OPTICAL DESIGN CONSIDERATIONS FOR THE 40M UPGRADE

PRELIMINARY!

- goals of 40 m upgrade
- arm optical parameters
- noise
- recycling cavity parameters
- radii of curvature, spot sizes
- mode cleaner
- seismic noise
- imperfect optics
- core optics size
- upgrade tasks
- SEM mirror control - later!

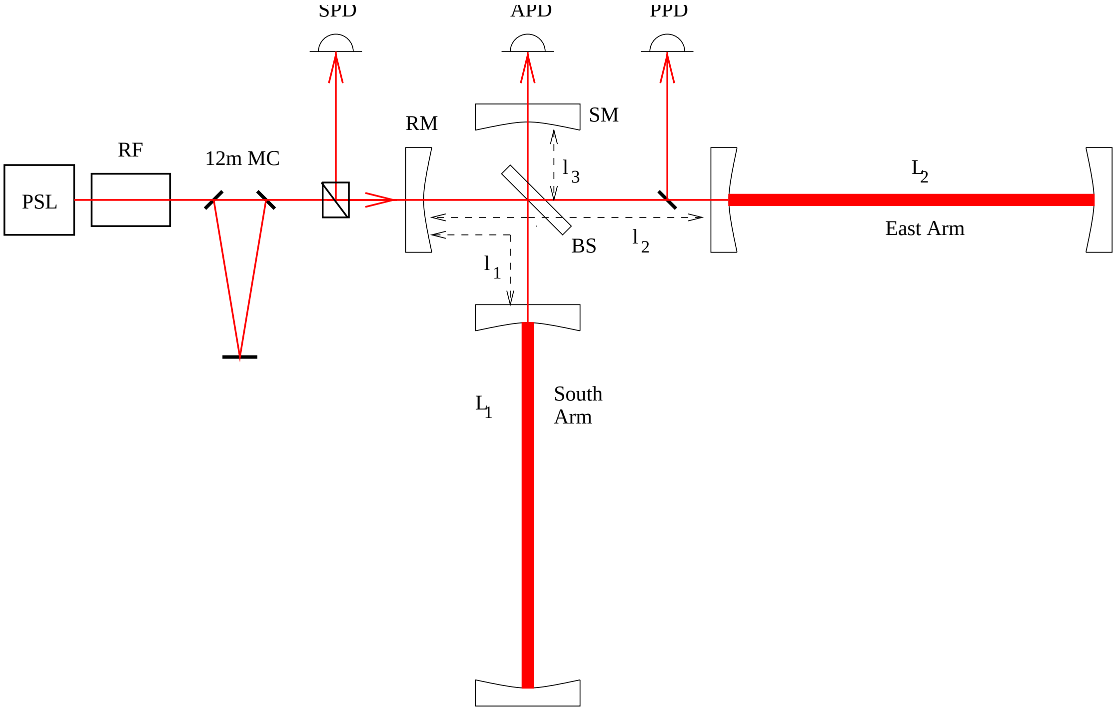
LIGO-G990133-00-R, /home/ajw/Docs/G990133-00.pdf

GOALS OF 40 M UPGRADE

- The primary goal of the 40 m upgrade is to demonstrate a scheme for using resonant sideband extraction (RSE), in a broadband configuration, to provide the low power recycling cavity (PRC) power gain characteristic of a narrow-band LIGO IFO while retaining the shot-noise performance of a broader-band LIGO IFO.
- in the coming 1-2 years, the lab will be upgraded to LIGO-like standards.
- At the same time, a control scheme will be developed for the signal mirror, for broad-band RSE operation.
- The plan is to be ready to prototype an RSE scheme by 2002.
- The 40m laboratory will continue to be used for testing and staging of other LIGO detector innovations; physicist training; and education and outreach.
- More information:
  http://www.ligo.caltech.edu/~ajw/40m_talk.ps

ARM OPTICAL PARAMETERS

The LIGO-like IFO configuration is a power-recycled Michelson IFO with Fabry-Perot arms (PRM-FP), with no "signal" mirror (SM) in the dark port.

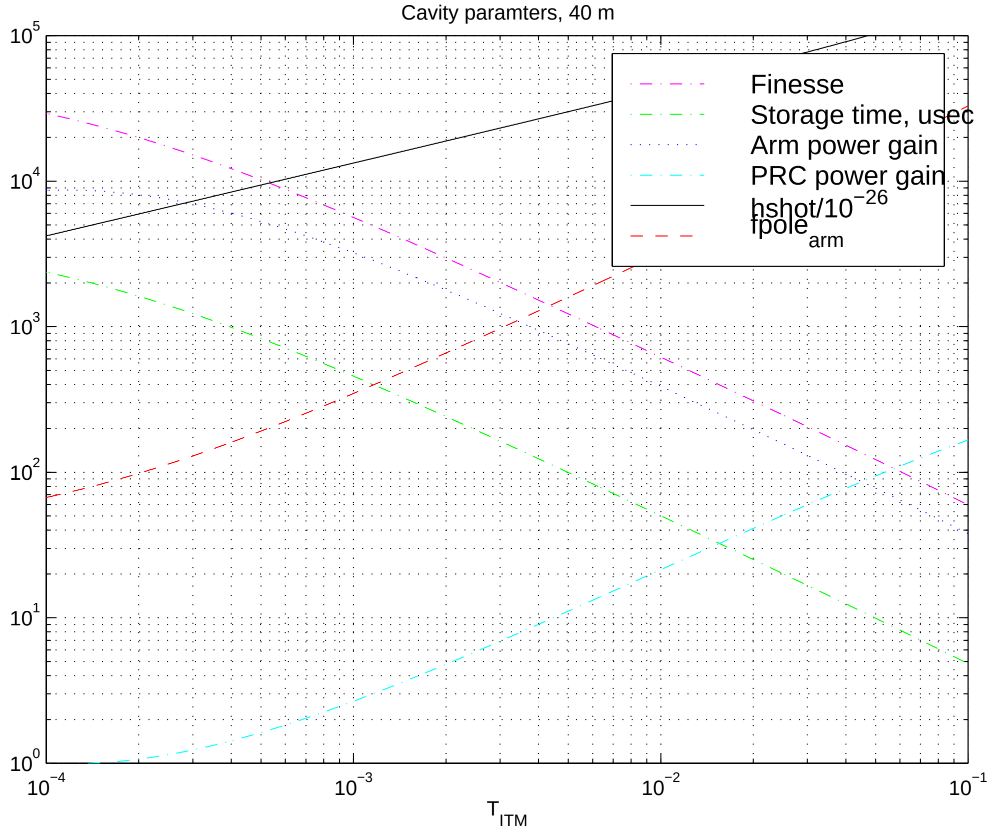


GROUND-RULES:

- ITM, ETM, and RM mirrors have losses of 50 ppm; the BS mirror has losses of 100 ppm (more precisely, the losses in the PRC due to beam passing through the BS and ITM substrates, and the PRC pickoff, should all sum to 100 ppm).
- The ETM has a tranmission of 15 ppm for monitoring.
- We want the arm cavities to be over-coupled.
- We want the PRC to be overcoupled, reflecting 1% of the incident laser light (for control and stability purposes).
- All the rest of the light is lost in the IFO: out the asymmetric port, out the ETM for monitoring, out the pickoff port, or lost due to scattering or absorbtion.
- We assume 6 watts of laser light

ARM OPTICAL PARAMETERS, 2

- With these ground-rules, the design of such an IFO is driven by one parameter only, which we can choose to be any one of:



- Note that LIGO I operates with: $T_{ITM} = 0.03$, Finesse $= 204$, $\tau_s = 1734$ usec, $f_{pole} = 91$ Hz, $G_{arm} = 130$, $G_{prc} = 60$, $h_{shot}(0) = 7.4\text{e-}24$.

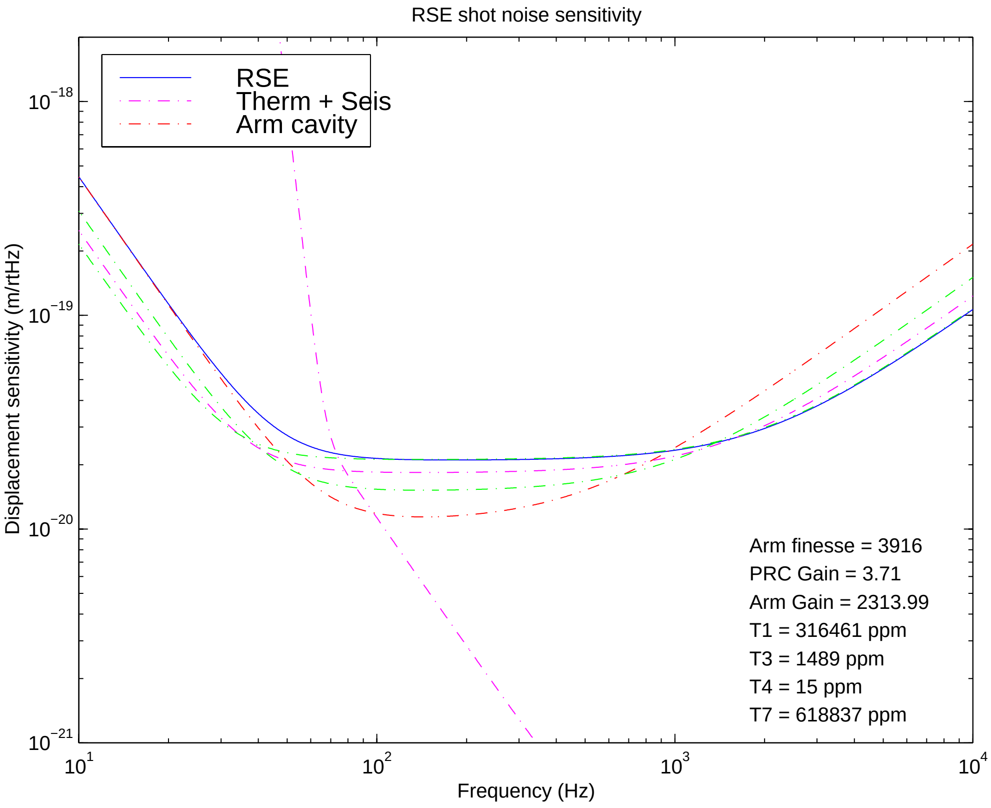
- (All shot-noise strain sensitivity numbers quoted here are uncertain as absolute numbers, but their ratios are meaningful).

CONTRASTING PARAMETERS

- To compare and contrast configurations, choose f_{pole} as our driving parameter.
- Most LIGO-like: choose $f_{pole} = 91$ Hz.
- This requires $T_{ITM} \simeq 100$ ppm, $\approx L_{arms}$
- Difficult to control such low transmission and high finesse with realistic optics.
- Also, $G_{prc} \approx 1$ in that case;
  decidedly non-ligo-like, and defeats our purpose (demonstrate reduction in G_{prc} using RSE).
- So back off, consider a much higher f_{pole}.
  Let's consider $f_{pole} = 2000$ Hz, which leads to:
  $T_{ITM} = 6298$ ppm, $T_{RM} = 0.0869$, finesse $= 976$, $\tau_s =$ 79 usec, $G_{arm} = 611$, $G_{prc} = 13.8$, $h_{shot}(0) =$ 3.4e-22.
- Such a high G_{prc}, with a high-powered LIGO-II laser, will lead to significant PRC losses, and thermal lensing effects. We need to reduce it. $\Longrightarrow$ RSE

CONTRASTING PARAMETERS 2

- We can reduce G_{prc} by reducing f_{pole} to, say, 500 Hz. This leads to: $T_{ITM} = 1489$ ppm, $T_{RM} = 0.3165$, finesse $= 3915$, $\tau_s = 318$ usec, $G_{arm} = 2314$, $G_{prc} = 3.7$, $h_{shot}(0) = 1.6\text{e-}22$.
- Now G_{prc} has been reduced by a factor of 4, but the bandwidth of the IFO at high frequencies has shrunk due to the smaller f_{pole}.
- Now we add the RSE signal mirror (SM) in the asymmetric port.
- The carrier is absent at the asymmetric port, so it doesn't see the SM. But the GW signal exits through the port, and it does see the SM.
- The compound mirror composed of the ITM/SM is in resonance for the carrier and the GW signal, producing a larger transmittance, and thus, a larger f_{pole}.
- We can choose a T_{SM} which reproduces $f_{pole} = 2000$ and $h_{shot}(0) = 3.4\text{e-}22$ while keeping finesse, τ_s, G_{arm}, G_{prc} at their $f_{pole} = 500$ values ($T_{SM} = 0.619$ will do it).



- The value of $h_{shot}(0)$ is, unfortunately, characteristic of the broad-band ($f_{pole} = 2000$ Hz) configuration; but we assume that, below f_{pole}, we are dominated by other noise sources, anyway, so we're not losing any sensitivity there.

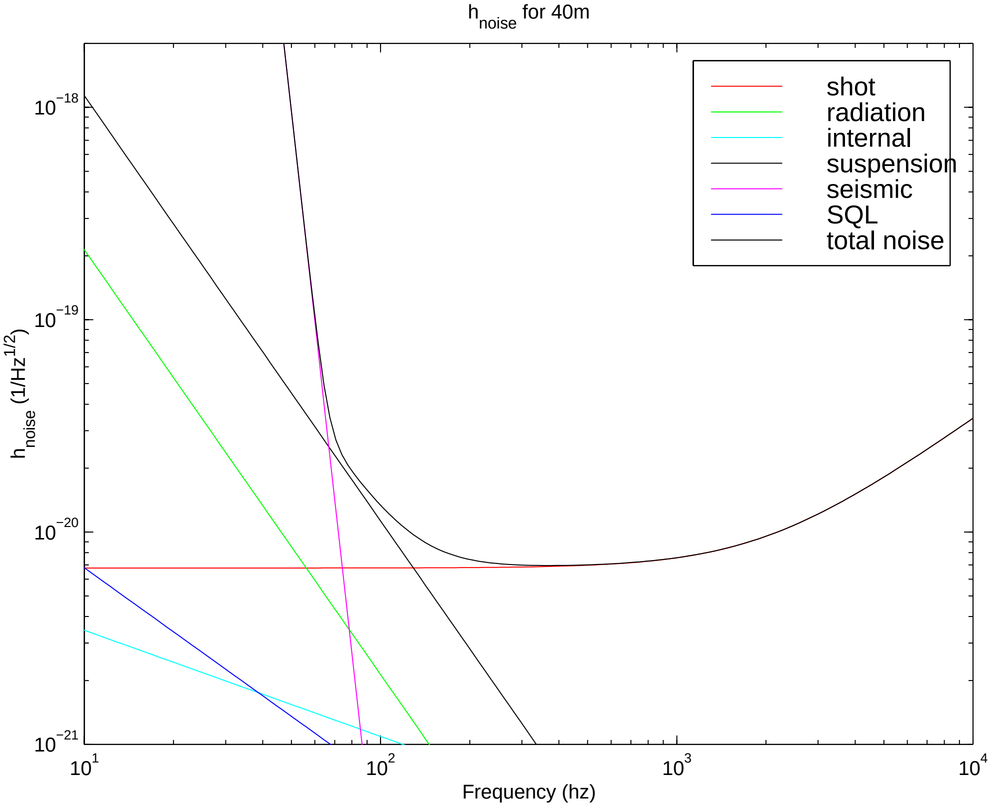
- That's not exactly true, for the 40m with the parameters we've chosen; it may be that we'll be shot-noise limited all the way down to 150 Hz. But that does not change the significance of the experiment. In fact, it will make it easier for us to demonstrate the expected change in the shot-noise limited response as one makes use of RSE.

GOAL OF THE EXPERIMENT

- First, establish shot-noise limited response of a LIGO-like IFO (without RSE) with, say, $f_{pole} = 2000$ Hz.
- Then, reconfigure for $f_{pole} = 500$ Hz, with a factor 4 smaller G_{prc}, but loss of sensitivity at high f.
- Add RSE to bring high-f sensitivity back to $f_{pole} = 2000$ Hz, level, but with G_{prc} at $f_{pole} = 500$ Hz level.

NOISE

Noise curves for most of the expected noise sources, with a LIGO-like config with $f_{pole} = 2000$ Hz.



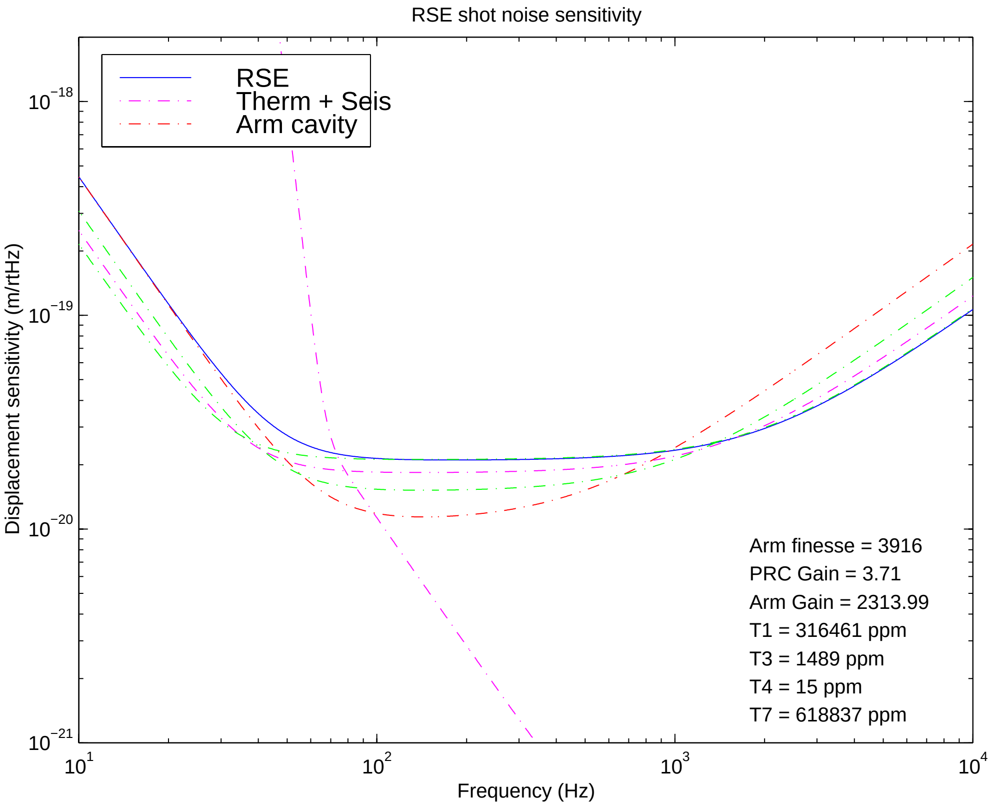
The noise is dominated by:

- the seismic “wall” below ~ 75 Hz,
- the shot-noise limit from 300 Hz through the knee at 2000 Hz and on up
- the suspension thermal noise in the region from 75 Hz to 300 Hz.

The exact location of these curves depends upon accurate modelling, and I claim no such thing at this time.

NOISE MODELLING

- Suspension noise: assume test masses of 4" diameter (ok, 10 cm), 8.9 cm thickness; a suspension phi = 2e-7 * f (viscous damping), $f_{susp} = 0.744$ Hz.
- Can increase the test masses to reduce this noise. See the discussion of pros and cons, below.
- See also discussions of the seismic noise, internal thermal noise, and radiation pressure, below.
- We see that we are shot-noise limited above 300 Hz; we choose f_{pole} values of 500 Hz and 2000 Hz to stay clear of all other noise sources.
- In the figure below, we show "optical readout noise" (photon shot noise and radiation pressure noise) for LIGO-like configurations with $f_{pole} = 500, 1000, 1500,$ and 2000 Hz, along with the RSE curve designed to bring f_{pole} from 500 → 2000 Hz, and the noise curve for all other sources.



- RSE curve matches the $f_{pole} = 2000$ Hz curve above ∼75 Hz, bue follows the $f_{pole} = 500$ Hz curve in the radiation pressure noise nominated region below that. This is because the radiation pressure noise is due to the carrier power in the arms, not the signal power out the dark port.
- Radiation pressure noise will not be a dominant source of noise for the 40 m with 4” optics, or for LIGO with 10” optics.

RECYCLING CAVITY PARAMETERS

- PRC dimensions: prior to the start of the recycling experiment, Logan and Rakhmanov carefully evaluated the PRC lengths (LIGO-T960013). Including the paths through the optical substrates, they found:
  L_{inline} = 0.250+2.249+0.066 = 2.565 m
  L_{perp} = 0.250+1.721+0.052 = 2.023 m
  L_{prc} = (L_{in} + L_{perp})/2 = 2.2294 m
  dL = (L_{in} - L_{perp}) = 0.542 m = Schnupp asymmetry
  where the first number is distance from RM reflective face to BS reflective face, the second is from BS reflective face to ITM reflective face, and the third is the correction due to paths through fused silica.
  During upgrade installation, these numbers will, of course, all be remeasured carefully.

- Modulation frequency: the lowest modulation frequency for which the carrier (at arm resonance) and sidebands are in resonance in the PRC is:
  f_{mod} = c/4L + n * c/2L = c/4L = 32.7 MHz

- Placed on beam AFTER the mode cleaner.

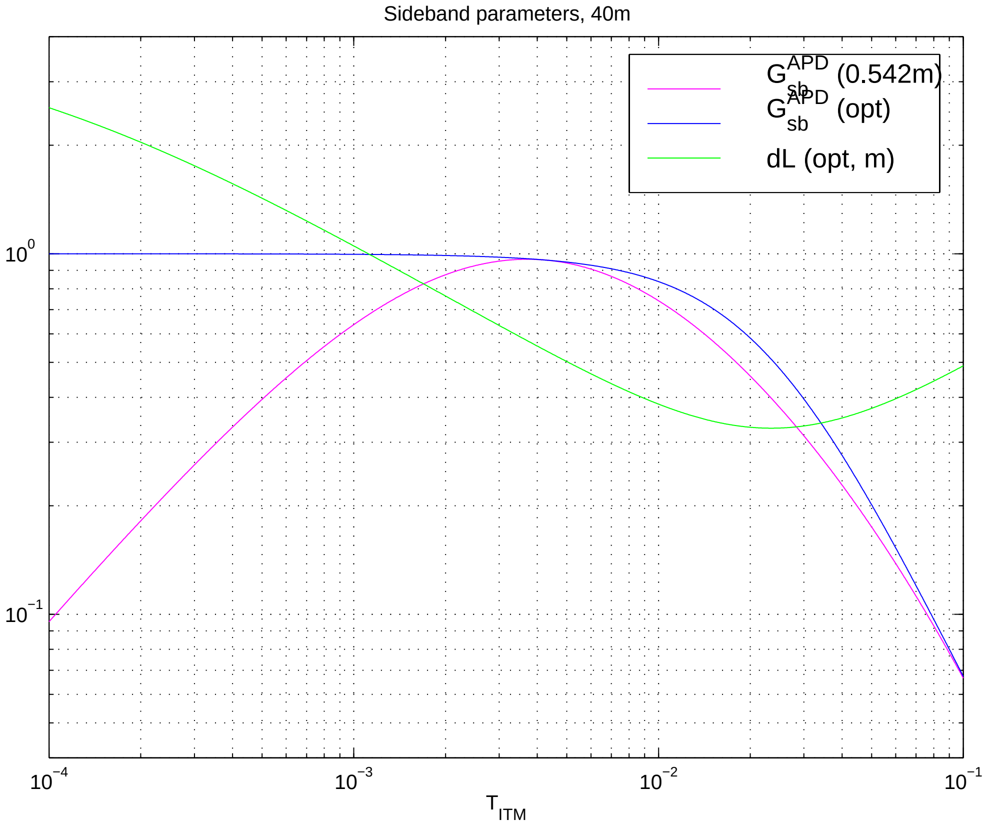
RECYCLING CAVITY PARAMETERS

- Sideband power gain out the dark port (APD):

$$G_{sb}^{APD} = \frac{t_{RM}^2 \sin^2 \alpha}{(1 - r_{RM} r_{ITM} (1 - L_{BS}) \cos \alpha)^2}$$

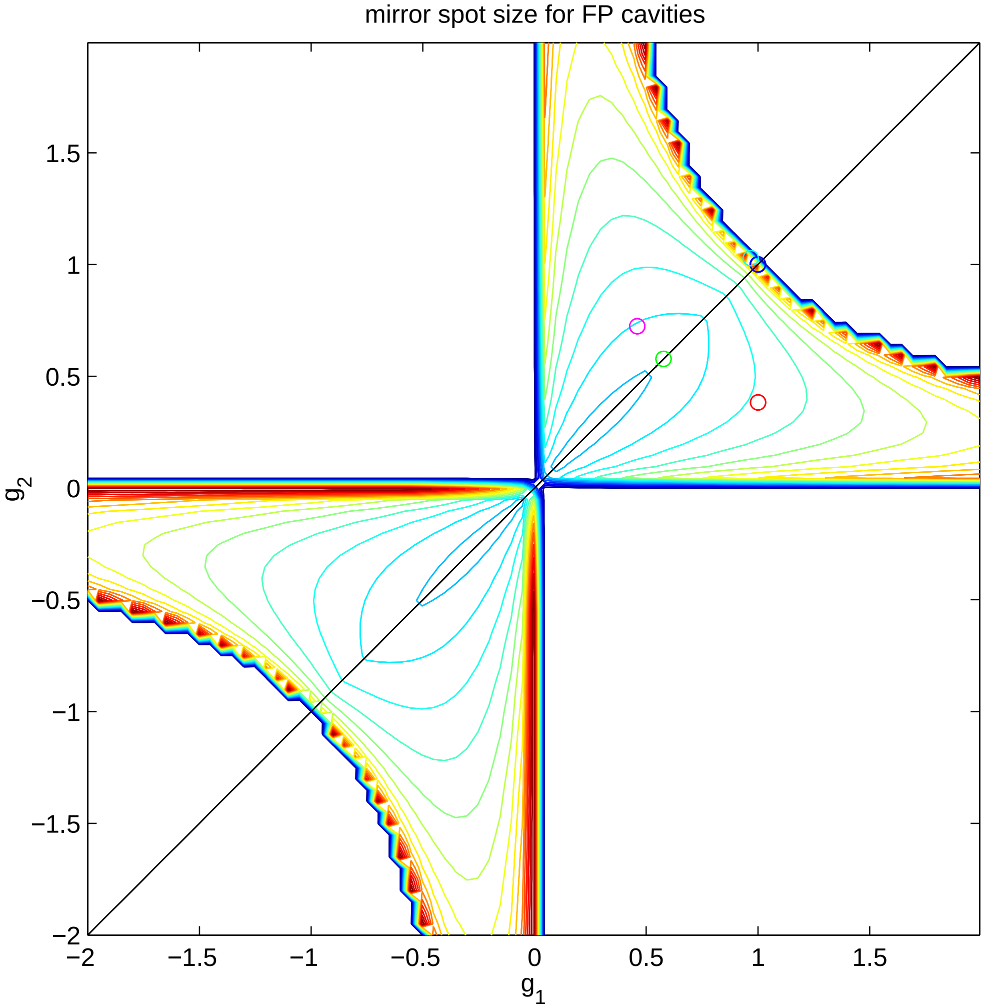
where $\alpha = 2\pi f_{mod} dL/c$

f_{pole} (Hz)	500	2000
G_{sb}^{APD} (0.542 m)	0.782	0.895
opt. asym (m)	0.878	0.455
G_{sb}^{APD} (opt. asym)	0.993	0.923



RADII OF CURVATURE, SPOT SIZES

- FP cavity design is driven by g-factor $g = g_1 g_2$
  $g_1 = (1 - R_{ITM}/L_{arm})$, $g_2 = (1 - R_{ETM}/L_{arm})$
- Spot size at the end mirrors, for FP cavity with L = 1 m, versus g_1 and g_2:



- structure near the g=1 hyperbolas are spurious.
- White space means unstable FP resonator cavities. 45° line is for symmetric cavities.

FP CAVITY 2

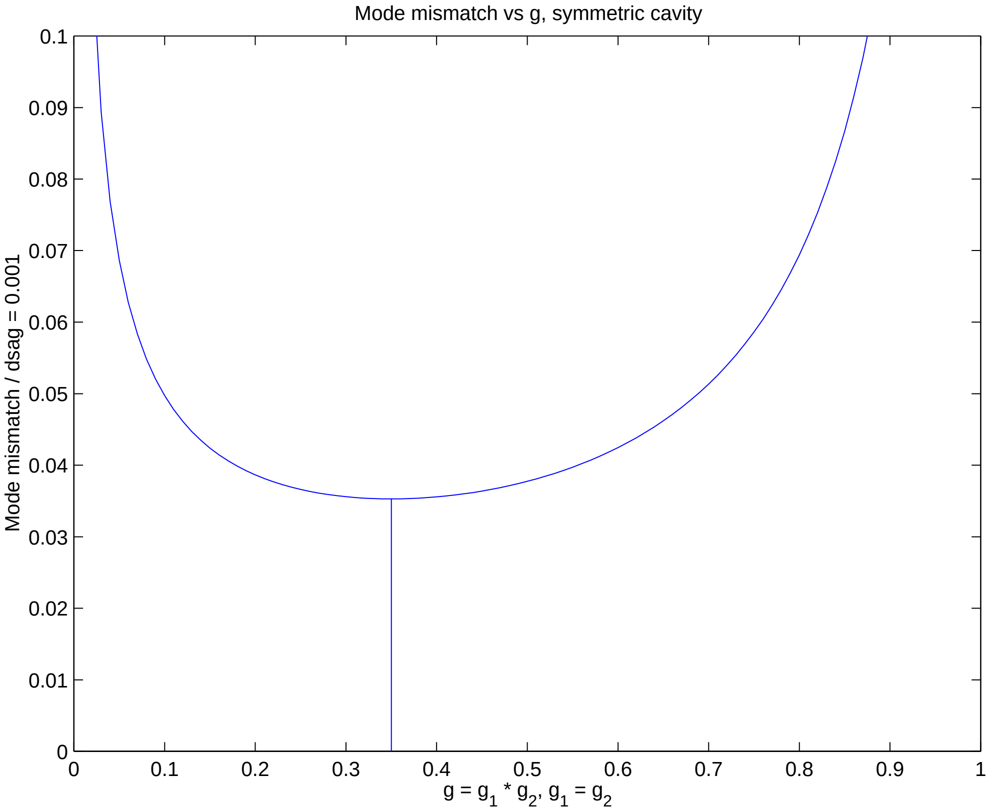
- Circles correspond to present 40 m configuration (red, (1,0.38)), 40 m upgrade config (green, (.577,.577)), LIGO arms config (magenta, (0.46,0.72)), and LIGO/40m PRC config (black, (1,1)).
- Stability requires $g < 1$; expect better performance for symmetric cavities ($g_1 = g_2$), small $g \approx 1/3$).

MODE MATCHING

- Modematching study: minimize mode mismatch due to imperfect radii of curvature of ITM, ETM mirrors:

$$MM = \left(\frac{\delta\omega_0}{\omega_0}\right)^2 + \left(\frac{\delta z_0}{2z_0}\right)^2$$

- ω_0, z_0 are beam spot size and Rayleigh length for nominal radii of curvature,
  $\delta\omega_0$, δz_0 due to sagitta error (0.001 m^{-1})



ARM PARAMETERS

- We choose a stable (g = 1/3), symmetric arm cavity. The beam waist is in the middle of the 38.25 m arms.

Location	R_{curv} (m)	spot (mm)
waist		3.54
ETM	90.5	3.98
ITM	90.5	3.98
BS	∞	4.16
RM	60.32	4.18

- LIGO arms have g = 1/3, but is a bit offset from symmetric, with g_1 = (1-4000/14500), g_2 = (1-4000/7407), to keep the spot size at the ETM such that less than 1ppm of the light falls out of the 24cm aperture (5.257 w_{ETM} < aperture). This is NOT a problem at the 40 m with 4” optics!
- Like LIGO and present 40m, the PRC is nearly unstable, with $g \approx 1$. I don’t know how to avoid this, or what its consequences are.

MODE CLEANER

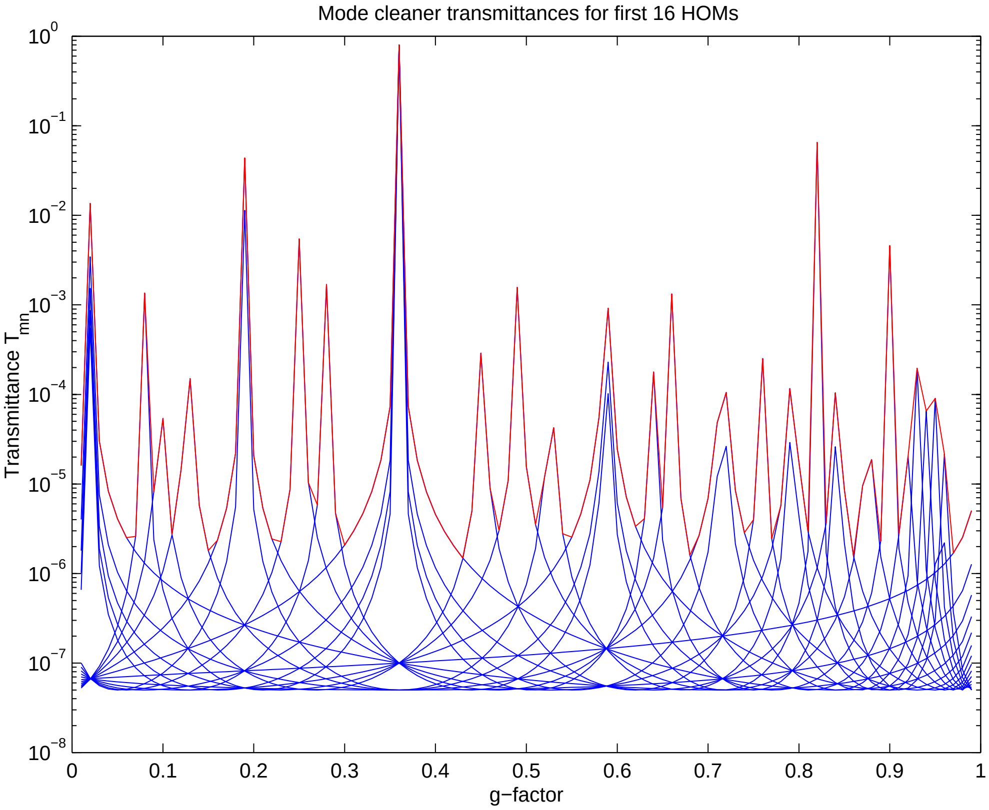
- Requirements of the 40 m upgrade with respect to initial laser pointing accuracy, jitter, higher order mode rejection, etc, have *not* been quantified!
- But, a new PSL with pre-mode-cleaner (PMC), and an improved fixed-spacer 1 meter mode cleaner, will certainly improve things!
- I hope we can use the existing 1 meter fused silica spacer currently in use at the 40m, as well as the existing spring mounts.

  I don't know anything about this, at present!
- To provide the most suppression at high frequencies (eg, at $f_{RF} = 32.7$ MHz), keep cavity pole f_{pole} as small as possible, ie, mirror T as small as possible.
- But not too small: to be roughly insensitive to uncertainties in losses, keep T $\gg$ Losses.

  Also, very small T means that even the desired TEM_{00} mode is lost, with transmissivity $\ll 1$.
- Want optimal coupling for TEM_{00} mode; so, approximately, $T_1 = T_2 + 2$ Losses.

MODE CLEANER 2

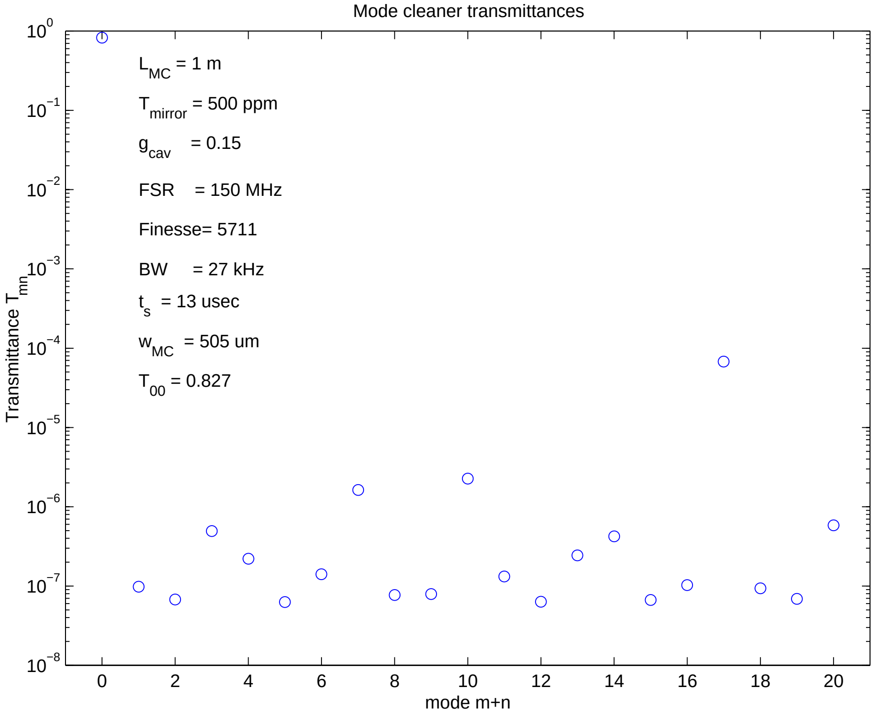
- Choose $T_2 = 400$ ppm, $T_1 = 500$ ppm; This gives $T_{00} = 0.8$, $f_{pole} = 12$ kHz, suppression of 2e-7 at 32.7 MHz.
- Now optimize the (symmetric) cavity g-factor to stay away from any HOM resonances.
- Transmission for 16 lowest HOMs:



- Look for a broad minimum.
- We choose $g_{cav} = 0.30$.

MODE CLEANER 3

- Here is an optical design for a stable, symmetric cavity that provides good rejection of higher order modes.



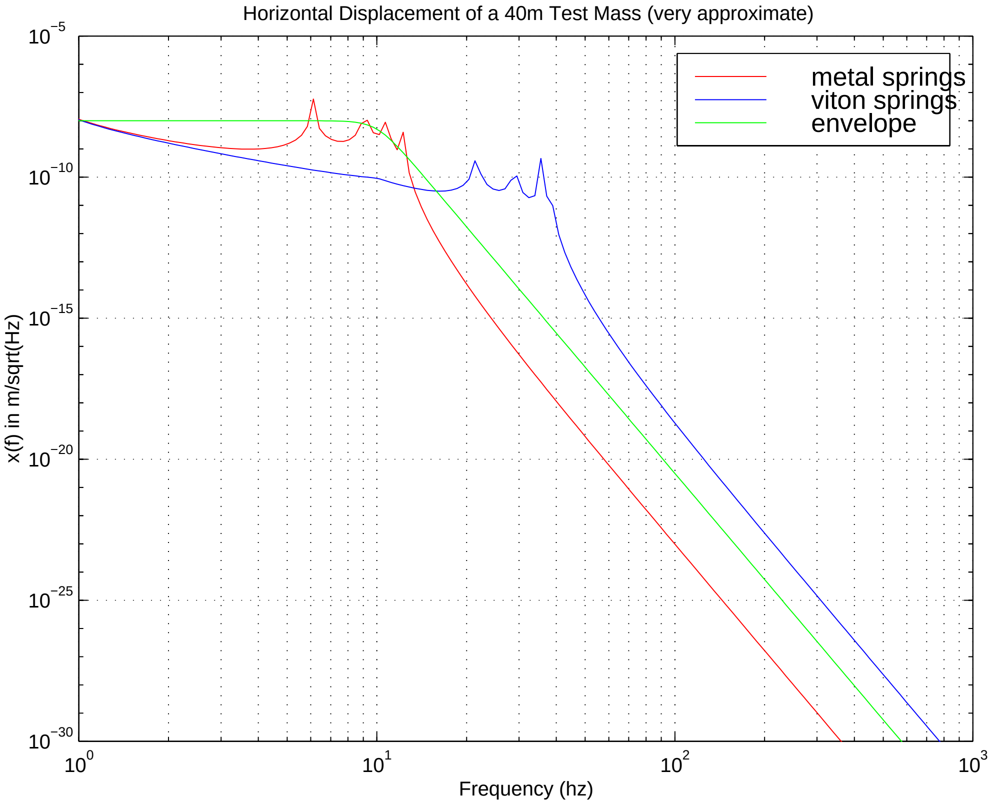
- Want to grade the transmission of the mirrors to be higher at larger radii, to increase suppression of HOMs which have $<r> \simeq waist\sqrt{n+m+1}$.
- I do not know how to set, or address, the specs on pointing accuracy, jitter, etc.
- I have to learn how to design telescopes for matching PSL ↔ MC and MC ↔ IFO.
- Output mode cleaner?

SEISMIC NOISE

- The five existing core-optics chambers (BS, SV, SE, EV, EE) have 4-stage, 3-leg/stage seismic stacks, fitted with viton springs.
- We plan to replace the viton springs with LIGO metal springs and flurel seats.
- We hope that this will reduce the amount of viton/flurel in the vacuum system (maybe not?). In any case, we expect that after the rebuild and bakeout, the seismic stacks, and thus the 40m vacuum, will be significantly cleaner. Our main concern is contamination of the mirror surfaces, NOT water vapor or other residual gas.
- As a side benefit, the seismic isolation will be much better.

SEISMIC NOISE

Here is the expected contribution to the horizontal displacement, x_{rms}(f), from seismic motion.



The smooth curve is an envelope function that is (more-or-less) greater than the metal spring curve, everywhere, and is thus “conservative”:

$$x_{rms} = \frac{1 \times 10^{-8} \quad \text{meters}}{1 + (f/10)^{12.5}}$$

$$h_{strain} = (2/L_{arm})x_{rms}(f)$$

SESMIC NOISE MODELLING DETAILS

- I crudely estimate the masses of the stack: top optical table and plate, 275 kg; leg elements, 75 kg each (to be measured carefully when we disassemble!).
- The damped metal springs can support a maximum load of 100 lbs or 45 kg. We put in as many springs as we need to hold the weight, and no more.
  This translates to the following numbers of springs for each stage of the 3 legs, from top to bottom (so multiply by 3 to get the total per stage): 2,4,6,7.
  Total: 57 springs per stack.
- The spring constant for the damped metal springs at 100 Hz is k = 379 lbs/in, or 67.7 kg/cm.
- The resonant frequency for stage i, in Hz, is $f_i = \sqrt{N_{springs} N_{legs} kg/M}/(2\pi)$ where g = acceleration due to gravity. We get, for the stages from top to bottom: 6.1, 9.1, 10.8, 12.3 Hz.
  (*cf.* Viton springs: 21.6, 29.0, 35.5, 38.3 Hz.
- Each stage has a simple pole transfer function,
  $T_i = f_i^2/(f_i^2 - f^2 + i f_i^2/Q_i)$;
  where we take Q = 300 (a total guess).

SESMIC NOISE MODELLING DETAILS 2

- The stack transfer function is the product: $T_1 T_2 T_3 T_4$.
- Then we have the pendulum transfer function, a simple pole with f = 0.74 Hz and Q = 3.
- Then we have the seismic spectrum itself. I don't know the spectrum at the 40m site (do you?). I use the "Hanford site noisy, w/ microseismic peak", and MUTLIPLY BY 10.
- The product of these spectra give the curves shown above.

$$x_{mirr}(f) = x_{seis}(f) T_1(f) T_2(f) T_3(f) T_4(f) T_{pend}(f)$$

IMPERFECT OPTICS

- The desire to operate at arm cavity pole frequencies far below the arm FSR drives us to small ITM transmissivities, of same order as losses (50 ppm).
- This suggests that small optical imperfections in the ITMs can lead to big changes in the IFO operation.
- FFT (Bochner, LIGO-P980004) is designed to address this question with a full simulation of the (DC) E-fields in the IFO, with realistically-deformed mirror maps.
- At the moment, I don't know how to make those mirror maps, so I've only run FFT with perfect optics.

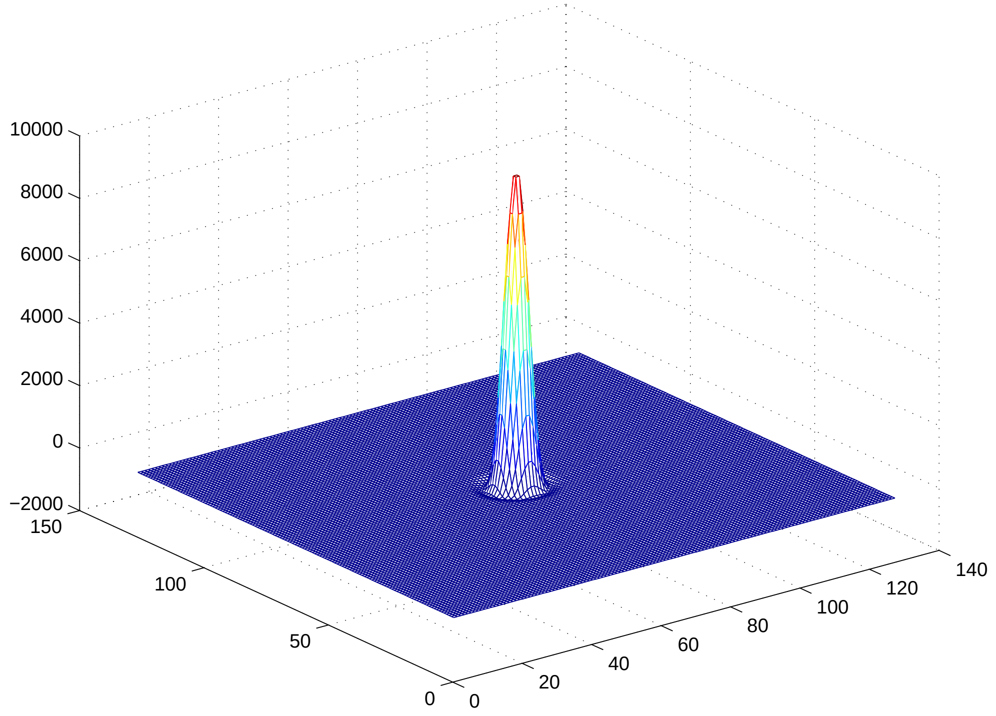
OUTPUT OF FFT, 40M

RMS deformation	0	$\lambda/1800$	$\lambda/1200$	$\lambda/800$	$\lambda/400$
RMS deformation (nm)	0	0.59	0.89	1.33	2.66
R_{RM} (%)	68.4				
Opt. Asymm (cm)	45.5				
Mod Depth Gamma	0.36				
G_{prc}, Carr, TEM00	8.9				
G_{arm}, Carr, TEM00	2600				
G_{APD}, Carr, TEM00	5e-3				
G_{APD}, Carr, Total	6e-3				
1-C	1.6e-3				
G_{prc}, SB, TEM00	7.2				
G_{APD}, SB, TEM00	0.95				
G_{APD}, SB, Total	0.95				
R_{ref}, Total	0.015				
f_{pole} (Hz)	2022				
$h_{SN}(0)$ (1e-22)	1.8				

CORE OPTICS SIZE

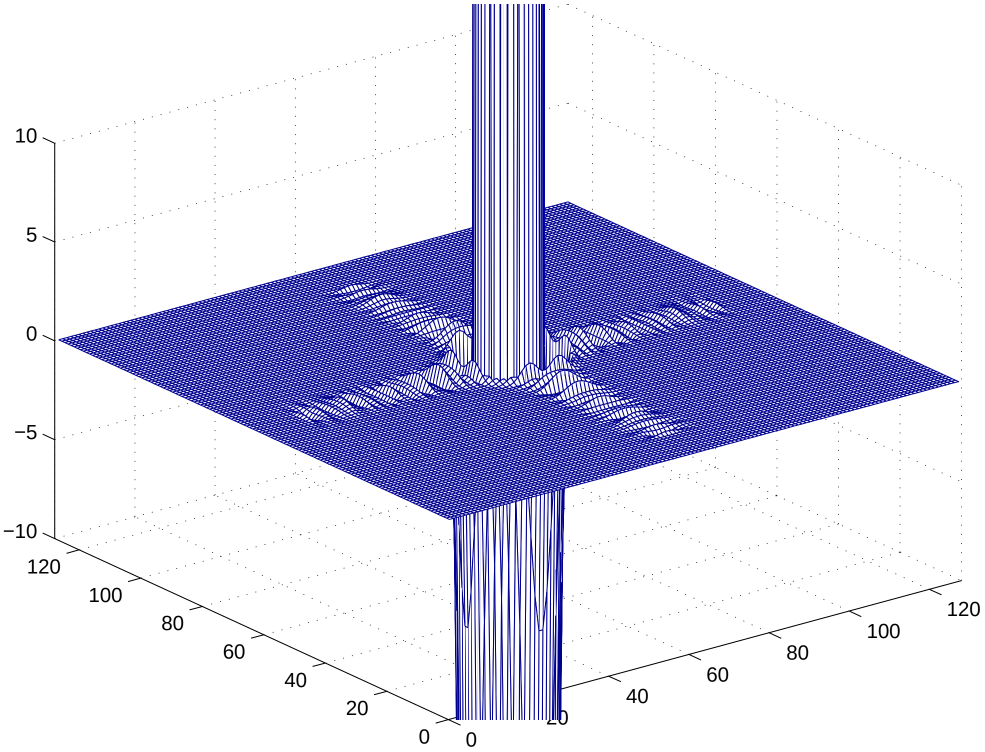
- Current 40 m optics are 4” diameter, 3.5” thick.
- We want to be able to use existing LIGO designs for the suspension controllers.
- LIGO has two types of suspension controllers: SOS for 3” optics (mode cleaner, etc), packaged as two controllers per rack-mounted crate; and LOS for 10” optics (core optics), packaged as one controller per rack-mounted crate.
- Per noise studies shown above, 3” optics will give unacceptably large suspension thermal and radiation pressure noise.
- We want to keep the size of the optic as small as is possible while giving acceptable suspension thermal and radiation pressure noise. 4” optics give acceptable noise.
- Smaller optics cost less.
- Smaller optics suspensions take up less real-estate in the already-cramped 40m chambers. This is perhaps the most important consideration driving us towards smaller optics.

- We hope that the 4” optics can make use of the SOS controllers; this has to be spec-ed.
- We hope that the scaling down of a LIGO LOS mechanical system to support a 4” optic will be simple and straightforward.
- Beam spot sizes are of order 4 mm; there is thus negligable clipping, diffraction, or other edge effects.
- The following output from the FFT program shows the beam spot on a FP arm end mirror. The mirror aperture extends almost to the edge of the mesh area.



UPGRADE TASKS

Interesting structure!



(Due to finite thickness of BS? No!)

(Imperfect convergence?)

UPGRADE TASKS

- Itemized list of tasks associated with upcoming bake-out, seismic stack rebuild, vacuum control upgrade:
  http://www.ligo.caltech.edu/~ajw/40m_bakeout.txt
- Itemized list of upgrade tasks:
  http://www.ligo.caltech.edu/~ajw/40m_wbs.txt
- Milestones:
  http://www.ligo.caltech.edu/~ajw/40m_milestones.txt
- Work on control system design:
  in collaboration with Jim Mason, Ken Strain, *etc.*