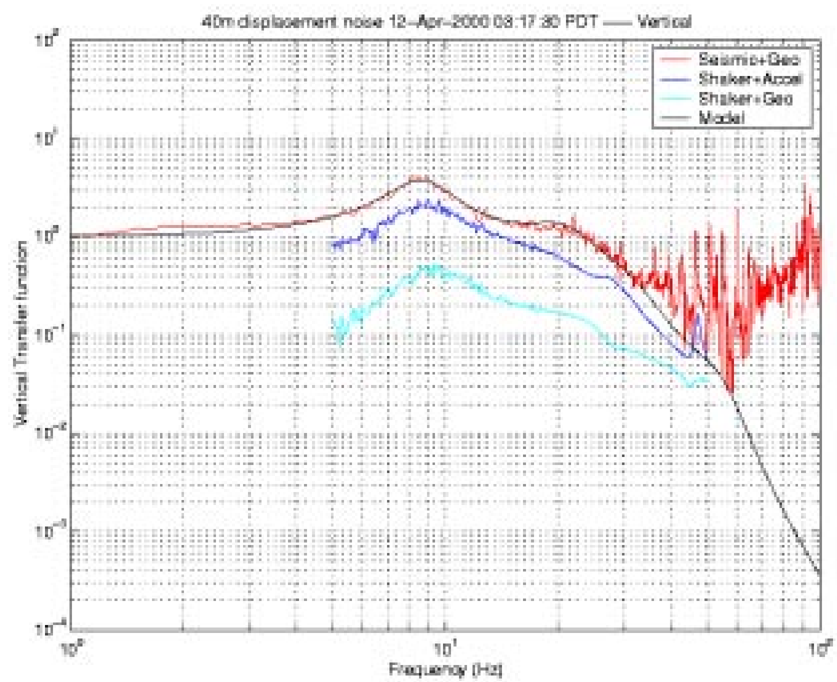
Transfer function of 40m stacks

Compare model with TF measured using
seismic motion / geophone, shaker / geophone, shaker / accelerometer

Horizontal transfer function



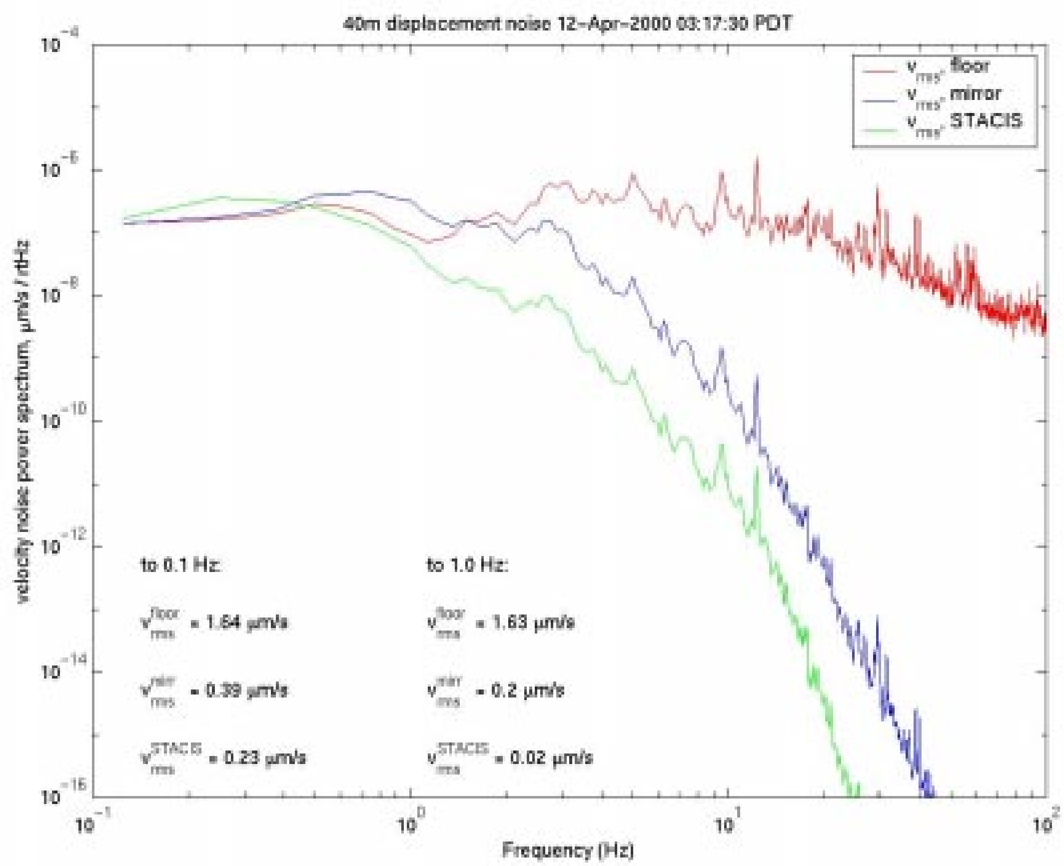
Vertical transfer function



Noise spectrum, floor+stacks+pendulum+STACIS

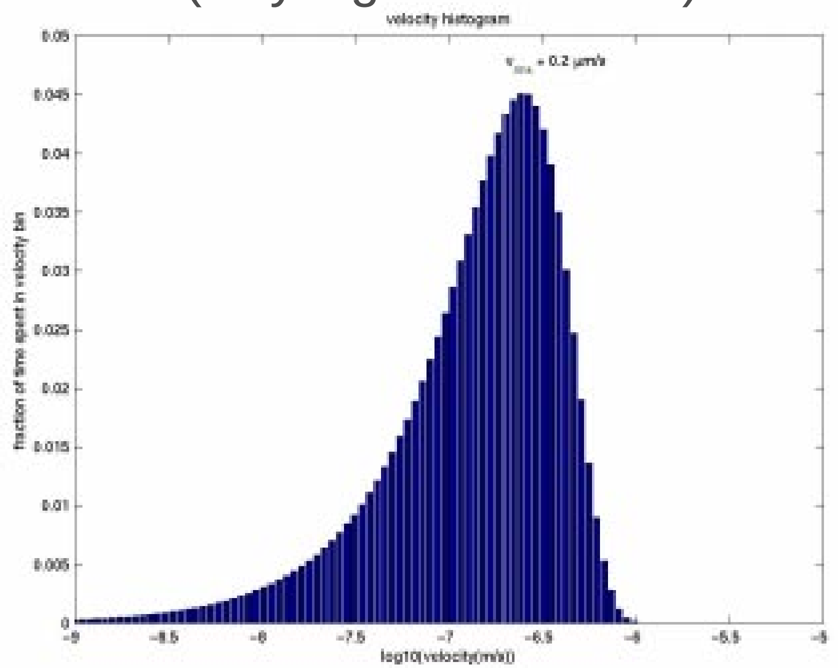
Conclusions depend critically on whether one includes 0.1-1.0 Hz, where:

- STACIS transfer function is not well known;
- ground motion is not well measured;
- relevance to control system, MMT, is not clear to me!

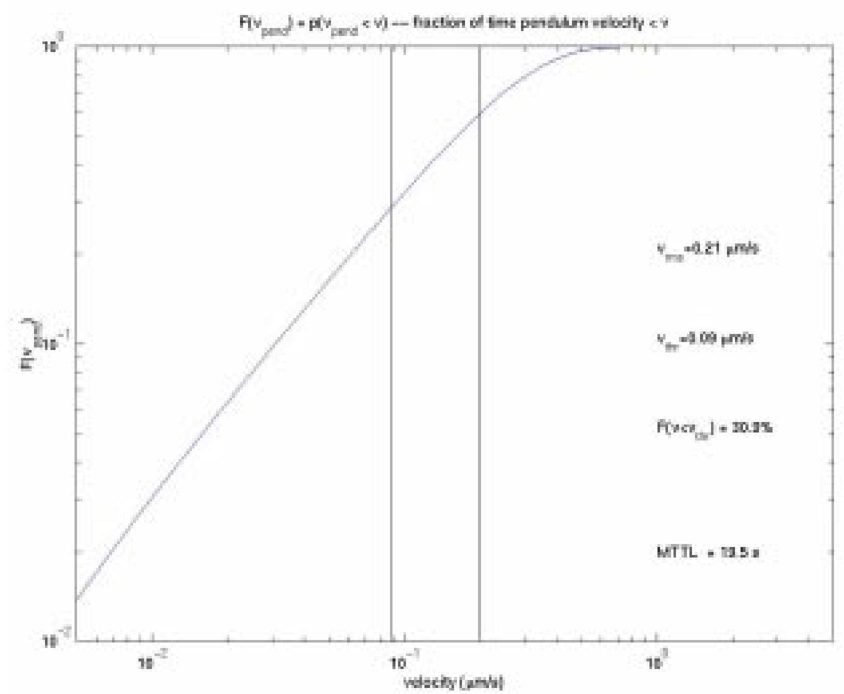


From v_{rms} to MTTL

Pendulum velocity v_{pend} histogram (Rayleigh distribution)



Fraction of time $v_{pend} < v_{thr}$

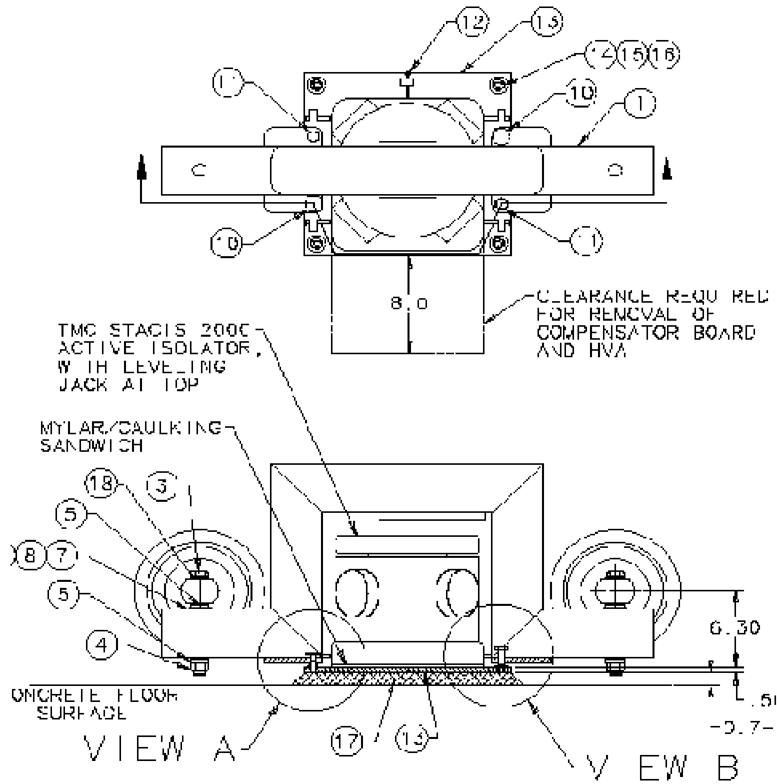


MMT = 20 secs w/out STACIS; 6 sec with.

Support brackets for STACIS

Installing the STACIS pedestals (3 each for 4 chambers) is rather problematic.

- It's a big mechanical engineering task (thought through by Larry Jones).
- Installation is complex & difficult.
- The pedestals must be on extremely level surface: must grout to the floor.
- The pedestals cannot withstand significant lateral stress (eg, from installation or an earthquake)
- EQ safety stops must not short out the devices.
- Regular maintenance of the support system (in addition to monitoring and maintenance of the pedestals themselves) is required.

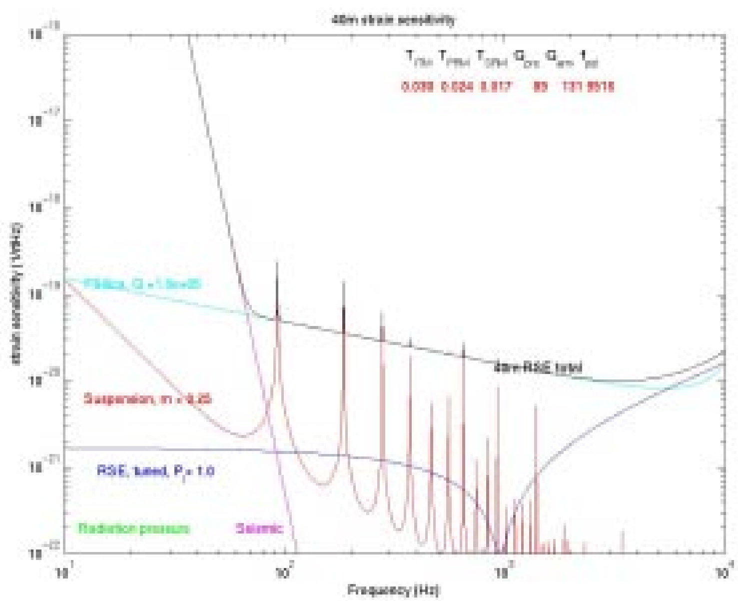


Size and mass of core optics

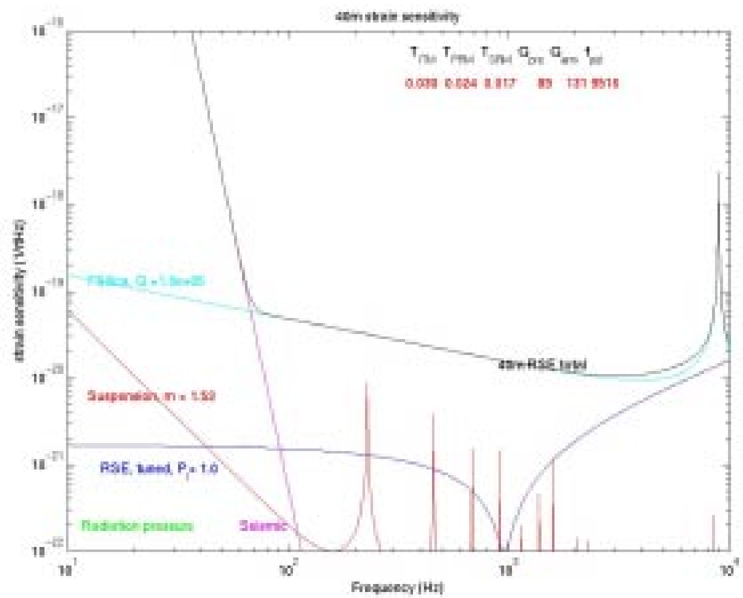
- 40m- recycling experiment used 4"diameter 3.5"thick core optics (1.56 kg, which require already-engineered scaled SOS/LOS suspension),
- LIGO SOS suspensions (MC, MMT) use 3"diameter 1"thick optics (0.25 kg).
- 3” optics have sufficient aperture, even after OSEMs are taken into account, to cover all but ~ 1ppm of the 40m beam power (<1.4" diam. everywhere).
- Smaller optics presumably cost less and take less time to grow.
- Smaller optics require a suspension with a smaller footprint on the already very crowded chamber tables.
- Suspension noise (which depends on mass of optic) is less than test mass internal thermal noise everywhere except for a few violin-mode spikes.
- LIGO experience with SOS, 3” optics is very valuable!
- I see no reason to not go with SOS 3” for all 40m core optics
- If we go to multiple pendula, we might need bigger masses for mechanical reasons (K.Strain).

Noise curves for two choices of test masses

3”ϕ x 1”t, 0.25 kg



4”ϕ x 3.5”t, 1.56 kg



- shot noise: P_{laser} = 1 w, G(PRC) = 89, RSE tune = -0.6 rad, T_{ITM} = 3%, T_{ETM} = 15 ppm, T_{RM} = 2.44%, T_{SRM} = 1.7%.
- Internal test mass noise uses Yury Levin formula, r_{beam} = 1.5 mm (power radius), Q = 1E5.
- Suspension noise uses f_{pend} = 1 Hz, mass = 0.25 kg or 1.56 kg, ϕ_{pend} = 3e6, ϕ_{violin} = 2. ϕ_{pend}
- Seismic noise is without active (STACIS) damping.

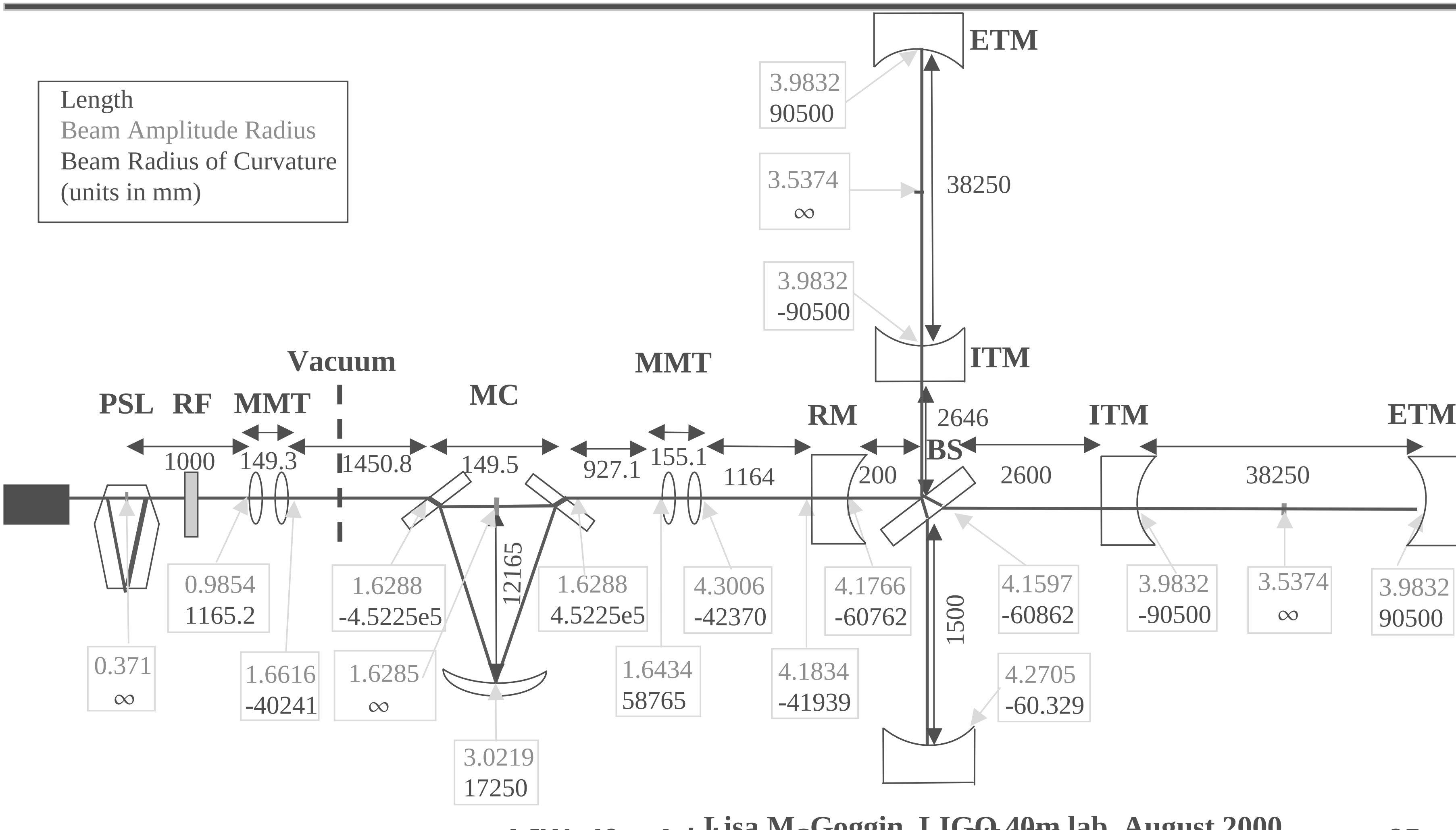
Other Optics issues

- Optical quality (absorption). Typical numbers for LIGO glass, as measured by Garilynn Billingsley:
  - Corning: ~13 ppm/cm
  - Heraeus 311 & 312: ~ 3 ppm/cm
  - Heraeus 311 SV: ~ 0.5 ppm/cm
- It takes a long time to procure the substrate, polish, and coat.
  - 4 months ARO for the SV material. No difference in delivery time between 3 or 4" optics.
  - Polishing is 2-3 months for something of this quality.
  - there is currently a long line at the door of the coating house (REO).
- Cost scales with weight of optic, and SV is ~twice as expensive as Corning.
- Bill Kells estimates the effect of thermal lensing (at 1 watt input power) to be negligible if correct ROC are applied, and SV glass used for ITMs, BS.
- Will choose Heraeus SV for ITMs and BS, Corning for ETMs, RM, SM, and MC.
- Can wait till "last minute" for coatings (T_{ITM}, T_{RM}, T_{SM})

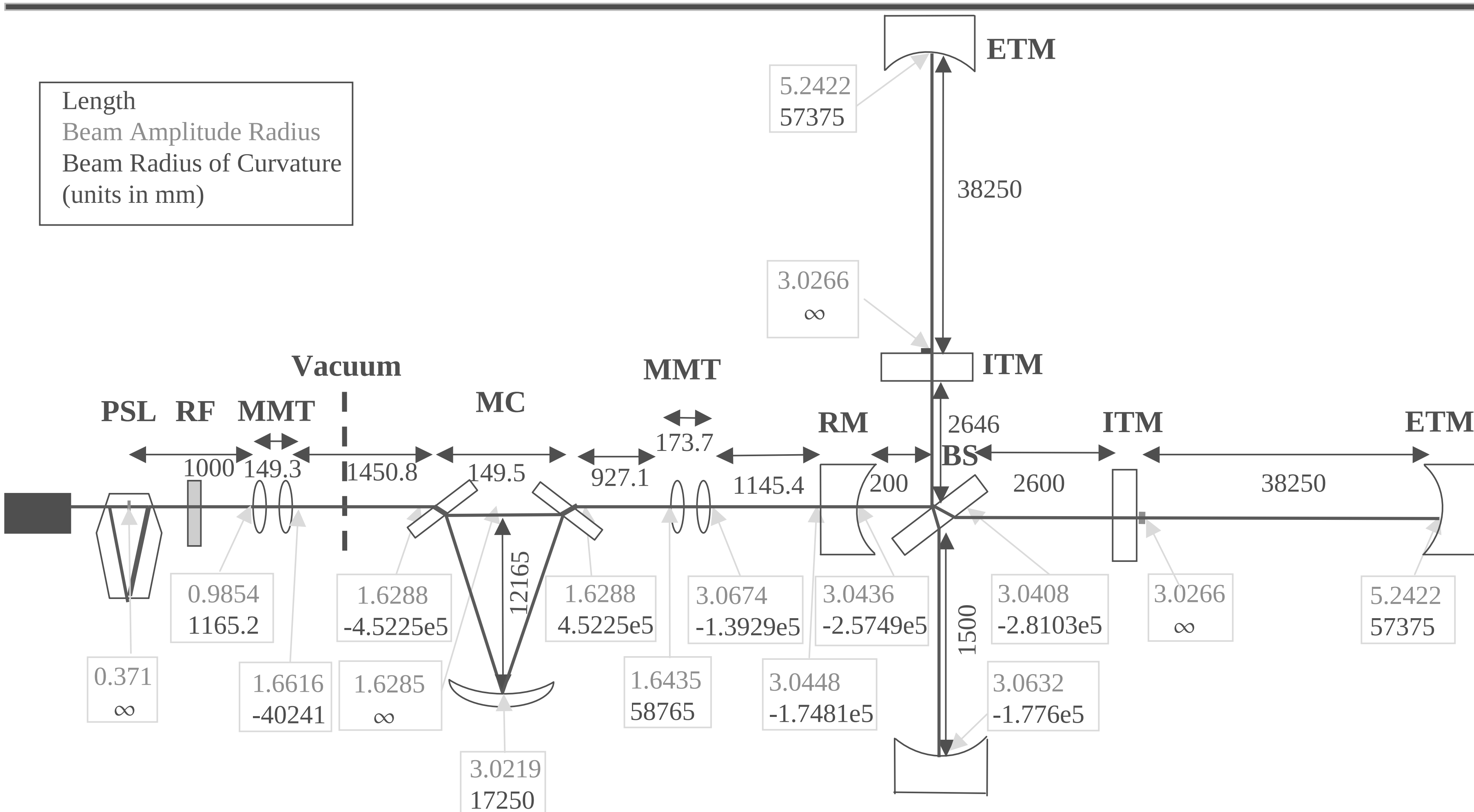
Radii of Curvature (ROC)

- Two options: symmetric arm FP cavities, or half-symmetric (flat ITMs)
  - » LIGO I is almost symmetric; waist is closer to ITM, to keep beam size small at BS
  - » 40m beam sizes are small everywhere.
  - » Still, they're smaller at BS, RM, MMT if flat ITM is chosen.
  - » But then, a bit less like LIGO.
  - » In either case, "correct" ROCs would be chosen for RM, SM.
  - » MZ: "putting the waist at the ITM (i.e., flat) made alignment and mode matching somewhat more convenient."
  - » MZ: " making at least some mirrors flat has a practical advantage in the sense flats are faster/easier to get "; but I believe that polishing time and cost is the same either way. (Unless you're buying OTS items. Not an option for Heraeus SV).
- How to choose?

Optics Parameters (symmetric arms)



Optics Parameters (flat ITMs)



Lisa M. Goggin, LIGO 40m lab, August 2000

CDS electronics work

- Rick Karwoski is assembling a (preliminary) parts list for all CDS electronics (suspension controllers, LSC, ASC, ISC, racks, crates, CPUs, reflective memory, GPS, PD heads, OSEMs, amplifiers, drivers, power supplies, cables, connectors), with help from Heefner & Bork.
- CDS for 40m is almost the same as for an entire LIGO IFO. It drives the cost of the upgrade!

40m advisory committee action items

- Do the goals and scope of the 40m upgrade make sense? Do they fill an essential R&D need for LIGO II? Can/should the lab do more?
- Advice on optics size: is 3"x1", SOS, adequate?
- Advice on IO: are fixed MMT, steering mirrors adequate?
- Do we need active seismic isolation?
- Where to put the beam waist in the arms?
- Does the OOC need to be baked?
- LSC involvement?

MINUTES of the meeting

Date: Mon, 21 Aug 2000 15:33:00 -0700 (PDT)
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Subject: Minutes of the 40m Technical Advisory Committee meeting

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Minutes of the third meeting of the
40 Meter Interferometer Technical Advisory Committee
Wednesday, August 16, 2000, LSC meeting at LHO.

Ken Strain (chair) kstrain@physics.gla.ac.uk +44 141 330 5884
Minutes by Alan Weinstein, ajw@caltech.edu, 626-395-6682

- Ken Strain gave a brief resume of the newly proposed
  LIGO-II control scheme
  (I wasn't taking notes, so I can't do it justice)

- Ken went on to describe plans for a quick test of this scheme
  at Glasgow 10m. (ditto).

- AJW presented a host of transparencies (see
  http://www.ligo.caltech.edu/~ajw/G000194-00.pdf).

  - Re-statement of objectives of the upgrade,
    posing the question of whether the control system risk
    is high enough to warrant 40m upgrade effort.

    ** There were very few comments made!
    AJW remains uncomfortable,
    and concerned about drumming up LSC interest/participation.

  - ** All of the key elements of the
    newly proposed LIGO-II control scheme
    can most likely be prototyped at the 40m
    in a straightforward and extrapolatable way.
    The smaller PRC at the 40m makes the control matrix
    a bit less diagonal, but do-able.

  - recent activity (dismantling, building rehab,
    vacuum control system, output chamber & seismic stack) described.

  - Preliminary optical layout presented, including 12m mode cleaner,
    and fixed steering mirrors and MMT lenses.

    ** AJW requested help/advice in analyzing noise produced
    by these fixed elements; no volunteers.

MINUTES, continued

- Need for active seismic isolation (STACIS) addressed.

  ** No one offered any wisdom on the analysis (MTTL, minimum frequency for evaluating rms motion, etc).
  ** It comes down to whether the installation can be effectively and safely managed. If Larry Jones says he can do it, we'll do it!

- Question raised as to appropriate size of core optics (3", 0.25 kg vs 4", 1.56 kg). (Use 3" SOS optics for MMT1-3, RM, BS, SM).

  ** Still under debate, advice welcome!

- Question raised as to choice of flat ITMs or symmetric arms.

  ** opinions favored flat ITMs. OK!

- Very brief mention of designs for LSC and ASC, in the context of Jim Mason's control scheme. Designs will be updated for the new proposed LIGO II control scheme.

OK, now here's AJW's reconstruction of the main features of the newly proposed LIGO-II control scheme, as described by Ken Strain and Peter Fritchel:

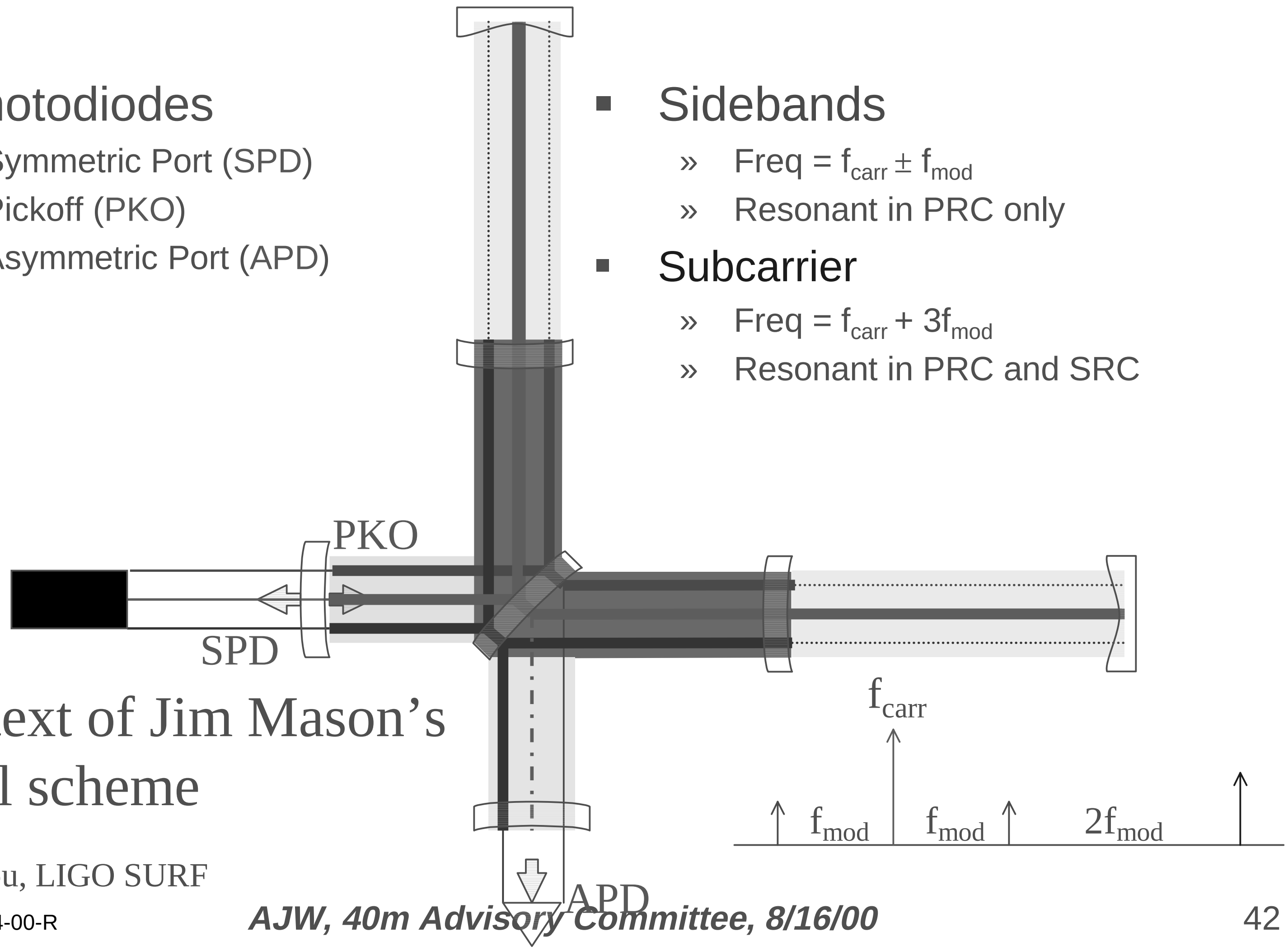
- phase-modulated sidebands placed before a 16.5 m mode cleaner at 9 MHz and at 180 MHz
  - two Pockels cells in series
  - parasitic modulations at 171 and 189 are not a problem...
  - some control signals using balanced RF sidebands cancel each other when operated in RSE mode, but only one sideband is used when detuned, so these control signals are present.
- small Michelson l- asymmetry to put 180MHz on a bright fringe out the asymmetric port, while only a small amount of 9 MHz goes there.
- beats between 9 and 180 (double-demodulated) gives clean separation between l+ and ls DOF.
- Other DOF (L+, L-, l-) derived in the usual way.
- GW signal to be obtained using DC locking:
  - let some carrier light come out the dark port, either by:
    - take arms slightly out of resonance in opposite directions
    - tiny (additional) Michelson l- asymmetry to let carrier out
    - They like the fist approach better; not sure why
  - beat carrier against signal sidebands to get GW signal
  - get rid of all RF signals with a short output mode cleaner (after picking the light off to control ls, L-)
  - Since only low-noise, arm-filtered light is used, extracting the signal at DC is not too noisy.

Modeling Length- and Alignment control schemes

- We worked in the context of Jim Mason's dual-recycling control scheme (other control schemes would be implemented quite differently, and would require re-modeling).
- Work by SURF 2000 students:
  - » Ted Jou, Caltech: 40m LSC with **`Twiddle`**, lots of help from Jim Mason
  - » Brian Kappus, Harvey Mudd: 40m ASC/WFS with **`ModalModel`**, lots of help from Nergis and Daniel Sigg

LIGO II Length Sensing

- 3 Photodiodes
  - » Symmetric Port (SPD)
  - » Pickoff (PKO)
  - » Asymmetric Port (APD)
- Sidebands
  - » Freq = $f_{carr} \pm f_{mod}$
  - » Resonant in PRC only
- Subcarrier
  - » Freq = $f_{carr} + 3f_{mod}$
  - » Resonant in PRC and SRC



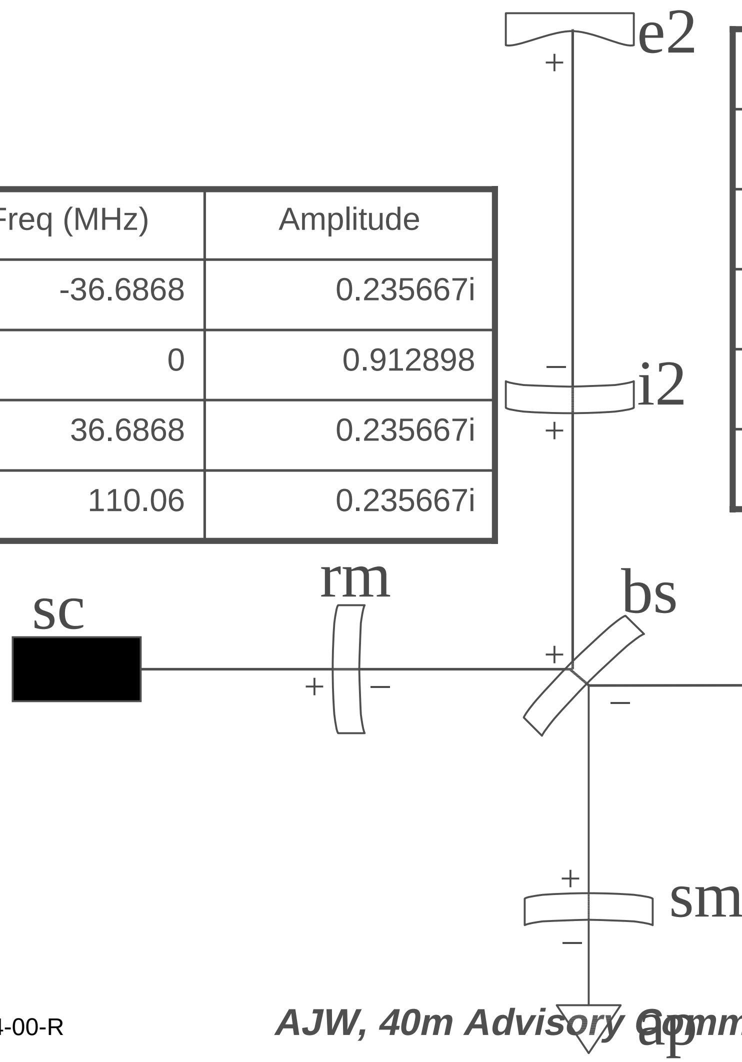
In the context of Jim Mason's DR control scheme

Work by Ted Jou, LIGO SURF

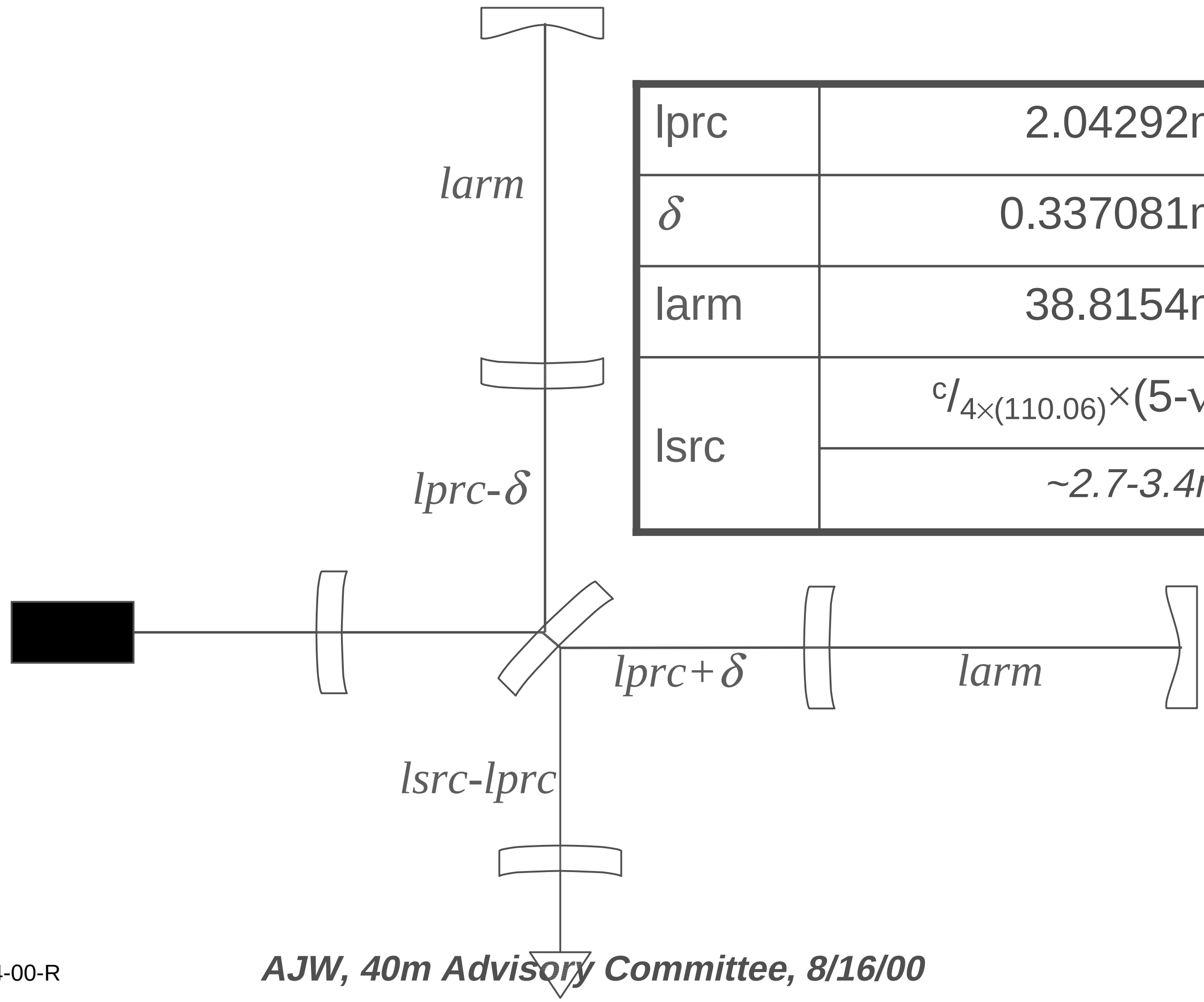
Optical Components

Source	Freq (MHz)	Amplitude
SB-	-36.6868	0.235667i
Carrier	0	0.912898
SB+	36.6868	0.235667i
SubCarr	110.06	0.235667i

Mirror	Refl	Trans	Loss
Recycl	*0.8*	0.2	2E-5
BmSpl	*0.5*	0.5	7.5E-4
ITM	*0.97*	0.03	2E-5
ETM	*1*	1.5E-5	2E-5
Signal	*0.8*	0.2	2E-5



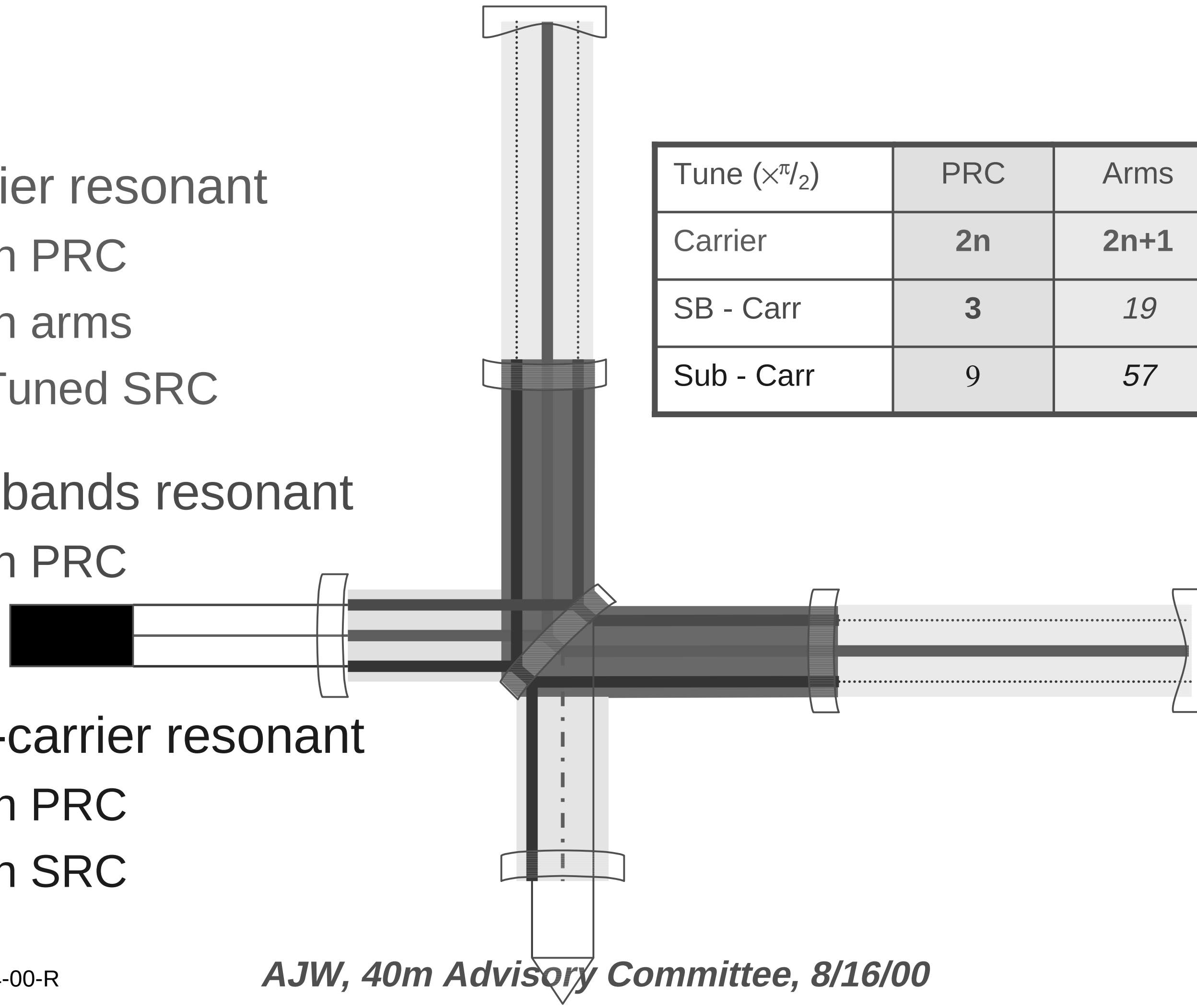
Lengths



lprc	2.04292m
δ	0.337081m
larm	38.8154m
lsrc	$^{c}/_{4\times(110.06)}\times(5-\nu)$
	~2.7-3.4m

Tunes

- Carrier resonant
  - » In PRC
  - » In arms
  - » Tuned SRC
- Sidebands resonant
  - » In PRC
- Sub-carrier resonant
  - » In PRC
  - » In SRC



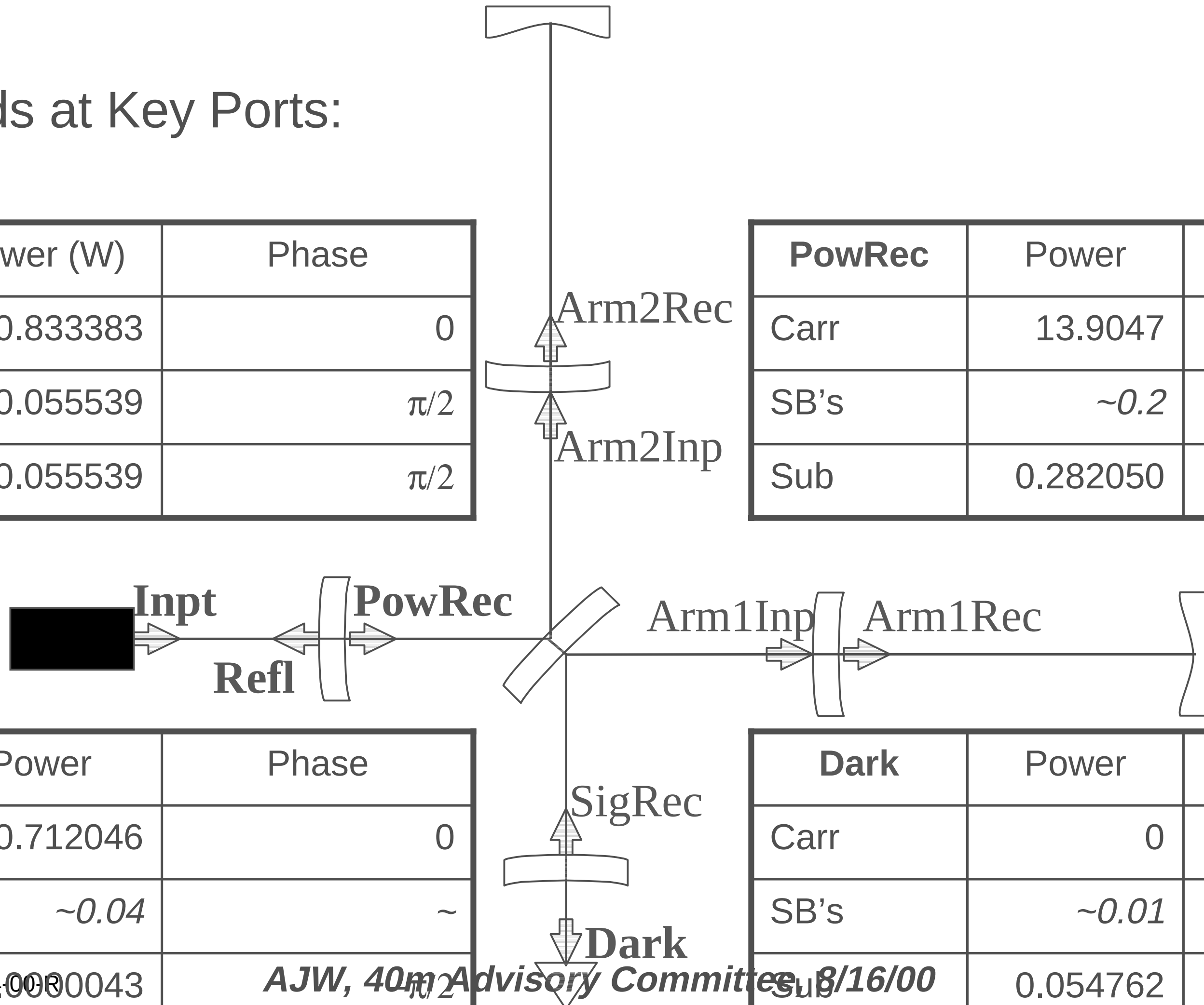
Tune ($\times^{\pi}/_{2}$)	PRC	Arms	SRC
Carrier	**2n**	**2n+1**	ν
SB - Carr	**3**	*19*	$(5-\nu)/3$
Sub - Carr	9	*57*	**5 -** ν

Ports

- Fields at Key Ports:

Inpt	Power (W)	Phase
Carr	0.833383	0
SB's	0.055539	$\pi/2$
Sub	0.055539	$\pi/2$

PowRec	Power	Phase
Carr	13.9047	0
SB's	*~0.2*	~
Sub	0.282050	$\pi/2$

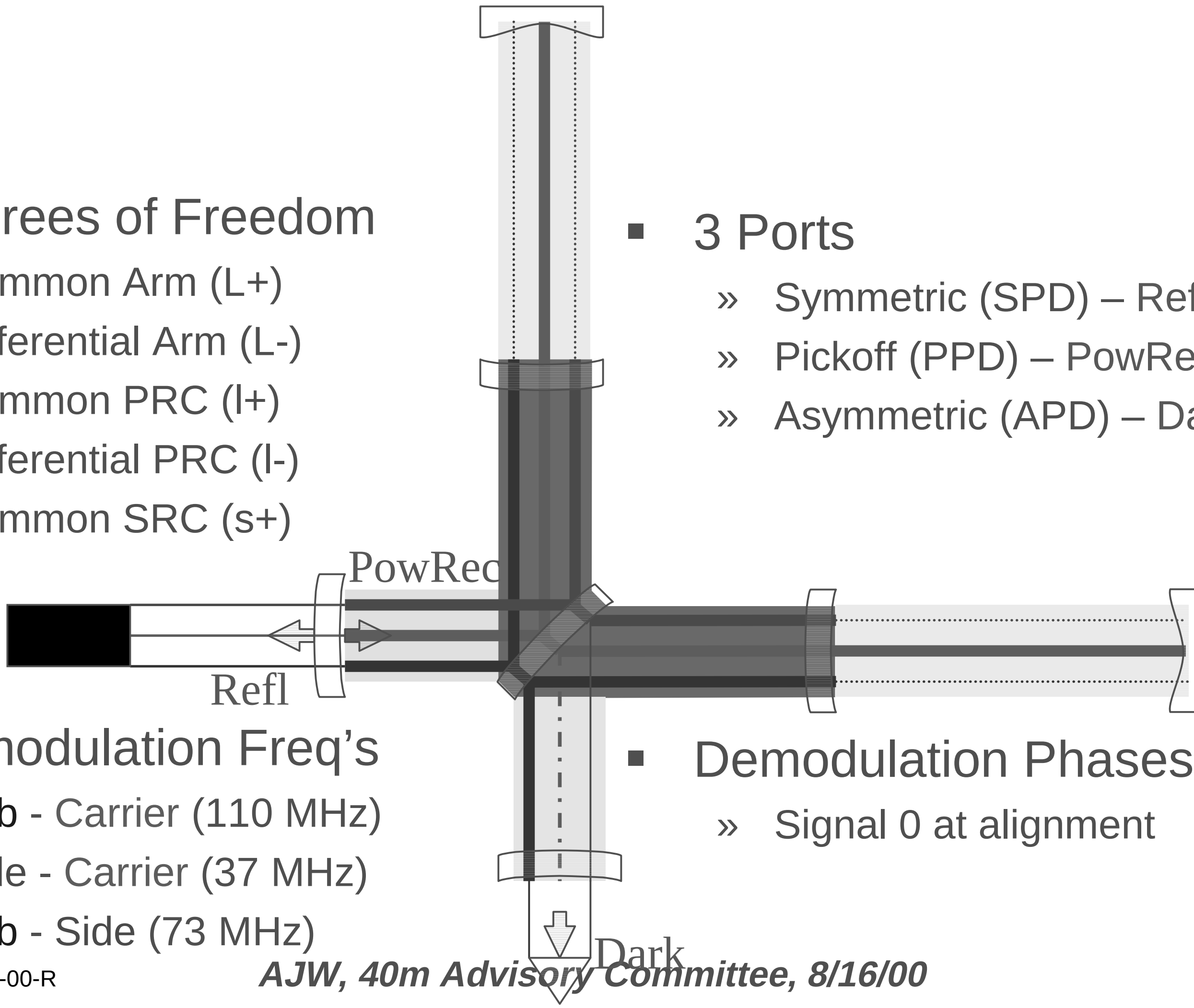


Refl	Power	Phase
Carr	0.712046	0
SB's	*~0.04*	~
Sub	0.0000043	$-\pi/2$

Dark	Power	Phase
Carr	0	$\nu\pi/2$
SB's	*~0.01*	~
Sub	0.054762	π

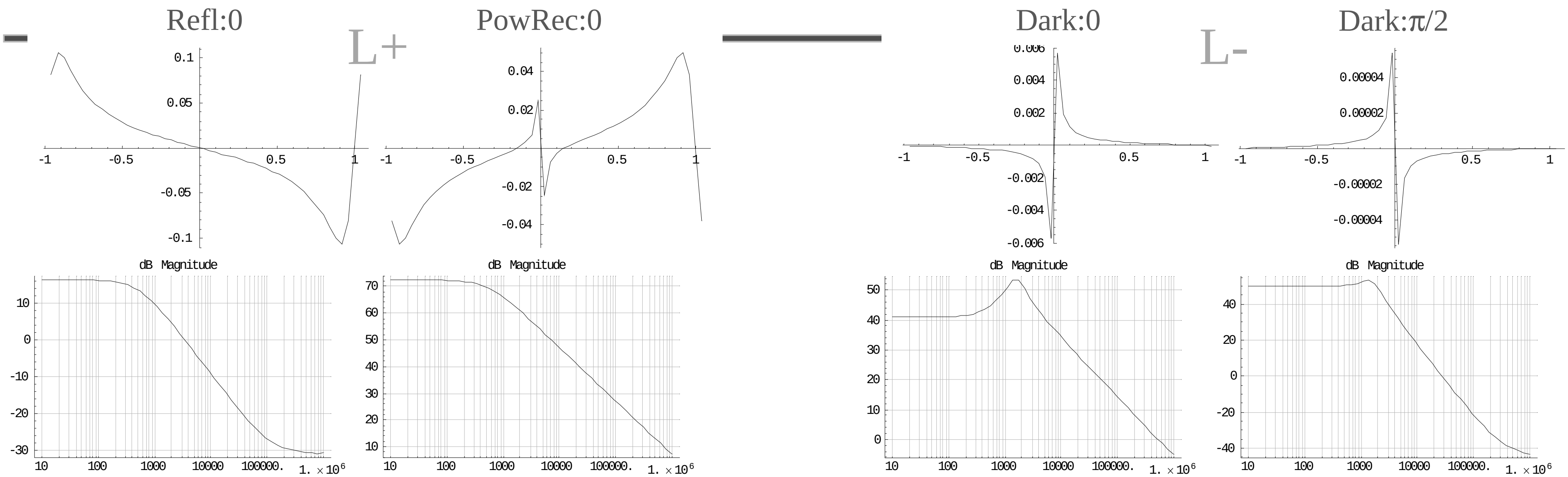
Length Sensing

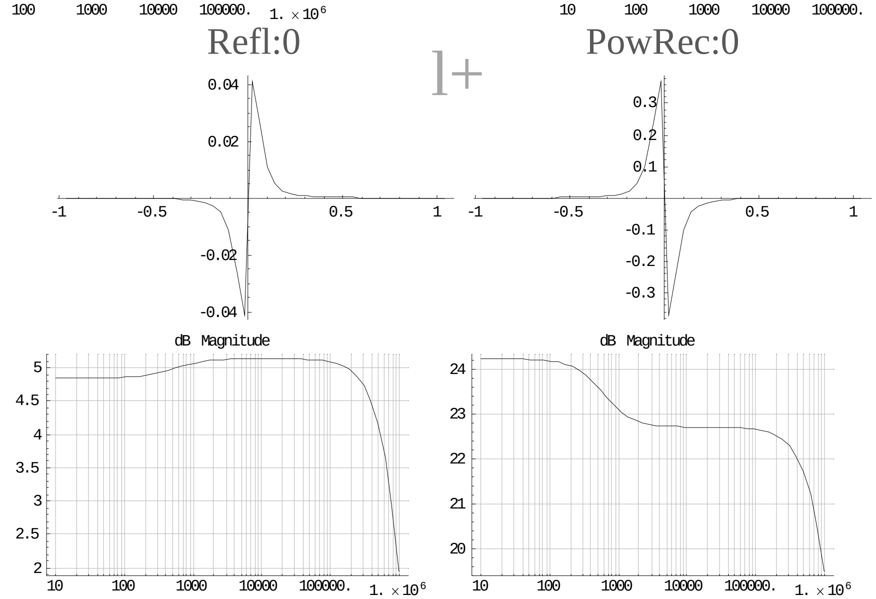
- 5 Degrees of Freedom
  - » Common Arm (L+)
  - » Differential Arm (L-)
  - » Common PRC (l+)
  - » Differential PRC (l-)
  - » Common SRC (s+)
- 3 Ports
  - » Symmetric (SPD) – Refl
  - » Pickoff (PPD) – PowRec
  - » Asymmetric (APD) – Dark



- 3 Demodulation Freq's
  - » Sub - Carrier (110 MHz)
  - » Side - Carrier (37 MHz)
  - » Sub - Side (73 MHz)
- Demodulation Phases
  - » Signal 0 at alignment

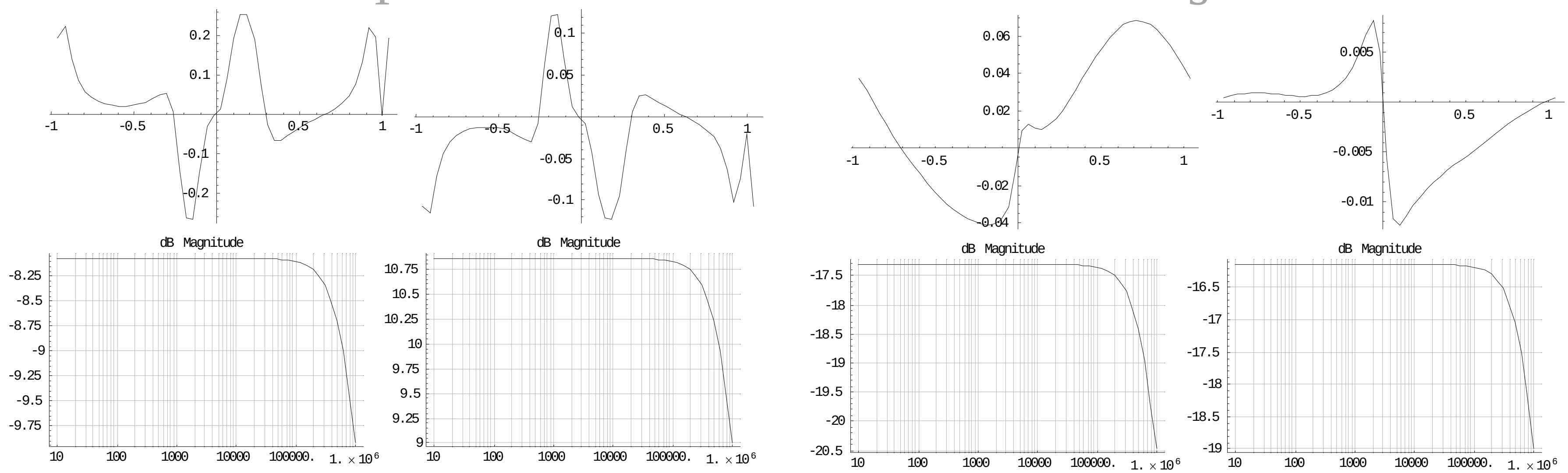
Error Signals





Error Signals

Refl:0.19π | l- | PowRec:0.19π | Refl:1.78π | s+ | PowRec:0.11π



DC Matrix

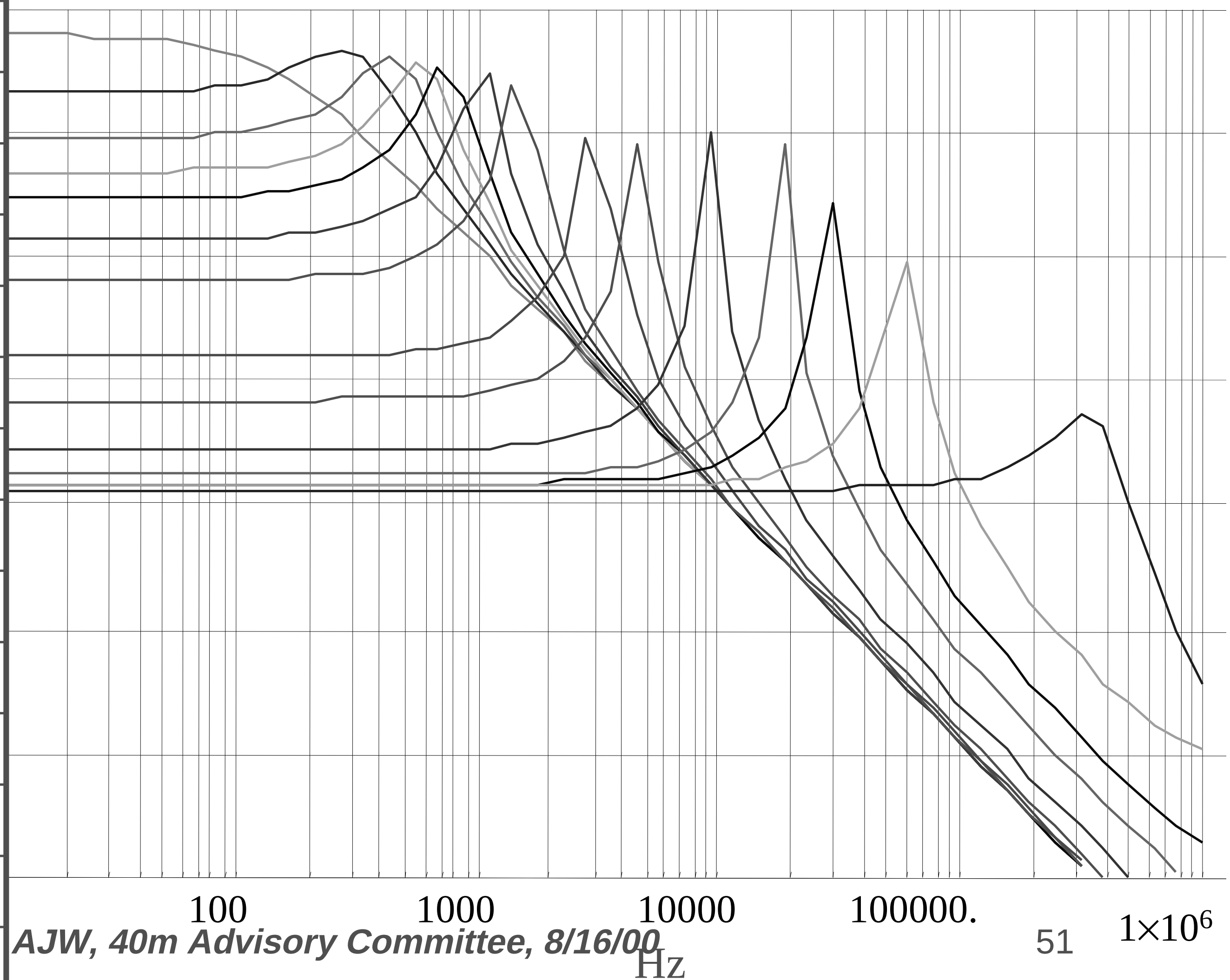
Freq	Phase	PD	L+	L-	l+	l-	s+
36.6868 MHz	0.19π	SPD	1516.95	0.014876	-9.33915	**1.95352**	-0.565124
		PKO	-922.376	0.13147	26.5742	**17.2651**	-4.99453
	0	APD	0	56.4169	0	0.429603	0
110.06MHz		SPD	**-8.19106**	0	**-1.74752**	0	1.75378
		PKO	**-4230.34**	0	**16.2174**	0	15.4998
		APD	0	**111.292**	0	0.847463	0
	$\pi/2$	APD	0	**304.368**	0	2.31769	0
73.3736 MHz	1.78π	SPD	0.000189	0.000033	0.111518	0.004317	**0.136336**
	1.32π	PKO	0.026592	-0.00327	-2.18296	-0.429417	1.3092
	0.11π	APD	-0.00179	-0.00044	0.079241	-0.057963	**-0.155943**

($\nu = 0.9$)

(*Values in* $^{W}/_{(\lambda/2\pi)}$)

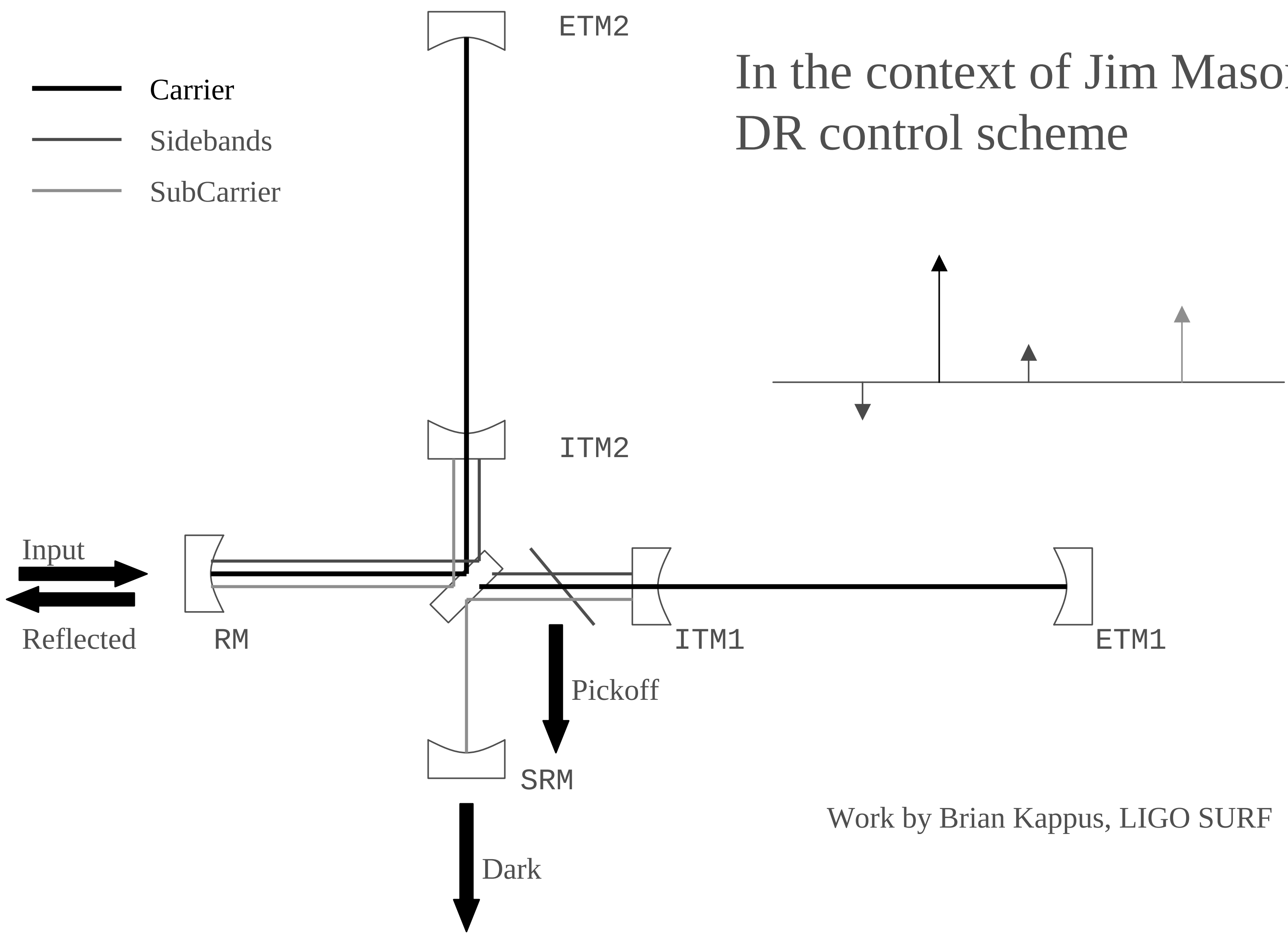
Signal Detunings

ν	s+ (m)	Pole (kHz)
1	2.7239	0
0.98	2.7375	0.28
0.97	2.7443	0.43
0.96	2.7511	0.53
0.95	2.7579	0.67
0.93	2.7716	1.1
0.9	2.7920	1.4
0.8	2.8601	2.8
0.7	2.9282	3.4
0.5	3.0644	9.5
0.3	3.2006	18
0.2	3.2687	30
0.1	3.3368	60
0	3.4049	300



Wavefront Sensing

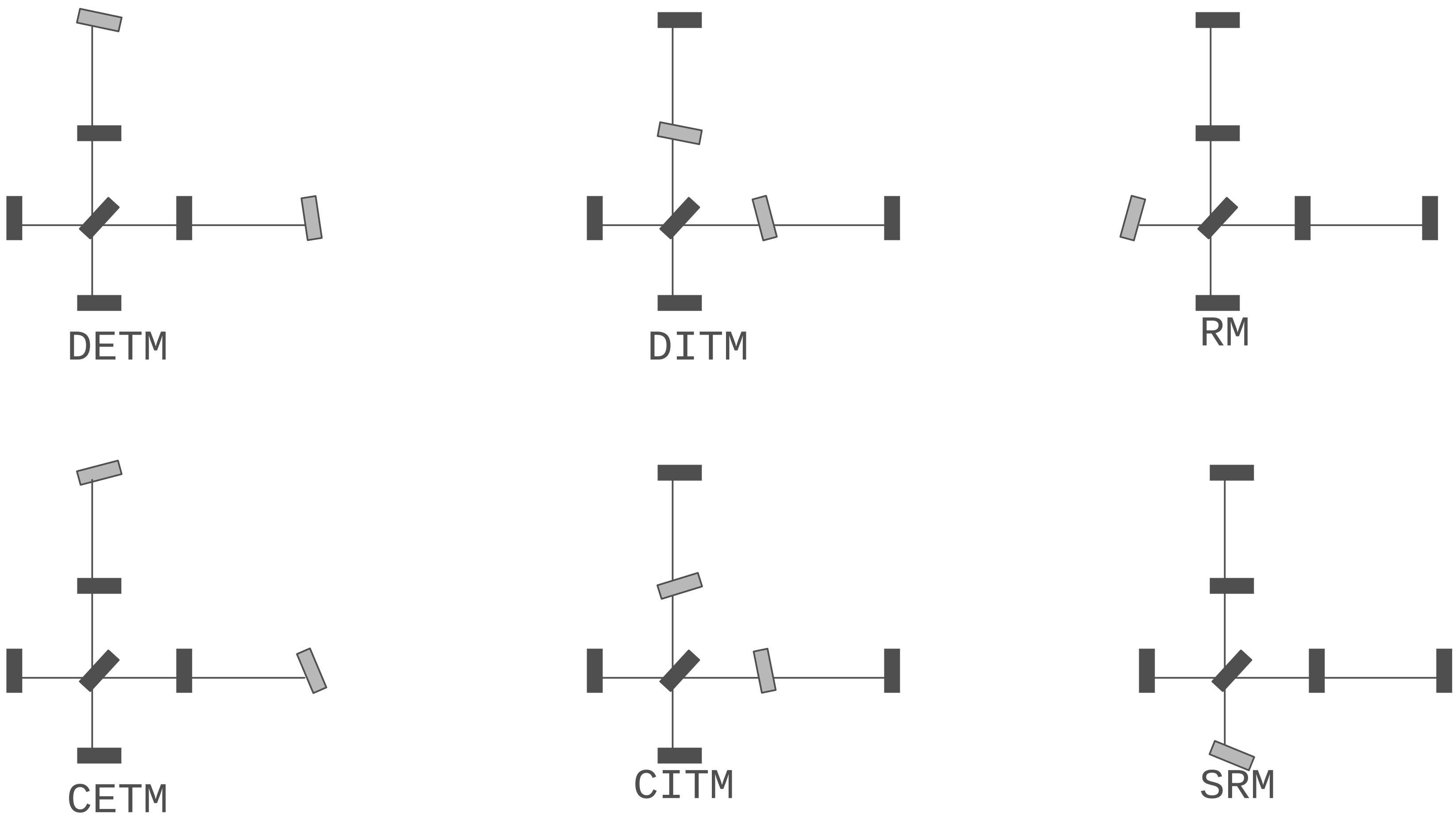
In the context of Jim Mason's DR control scheme



Work by Brian Kappus, LIGO SURF

Wavefront Sensing

Degrees of Freedom - yaw (pitch equivalent)



Wavefront Sensing

Wavefront Sensor signal is sum of contributions from misalignments Θ_i from i^{th} degree of freedom:

$$WFS(\eta,\vec{\Theta}) = P_{in}\, f_{PD} \sum_i A_i \Theta_i \cos(\eta - \eta_i)\cos(\phi_D - \phi_i)$$

- f_{PD} is response of split photodiode
- Θ_i is (normalized) misalignment from i^{th} degree of freedom
- A_i is amplitude of response from i^{th} degree of freedom
- η_i is Guoy phase of response from i^{th} degree of freedom
- ϕ_i is RF phase of response from i^{th} degree of freedom
- η is Guoy phase of beam at PD (adjust with Guoy telescope)
- ϕ_D is RF demodulation phase of mixer

Choose η and ϕ_D to enhance a particular DOF at a particular wavefront sensor

Signals 90 Degrees out of phase are canceled

Wavefront Sensing

Modal Model results (no SRM) for LIGO4km:

	DETM	DITM	CETM	CITM	RM
Dark – Cr–SB	–24.9815	–11.3941	-9.89027×10^{-6}	-4.51095×10^{-6}	–0.00122482
RF Phase	90.	90.	90.	90.	90.
Guoy Phase	90.2	90.5	156.2	156.5	90.2
Bright – Cr–SB	0.0228234	–1.36698	–0.725762	6.20788	–9.60156
RF Phase	90.1	90.	0.	0.	0.
Guoy Phase	143.7	143.7	96.8	145.9	146.5
Pick – Cr–SB	6.13013	–367.157	47.7087	1730.26	–2401.56
RF Phase	90.	90.	0.	0.	0.
Guoy Phase	143.7	143.7	61.1	143.	143.7

Agrees with *Alignment of an Interferometric Gravitational Wave Detector* by P.Fritschel, N. Mavalvala, et al.

40m Sensing Scheme

40m Modal Results including an SRM (tune = .9) -- Sea of Numbers

	DETM	DITM	CETM	CITM	RM	SRM
Dark – Cr–SB	–1.84566	–0.666123	0.00080783	0.000291557	–0.00611958	-9.98756×10^{-16}
RF Phase	152.9	152.9	152.9	152.9	152.9	104.6
Guoy Phase	89.7	89.9	48.2	48.3	89.5	93.9
Bright – Cr–SB	0.157339	–7.42251	–3.75393	–20.1029	23.987	1.41319
RF Phase	143.1	143.3	133.9	148.9	150.9	139.5
Guoy Phase	125.8	126.5	86.5	124.2	126.9	125.6
Pick – Cr–SB	1.54802	–73.0236	–34.4153	–197.855	238.406	13.9031
RF Phase	143.3	143.3	158.6	150.2	149.5	139.5
Guoy Phase	125.8	126.5	85.7	124.5	126.8	125.6
Dark – SB–SC	0.025871	–1.22616	0.0472952	-2.24155	2.73872	-0.27049
RF Phase	28.1	28.1	0.6	0.6	3.5	140.
Guoy Phase	132.9	132.9	41.5	41.5	31.6	104
Bright – SB–SC	-0.0788971	3.73938	-0.249326	11.8169	-14.7598	–1.08385
RF Phase	132.5	132.5	167.8	167.8	166.3	3.6
Guoy Phase	12.9	12.9	54.9	54.9	56.8	59.2
Pick – SB–SC	-0.917404	43.4809	–3.20855	152.07	–174.458	13.9161
RF Phase	149.6	149.6	170.9	170.9	169.4	0.5
Guoy Phase	12.8	12.8	39.9	39.9	34.3	39.5
Dark – Cr–SC	-4.89869×10^{-6}	7.31341×10^{-6}	-1.09831×10^{-8}	1.14711×10^{-8}	-1.673×10^{-6}	9.53968×10^{-16}
RF Phase	136.4	46.3	44.	142.6	152.2	31.
Guoy Phase	46.2	136.2	92.2	11.	61.7	129.3
Bright – Cr–SC	–0.00877758	–0.0363025	–1.62343	6.71421	–2.68049	0.
RF Phase	9.8	99.7	107.2	17.1	33.6	–
Guoy Phase	66.5	156.6	17.	107.1	91.5	–
Pick – Cr–SC	–0.0910084	–0.376395	–16.8321	69.6148	95.3959	0.
RF Phase	9.8	99.8	107.2	17.1	151.4	–
Guoy Phase	66.5	156.6	17.	107.1	147.5	–

40m Sensing Scheme

40m WFS matrix:

	DETM	DITM	CETM	CITM	RM	SRM
1: Dark -- Cr - SB RF: 152.9 Guoy: 90	−1.8	−0.66	0.0006	0.00021	−0.0061	0
2: Pick -- SB - SC RF: 80.9 Guoy: 124.3	0.12	−5.7	0	0	0	0.21
3: Bright -- Cr - SC RF: 107.1 Guoy: 1.5	0	0.032	−1.6	0	0	0
4: Pick - Cr - SC RF:61.4 Guoy: 107.1	−0.042	−0.19	0.020	49	0	0
5: Pick - Cr - SC RF: 107.1 Guoy: 107	0.0087	−0.24	0	0	52	0
6: Dark -- SB - SC RF: 111.8 Guoy: 121.6	0	0	−0.003	0.14	0	−0.23

Very non-singular

40m Sensing Scheme

WFS reasoning:

Row by row:

1: This port had the largest relative DETM signal, RF and Guoy chosen to maximize signal from DETM and DITM

2: This port had a relatively large DITM signal, but more importantly, had its rf and guoy phases significantly seperated from CITM and RM. RF chosen to eliminate CITM, guoy chosen to eliminate RM

3: control of CETM could also have gone to the pickoff -- Cr - SC, but the bright port has a larger relative signal. Both of these ports exibit the nice properties of having almost no DETM/DITM influence and the two common modes are out of RF phase. RF chosen to eliminate CITM, guoy chosen to eliminate RM.

4: Same reasoning as 3, only the pickoff favored CITM. RF chosen to eliminate RM, guoy chosen to eliminate CETM

5: This was the only port where RM did not have almost the exact RF and guoy phase as CITM. RF chosen to eliminate CITM, guoy chosen to eliminate CETM

6: This was the best port for controlling the SRM for one reason: it was the only SRM signal with RF and guoy phases significantly seperated from all other signals and had a good relative signal strength. And RM had a guoy phase very close to CITM/CETM which helped reduce all of the signals; Pick -- SB - SC is another option for this WFS but doesn't have quite as good guoy phase agreement between RM and CITM/CETM. RF chosen to eliminate DETM/DITM, guoy chosen to eliminate RM and reduce CITM.

LIGO II Preview

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

LIGO II Preview

WFS scheme with LIGO4km parameters and a tune of .9

	DETM	DITM	CETM	CITM	RM	SRM
1: Dark -- Cr - SB RF: 112.4 Guoy: 90	–2.4	–1.1	0	0	–0.0001	0
2: Pick -- SB - SC RF: 79.8 Guoy: 143.8	–1.3	77	0	0	–0.05	0
3: Bright -- Cr - SC RF: 102.9 Guoy: 4.2	–0.00034	0.00028	0.54	0	0	0
4: Pick - Cr - SC RF:103 Guoy: 95	–0.0047	–0.11	0	251	0	0
5: Pick - Cr - SC RF: 103 Guoy: 49.6	–0.026	–0.064	0	0	282	0
6: Dark -- SB - SC RF: 153 Guoy: 147.3	–0.0061	0.37	–0.0022	0.13	0	–0.27