



Proposed 40 Meter optical configuration

- LIGO II and 40m
- Optical configuration design
- detuning and shot noise response
- choice of cavity lengths, RF frequencies
- Beam spot sizes, mirror ROCs
- Input mode cleaner

Alan Weinstein, 11/1/00



DR configuration at 40m

- Determine configuration for LIGO II and 40m simultaneously (same matlab and twiddle files) to make sure they are similar, and differences are understood.
- Optical configuration design (mirror reflectances, etc) chosen to be the same as current LIGO II design.
- Because of shorter arm length, detuning must be different – that is all!
- The control of the IFO has very little dependence on the detune phase, so this is a meaningful test.
- Because of shorter vacuum envelope, choice of cavity lengths, RF frequencies, etc, will be different. We can make the control scheme very close to that of LIGO II, and err on the side of a somewhat less robust (diagonal) control matrix.
- Beam spot sizes, mirror ROCs, will of course be different as well.
- Input mode cleaner will be almost identical to LIGO I.
- Output mode cleaner – don't know what it will look like – to be designed later.



Optical configuration

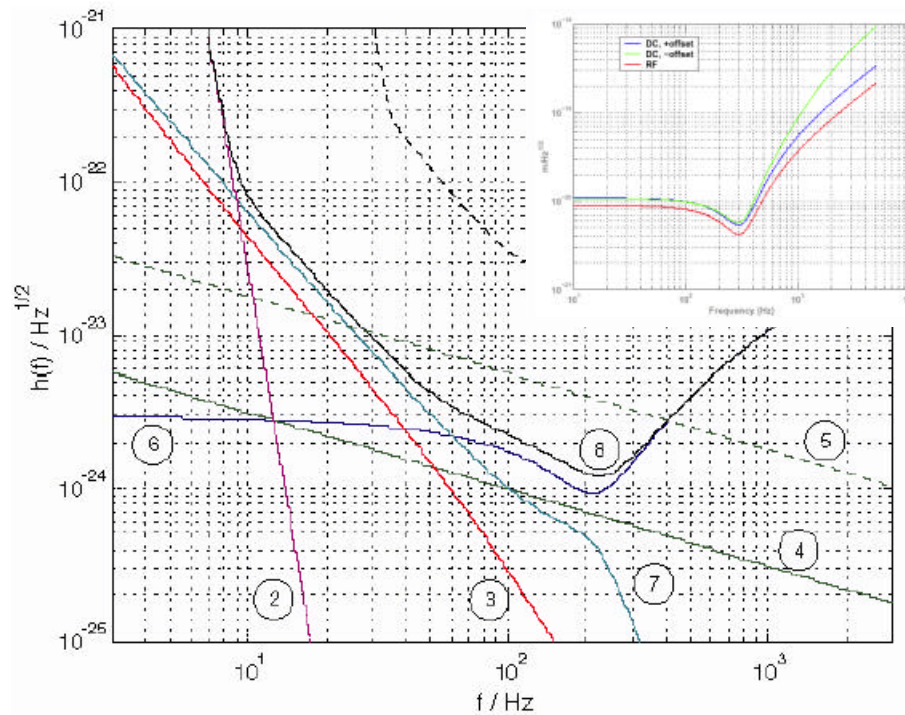
- Assumptions made in LIGO II and 40m design:
 - » Absorption & scattering losses in all optics: 37.5 ppm
 - » Absorption, scattering, pickoff losses in PRC (BS, ITM substrates) add up to 750 ppm
 - » $T_{\text{ETM}} = 15$ ppm to let some light out for monitoring, lock acquisition
- Choose high(er) finesse arms: $T_{\text{ITM}} = 0.005$
 - » finesse = 1231; $G_{\text{arm}} = 770$;
 - » $f_{\text{pole}} = 15$ Hz (LIGO), 1591 Hz (40 m)
- Choose T_{RM} to let 1% of carrier light power out the SP
 - » $T_{\text{RM}} = 0.086$; finesse_{PRC} = 38 ; $G_{\text{PRC}} = 14$ (depends on losses!).
 - » Same for LIGO II and 40m
- Choose T_{SM} "by eye" to get "optimized" dip in shot noise curve.
 - » $T_{\text{SM}} = 0.05$ for LIGO II and 40m
 - » may change; this is ripe for LIGO II re-optimization)



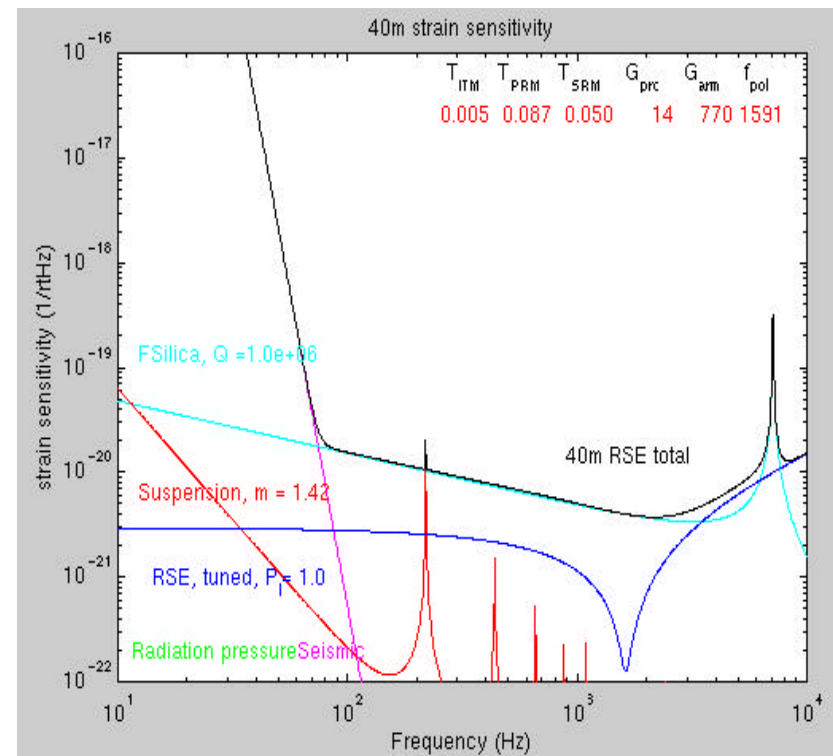
LIGO II and 40m noise curves

LIGO II

40m



- 1 LIGO I total
- 2 Filtered seismic noise
- 3 Suspension thermal noise
- 4 Internal thermal noise - sapphire
- 5 Internal thermal noise - fused silica
- 6 Shot noise
- 7 Radiation pressure noise
- 8 LIGO II total



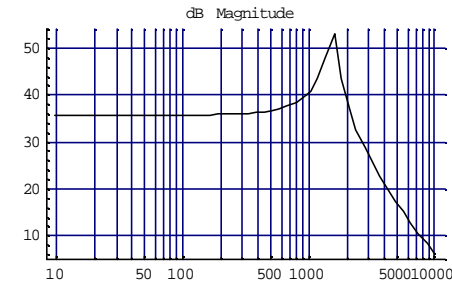


Carrier detuning in SRC

- The carrier detune in the SRC is chosen to give a peak in the transfer function at some frequency $f_{pk} = \mathbf{w}_{pk} / 2\mathbf{p}$

$$\mathbf{n}_s = \frac{1}{\mathbf{p}} \left\{ \tan^{-1} \left[\frac{(1 - L_I - R_I) \sin(\mathbf{w}_{pk} \mathbf{t}_{arm})}{r_I / r_E (1 + (1 - L_I) R_E) - (1 - L_I + R_I) \cos(\mathbf{w}_{pk} \mathbf{t}_{arm})} \right] - \frac{L_{SRC}}{L_{arm}} \mathbf{w}_{pk} \mathbf{t}_{arm} \right\}$$

- We choose $f_{pk} = 1500$ Hz , $\mathbf{n}_s = -0.487 \mathbf{p} / 2$
 - » test mass thermal noise falls with f, so keep it high, but
 - » well below Nyquist frequency of ADCs (8192 Hz)



- This corresponds to bringing the arm cavity pole in to lower frequencies ($f_{pole} = 1591$ Hz); the opposite of what one would do in LIGO II.
- In LIGO II, $f_{pole} = 15.91$ Hz, $f_{pk} = 331$ Hz , $\mathbf{n}_s = +0.028 \mathbf{p} / 2$ (peak is chosen to optimize binary inspiral S/N in presence of thermal noise)



Cavity lengths, RF, at 40m

- We can fix the arm length (to $L_{arm} = 38.25$ m) and determine all other cavity lengths and RF frequencies from the required resonance conditions.

- All RF frequencies must be multiples of the MC FSR:

$$L_{MC} = 12.68 \text{ m}, \quad f_{FSR} = c / 2 L_{MC} \approx 11.8 \text{ MHz}$$

$$f_1 = n_2 f_{FSR}$$

- Later we will fine tune L_{MC} / L_{arm}
- f_1 must resonate in PRC:

$$L_{PRC} = (n_4 + 1/2) c / 2f_1 = (n_4 + 1/2) / n_2 L_{MC}$$

- The PRC at the 40m is around 2.2 m. So we need

$$n_2 = 3, \quad n_4 = 0 \quad \Rightarrow \quad f_1 = 35.466 \text{ MHz}, \quad L_{PRC} = 2.125 \text{ m}$$



f_2 and the SRC

- The higher RF frequency must be an integral multiple of f_1 , so that it too will be resonant in PRC. Make as high as possible, but not much higher than 180 MHz

$$f_2 = n_3 f_1, \quad n_3 = 5 \quad \text{P} \quad f_1 = 177.328 \text{ MHz}$$

- The higher RF frequency must be resonant in the (PRC+SRC):

$$f_2 = (n_5 - \mathbf{n}_S / 2) c / 2(L_{PRC} + L_{SRC})$$

where \mathbf{n}_S is the carrier detune (round trip phase / 2π)

$$L_{SRC} = (n_5 - \mathbf{n}_S / 2) c / 2 f_2 - L_{PRC}$$

- For 40m, $\mathbf{n}_S = -0.487$. Choosing $n_5 = 5$ P $L_{SRC} = 2.319 \text{ m}$ (SM in BS chamber)
- We can choose $n_5 = 6$ P $L_{SRC} = 3.165 \text{ m}$ (SM in OOC).



Schnupp Asymmetry

- Choose asymmetry to make the dark port "bright" for the higher sideband (f_2).
- Since $f_1 \ll f_2$, little f_1 sideband light goes out there.
- Thus, the f_2 sideband sees the SM but the f_1 sideband does not; beats between them are sensitive to the position of the SM, and provide an error signal.
- $\Delta l = c / 4 f_2 = 0.423 \text{ m}$,
- $l_{inline} = L_{PRC} + \mathbf{D} \ l / 2$, $l_{perp} = L_{PRC} - \mathbf{D} \ l / 2$



$$L_{MC} / L_{arm}$$

- Naively, want sidebands *anti*-resonant in arms:

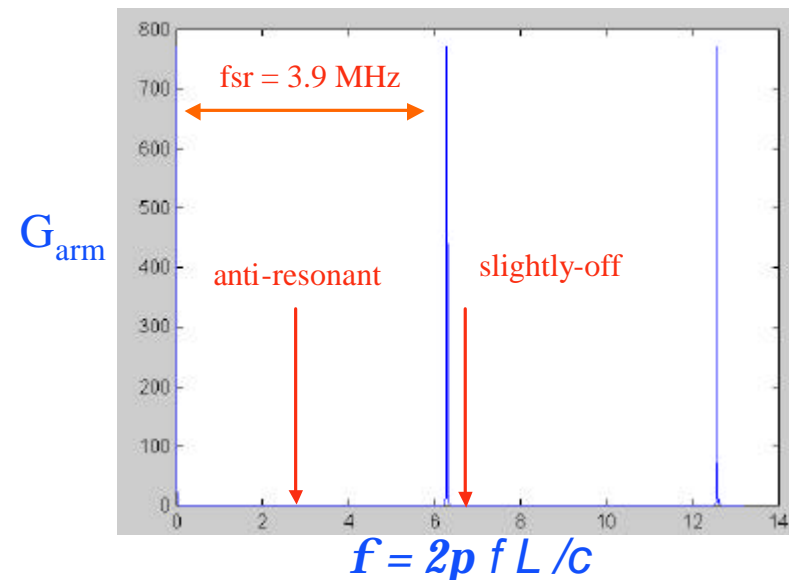
$$f_1 = (n_1 + 1/2) c / 2 L_{arm}$$

$$\text{or: } L_{MC} / L_{arm} = n_2 / (n_1 + 1/2)$$

- However, this is not essential: slightly off resonance is non-resonant.
- In fact, don't want sidebands exactly anti-resonant: 1st harmonic will be resonant!

- Can play with L_{MC} / L_{arm} to get a convenient ratio, but this changes (at a noticeable level) the length sensing matrix; so, optimize (by eye, trial-and-error).

- $n_1 = 8.55$ gives convenient $L_{MC} = 12.68$ m, reasonable length sensing matrix ($n_1 = 8.5$ is resonant; LIGO II has $n_1 = 239.666$).



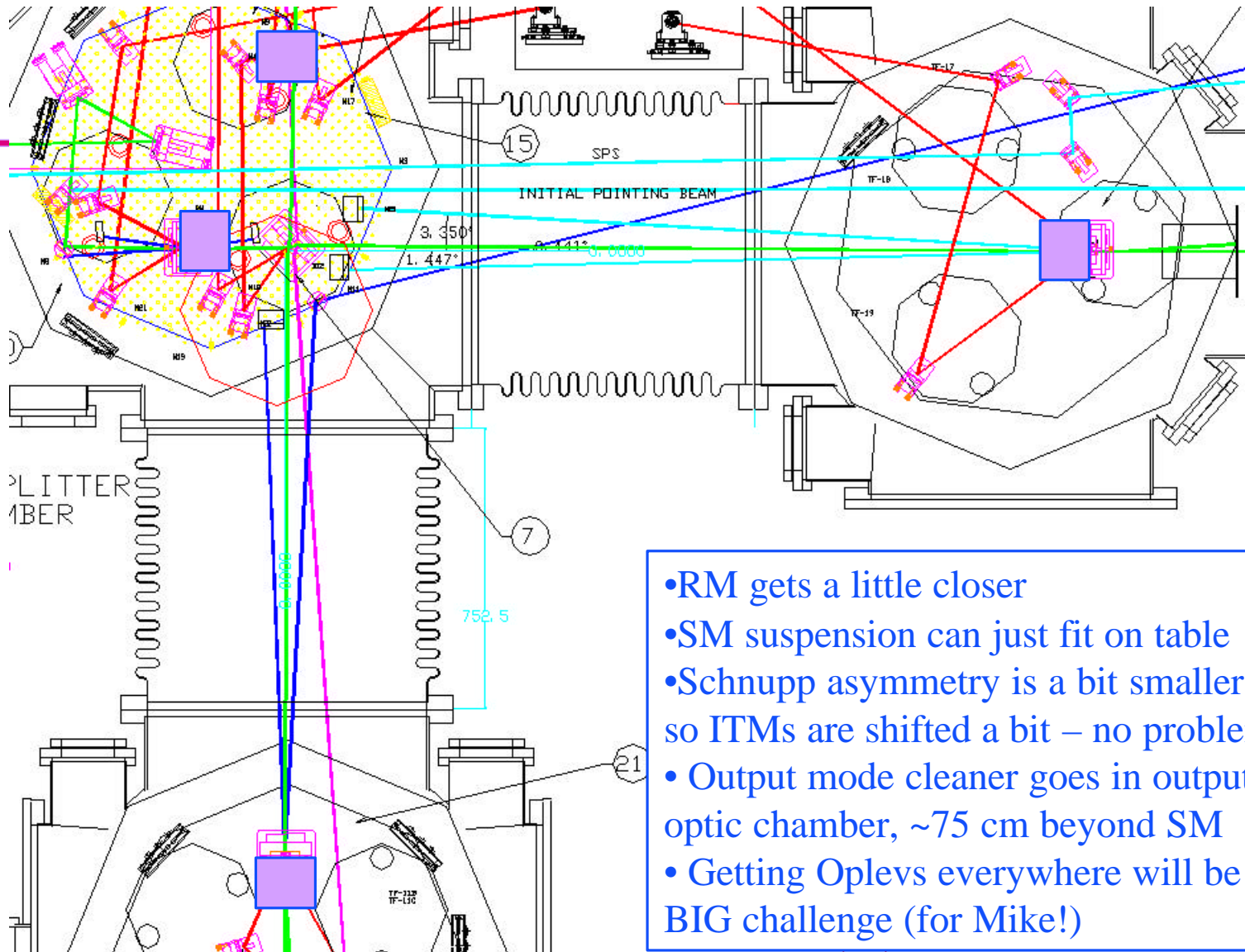


LIGO II and 40m, compared

	n_1	n_2	n_3	n_4	n_5	L_{arm} (m)	L_{PRC} (m)	L_{SRC} (m)	L_{MC} (m)	f_1 (MHz)	f_2 (MHz)
LIGO II	239.7	1	20	0	21	4000	8.330	9.146	16.66	9	180
40m	8.55	3	5	0	5	38.25	2.113	2.319	12.68	35.5	177.3



Will it fit?



- RM gets a little closer
- SM suspension can just fit on table
- Schnupp asymmetry is a bit smaller, so ITMs are shifted a bit – no problem
- Output mode cleaner goes in output optic chamber, ~75 cm beyond SM
- Getting Oplevs everywhere will be a BIG challenge (for Mike!)



Fields in the cavities

frequency	$-f_2$	$-f_1$	carrier	f_1	f_2
Modulation depth Γ	0.1	0.1		0.1	0.1
Input from Laser	0.00249	0.00249	0.99003	0.00249	0.00249
Reflected (SP)	0.00249	0.00224	0.01005	0.00232	0.00016
Asym port (AP)	0.00000	0.00016	0.00000	0.00009	0.00219
PR Cavity	0.00006	0.04859	13.8354	0.04631	0.04393
SR Cavity	0.00005	0.00314	0.00000	0.00170	0.04167
Arm Cavity	0.00000	0.00184	5323.0	0.00095	0.00011

- Input is 1 watt of laser power; modulation depth not optimized
- All the carrier power everywhere agrees with naïve formulas (since Twiddle numerically evaluates the naïve formulas).
- No DC offset. When added, everything changes a little; and carrier light goes out AP.
- Note the asymmetry between $-f_1$ and $+f_1$, and same for f_2 .
- Note significant $+f_2$ in SR and PR cavity. Little f_1 in SRC.
- Only $+f_2$ used for control of cavities.
- Little (but non-zero) SB in arms.



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

- Much more diagonal than LIGO I!
- These numbers vary as one varies arm length, unmatched arms, imperfections, losses, etc.
- l_+ and l_- signals are not very robust, but neither are they at LIGO I.
- PO signal must be multiplied by PO power reflectance (600 ppm nominal); is the signal big enough to be significantly above PD noise? Can make it bigger, with some sacrifice in GW shot noise response; maybe that's appropriate here. Ditto, for modulation depth.
- Double demodulation is difficult; hard to determine demod phases.
- Thanks to Jim Mason for all his help!



DC offset

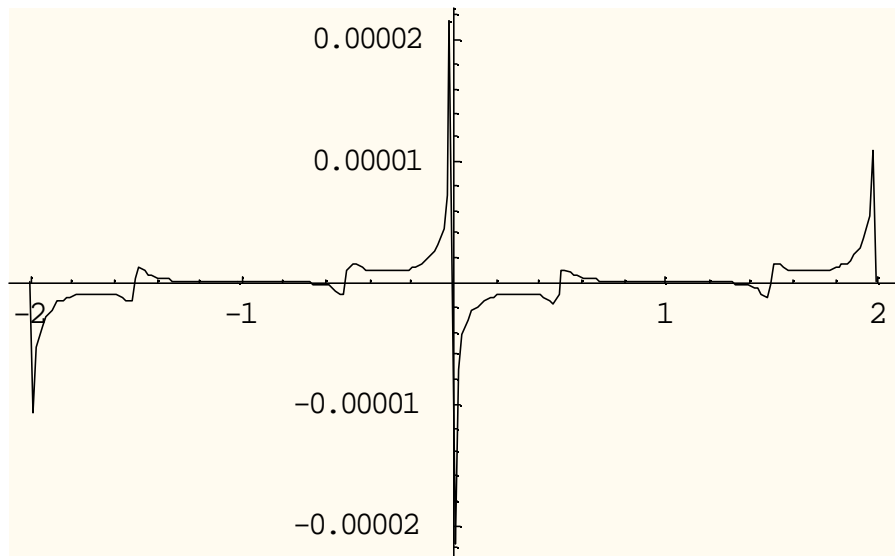
- We offset the arms by a tiny fraction of the linewidth (eg, $\pm 10^{-11}$ m) to make the arms unbalanced, so that a little bit of carrier light exits the dark port.
- This will permit DC detection of the GW, after a short output mode cleaner which scrapes off all the RF sidebands and non-TEM₀₀ modes.
- This has negligible effect on the optical configuration, shot noise response, cavity lengths, or length control matrix.



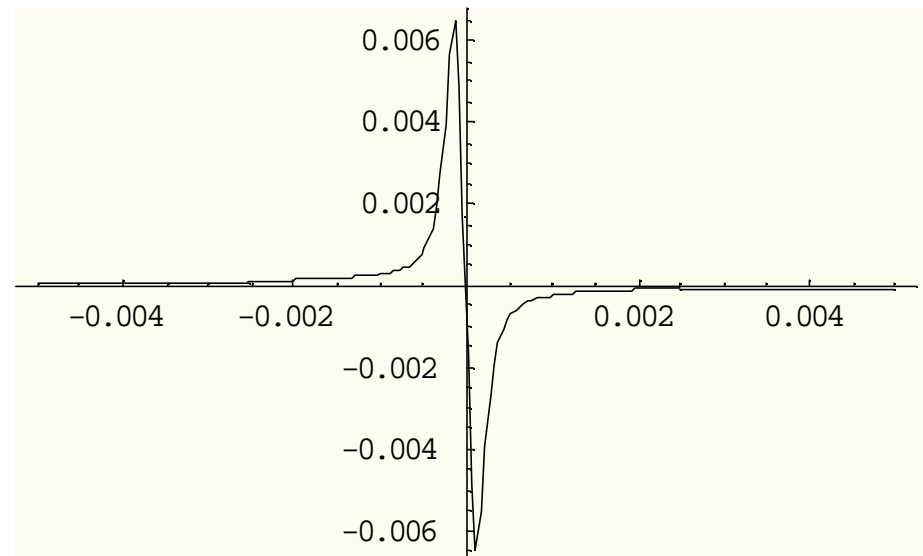
Control signals from Twiddle: L-

L- (GW signal), AsymPort, f_2

Full range of L- sweep in units of $\lambda/2$



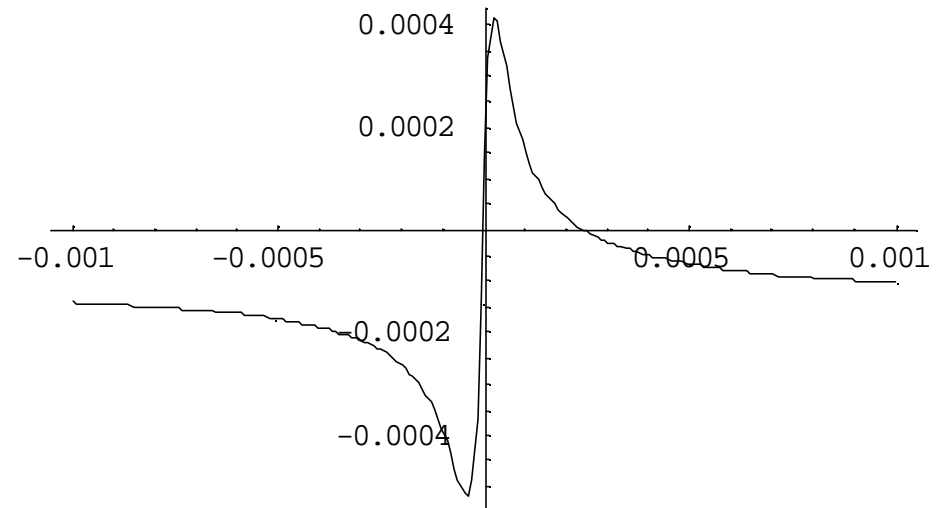
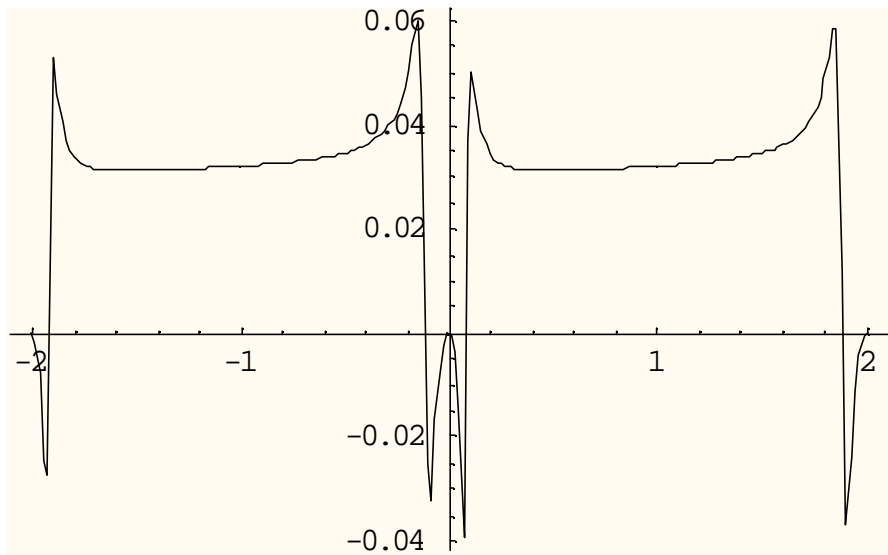
Closeup of error signal





Control signals from Twiddle: L+

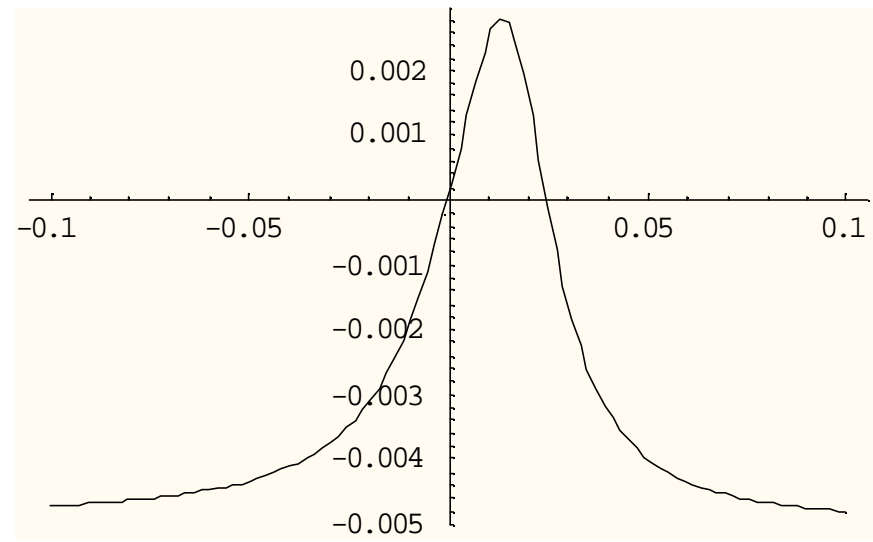
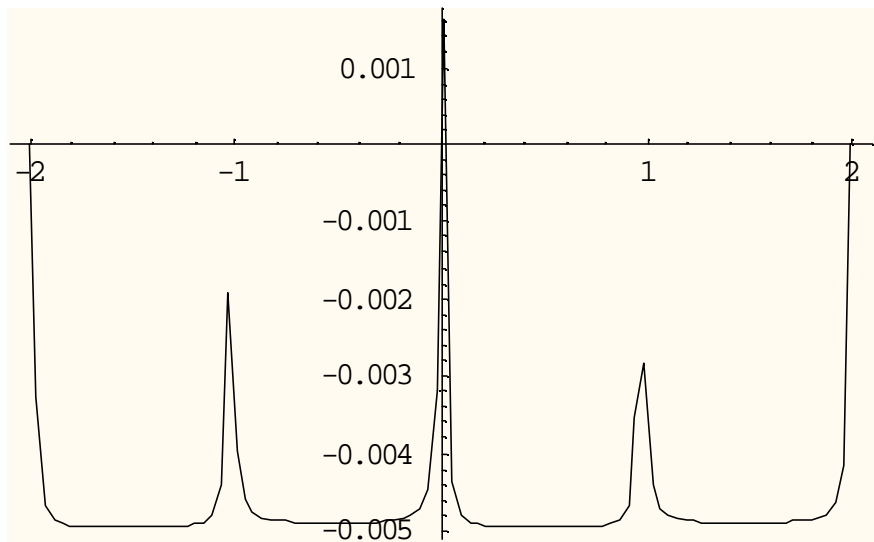
$L+$, SP , f_1





Control signals from Twiddle: I+

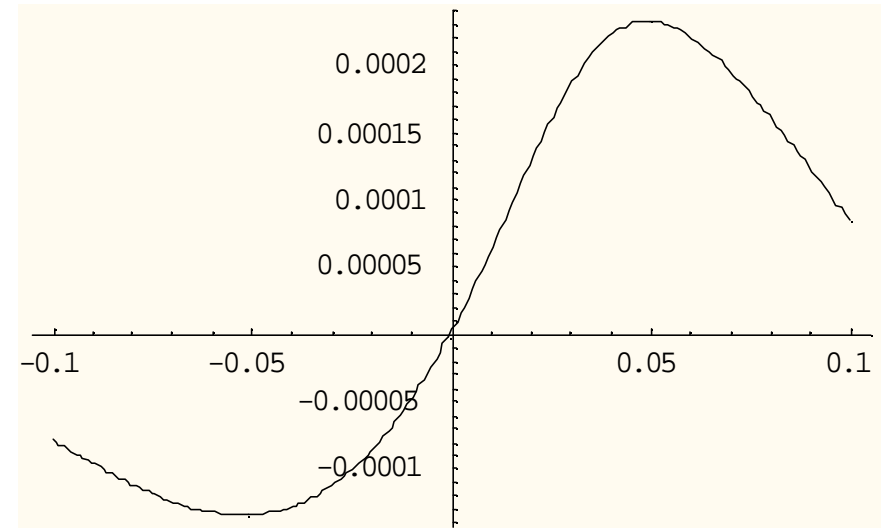
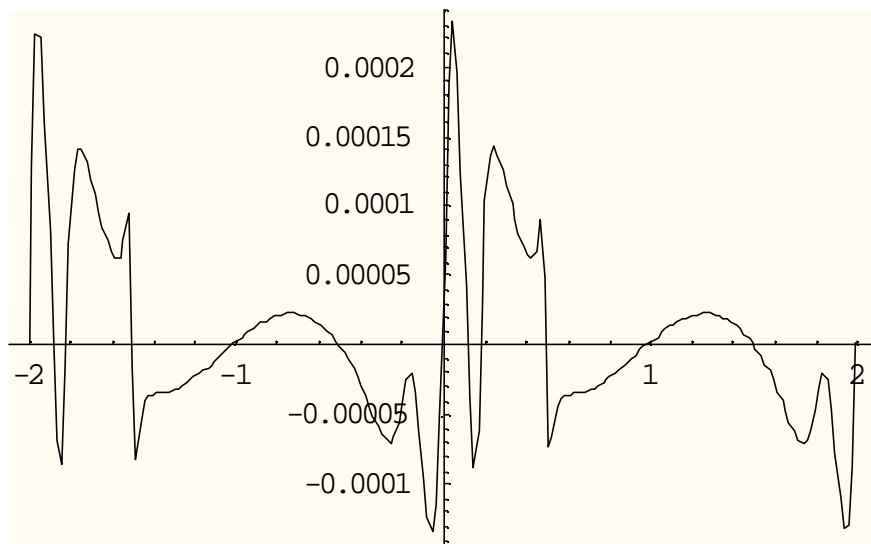
I+ (PRC), SP, f_2-f_1





Control signals from Twiddle: I-

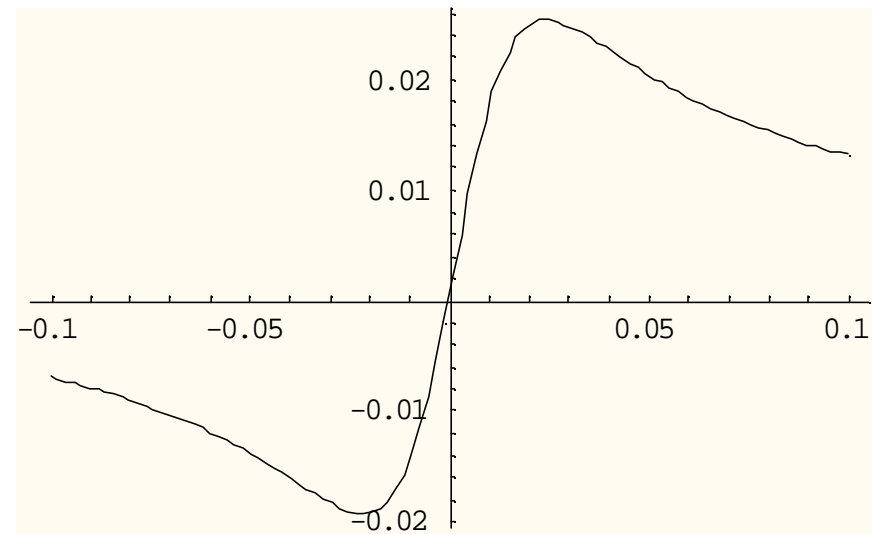
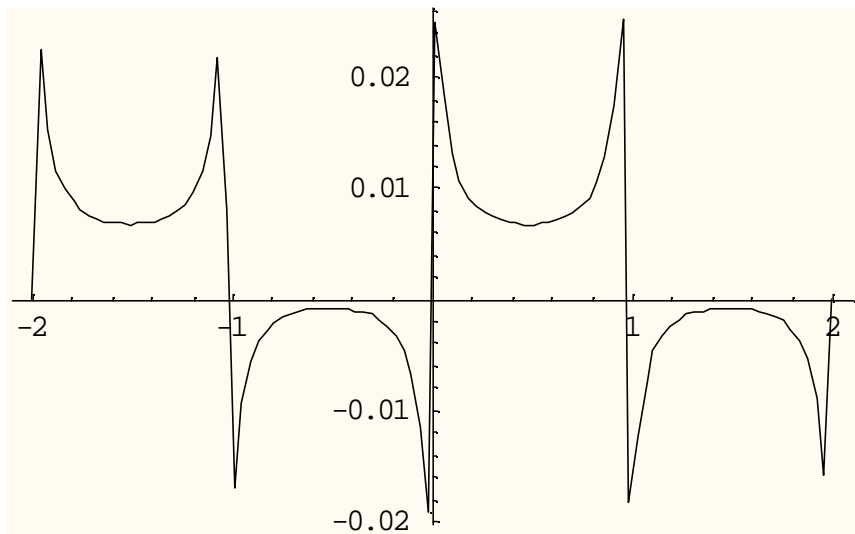
1- (Michelson), AP, $f_2 \otimes f_1$
(double demodulation)





Control signals from Twiddle: I_s

I_s (SRC), PO, f_2-f_1





LSC and Lock acquisition

- Several error signals have more than one zero-crossing of the control signal; that DOF can achieve lock at the wrong point.
- IFO experience tells us that even when this is so, the IFO can eventually achieve lock in the right place
- locking at the wrong point in one DOF is often unstable when other DOF's acquire lock.
- It's time for a full lock acquisition study, with E2E.
- This takes some time. Meanwhile, there's some confidence that this is a workable scheme.



Mirror radii of curvature, beam spot sizes

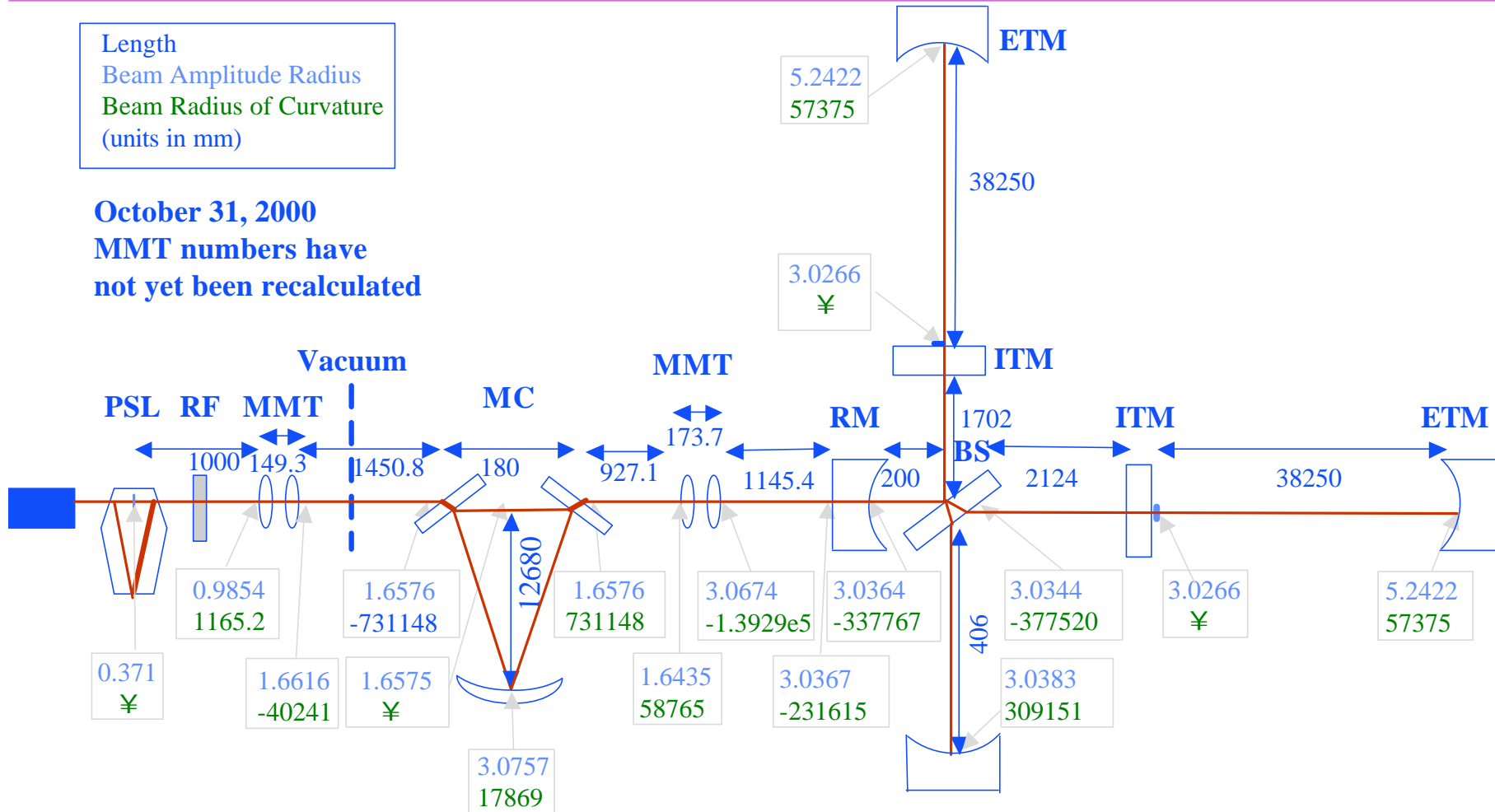
- Cavity lengths are fixed by above LSC analysis.
- These are optical path lengths. Since optical phase advances more slowly through glass, physical path length is larger, by
$$D(n-1)/n = 5(0.45/1.45) = 1.55 \text{ cm (ITMS)}$$
$$D\sqrt{2} (n-1)/ = 2.8*1.414*0.45/1.45 = 1.23 \text{ cm (BS)}$$
- Arm cavities (equal length, 38.25 m) have flat ITMs.
- Choose $g=1/3$ (stable cavities, minimum beam spots).
- This fixes $R_{\text{ETM}} = 57 \text{ m}$, $w_{\text{ITM}} = 3.03 \text{ mm}$, $w_{\text{ETM}} = 5.24 \text{ mm}$
(w = beam amplitude gaussian sigma). $d^{1\text{ppm}}_{\text{ETM}} = 27.6 \text{ mm}$.
- Do we coat only to $d^{1\text{ppm}}_{\text{ETM}}$, or all the way to the edge?
- Propagate beam through ITM substrate, average $D(\text{ITM-BS})$, BS substrate, to RM and SM. This fixes R_{RM} , w_{RM} , R_{SM} , w_{SM}
- Mode cleaner length is a bit different than LIGO I.
Recalculate R_{MC3} , spot sizes, all other parameters.
- MMTs (fixed lenses) will be recalculated once Mike Smith determines distances between PSL PMC – MMT1 – MC – MMT2 – RM.



40 M Optics Parameters (flat ITMs)

Length
 Beam Amplitude Radius
 Beam Radius of Curvature
 (units in mm)

October 31, 2000
 MMT numbers have
 not yet been recalculated





Mode cleaner parameters

Table 17: Optical parameters for the 4-K mode cleaners

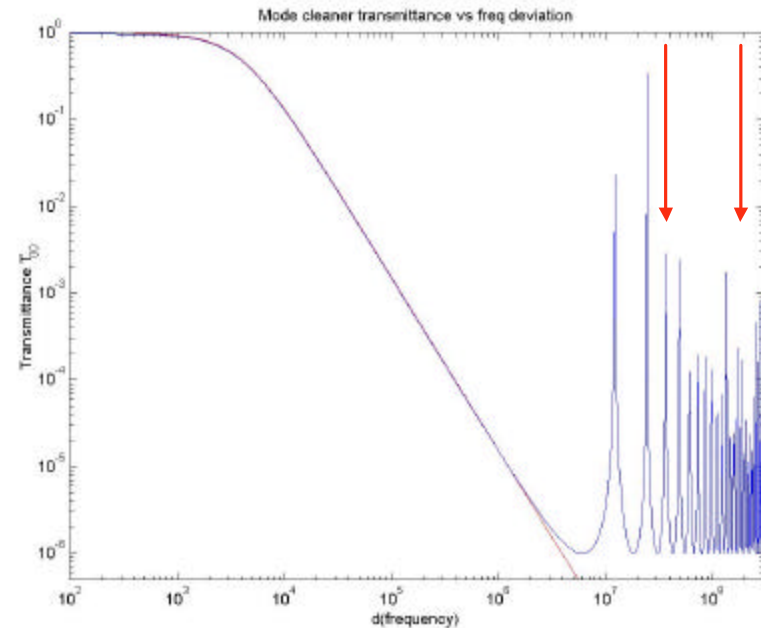
<i>Item</i>	<i>Unit</i>	4K IFO		40 Meter
Plane mirror transmittance		0.002	+/- 100ppm	0.002
Plane mirror reflectance		0.998	+/- 100ppm	0.998
Curved mirror transmittance		1E-05	+0, -10ppm	1e-5
Rear surface AR coating		>99.8%	+0.2%,-0	> 99.8%
Mirror absorbance/scattering	each	<0.00010		<0.00010
Finesse		1550		1550
Free spectral range	MHz	12.246		11.822
Cavity full width/half max	kHz	7.83		7.63
Cavity full width/half max	nm	0.342		0.343
Cavity optical half-length	mm	12240		12680
Curved mirror radius of curvature	mm	17250	+250,-350	17869
$g = 1 - L/R$		0.290		0.2904
waist size	mm	1.629		1.657
Raleigh range	m	7.83		8.111
Beam divergence	μ rad	208		210
1 ppm intensity, curved mirror	mm	15.9		16.2
100 ppm intensity, curved mirror	mm	13.0		13.2

▪ This table taken from LIGO-T980009-01, LIGO-T970144-00



Mode cleaner performance

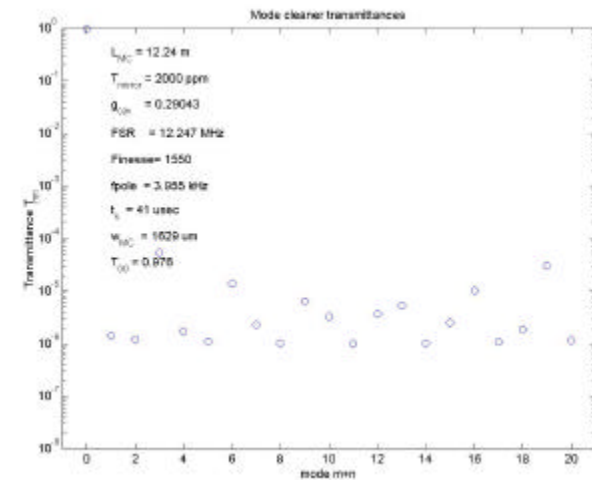
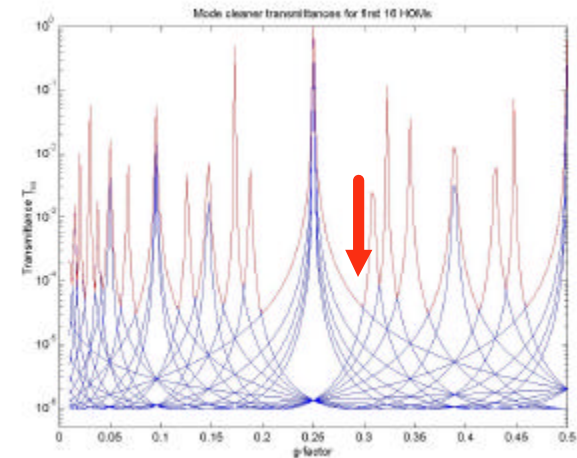
- Rejection of frequency noise
- Place all IFO-sensing sidebands at multiples of FSR of the MC (12.2 MHz)
- $f_{MC} = 12$ MHz
- $f_{SB1} = 3 f_{MC} = 36$ MHz
- $f_{SB2} = 5 f_{MC} = 180$ MHz





Rejection of HOMs

- Large Guoy phase difference in MC cavity ($g \ll 1$) suppresses resonance of HOM's
- We reproduce all the numbers from LIGO MC design

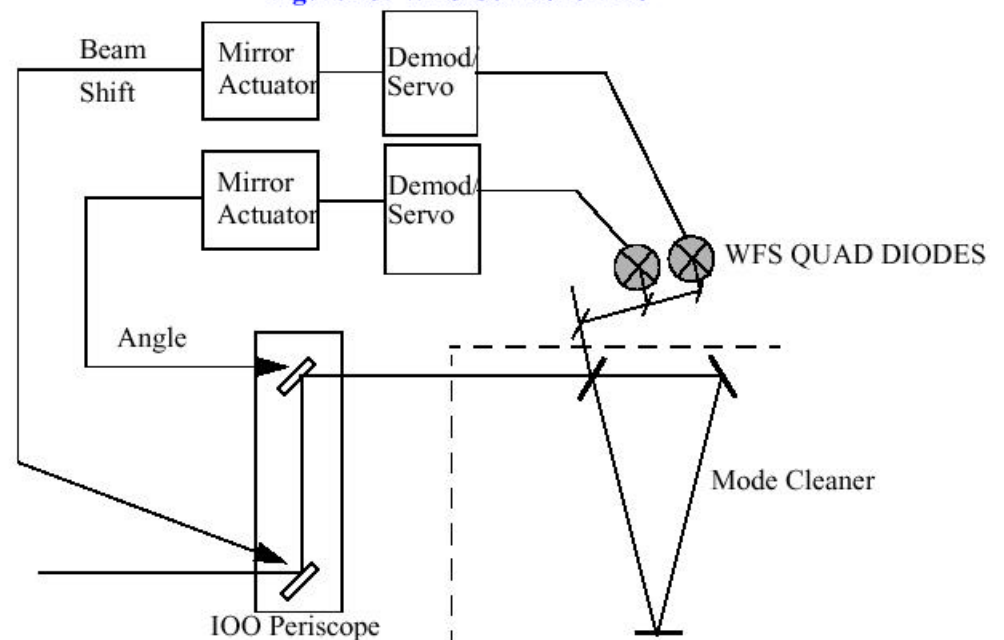


MC alignment control

- Two WFSs control launch position and angle (pitch & yaw)

LIGO-T970144-00-D

Figure 15: WFS Control of MC





Conclusions

- Unless independent detailed checks of these calculations find a problem, I think we have an optical configuration (T/R's, L's, ROC's, length sensing matrix) which is workable for both LIGO II and 40m.
- Need to specify tolerance for all these parameters
- Can also optimize various parameters for GW detection (pickoff reflectivity, modulation depth, etc), but not really necessary here!
- Must verify that lock can be acquired (E2E modeling).
- I think we can proceed with polish & coat mirrors, design telescopes, RF mod/demod, etc.
- Everything depends on how LIGO II design evolves.