Sensing and Control for LIGO 2

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LSC Meeting, 16 Aug 2000
LIGO Hanford Observatory

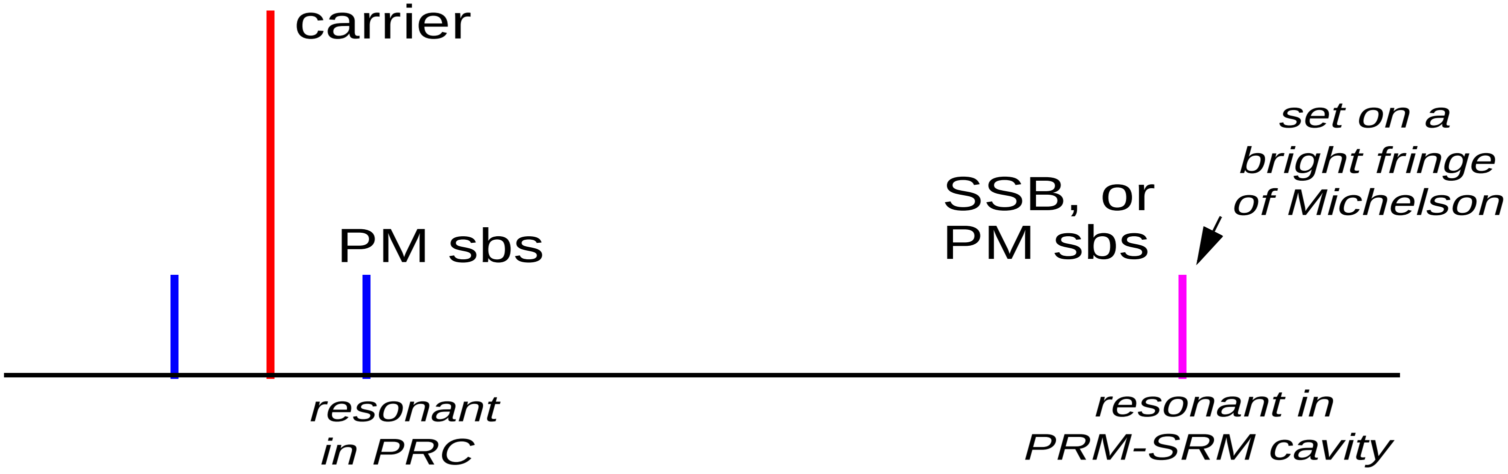
LIGO-G000225-00-D

Sensing: separate into 2 functions:

- Auxiliary degree-of-freedom sensing:
  - > power recycling cavity length
  - > signal recycling cavity length
  - > Michelson length
  - > Arm cavity common mode
  - > (Arm cavity differential mode)
- Gravitational wave signal readout
  - > needs to be designed for high signal sensitivity and good immunity to laser noise

Auxiliary lengths

- Basic idea: add a frequency to LIGO I:



carrier

PM sbs

resonant in PRC

SSB, or
PM sbs

set on a bright fringe of Michelson

resonant in PRM-SRM cavity

- This basic scenario presents a number of possibilities for extracting the signals

Variables and techniques

- Asymmetry: smaller asymmetry <-> higher frequencies
- First PM frequency:

  > lower frequency (closer to Michelson dark fringe), tends to give better separation of Michelson d.o.f.

  > SBs not exactly on center of PRC fringe; gives PRC length in an orthogonal RF phase from the common arm length (amplitude vs phase detection)
- Detect small lengths using only the field components that don't enter the arms

  > SB x SB: avoid the larger arm signal

  > double demodulation to extract Michelson signal

Example sensing matrix

- PM at 9 MHz (first fsr of a ~16.5 m MC) and 180 MHz
  - > asymmetry: 20 cm
  - > L+ sensed at 9 MHz at reflection port
  - > L- sensed at 180 MHz at antisymmetric port

Port	**MHz**	**L+**	**L-**	**l+**	**l-**	**lsr**
Reflected port	171	-0.4	0	**80**	-1	40
	189	-0.4	0	80	-0.6	40
PRC pickoff	171	-2	0	72	-63	**960**
	189	-2	0	180	-76	960
Antisymmetric port	171	0	0	0.1	**-1**	**1.95**
	189	0	0	-0.3	**-1**	**-1.91**

double demodulation

GW signal readout

- 4 techniques
  > frontal modulation, RF sidebands resonant in PRC & SRC

  > frontal modulation, RF sidebands also resonant in one or both arms

  > DC readout

  > Mach-Zehnder

- Any readout would likely require an output mode cleaner
  > may expect ~10^{-3} of beamsplitter power at AS port: ~2W

  > would several times this level in LO power; total detected power ~10W

  > better to clean up beam with output mode cleaner

DC readout

- Idea very simple: move slightly off dark fringe and measure baseband power fluctuations

  > field at AS port due to phase offset and signal phase

$$E_{AS} \propto \phi_0 + \delta\phi$$

  > power is linear in the signal $\delta\phi$

$$P_{AS} \propto 2\phi_0 \cdot \delta\phi + \phi_0^2$$

- Advantages

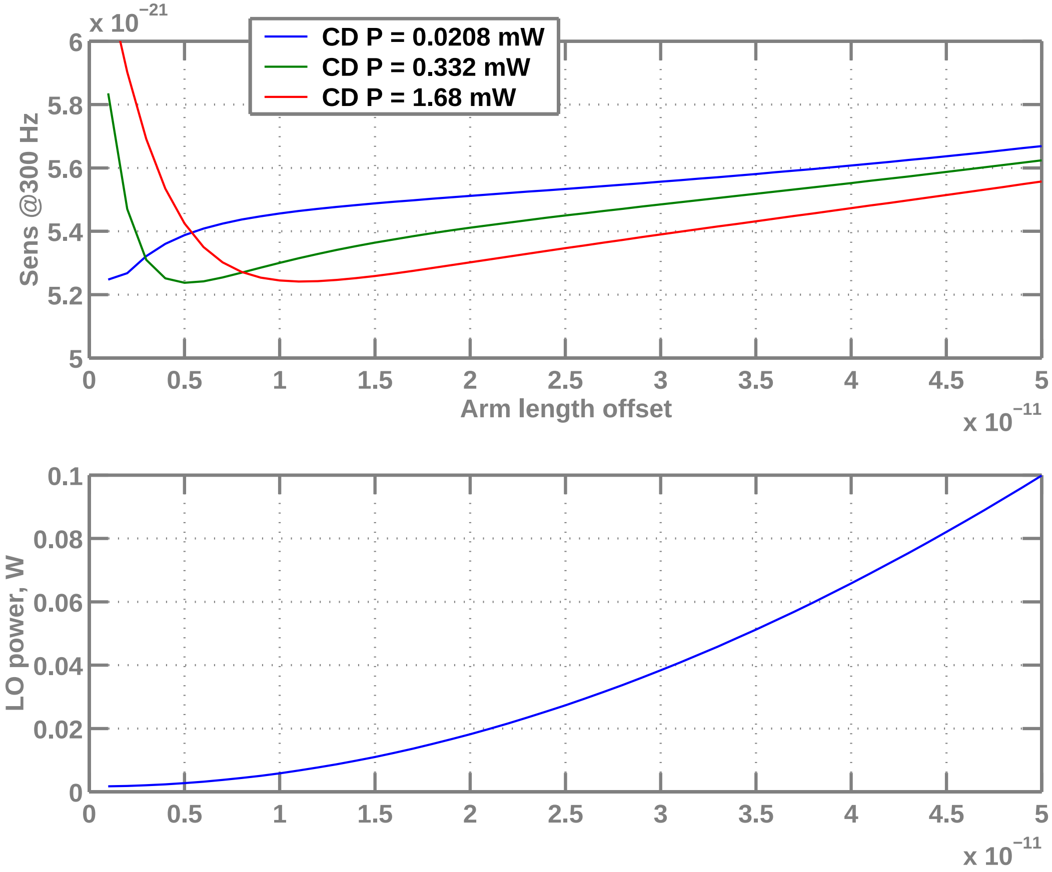
  > benefits from filtering of double-cavity pole

  > uses carrier only, which is less sensitive to thermal distortions in the ITMs

  > photodetector doesn’t need to operate at RF

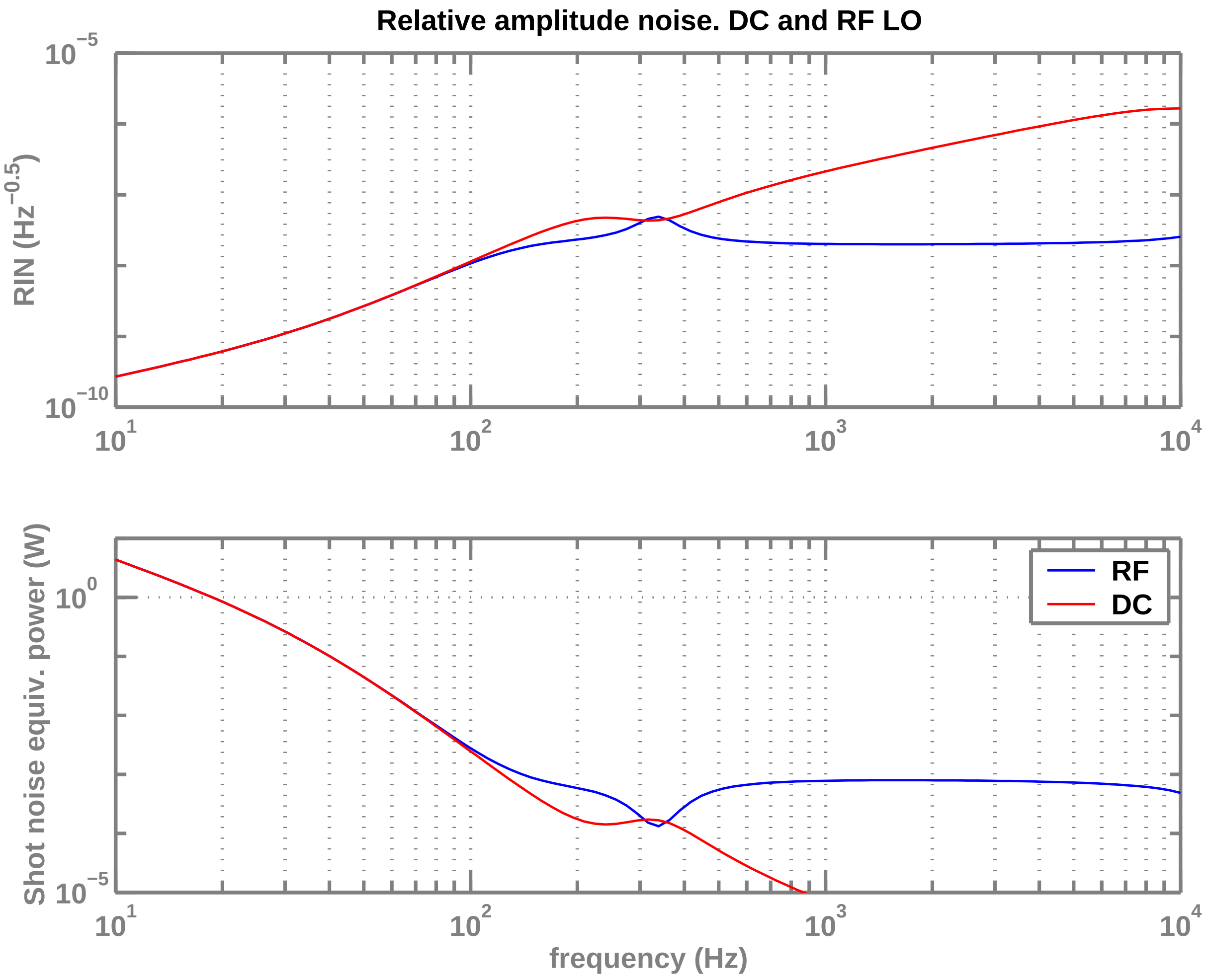
  > output mode cleaner not constrained to pass RF sideband

Optimum offset vs loss difference



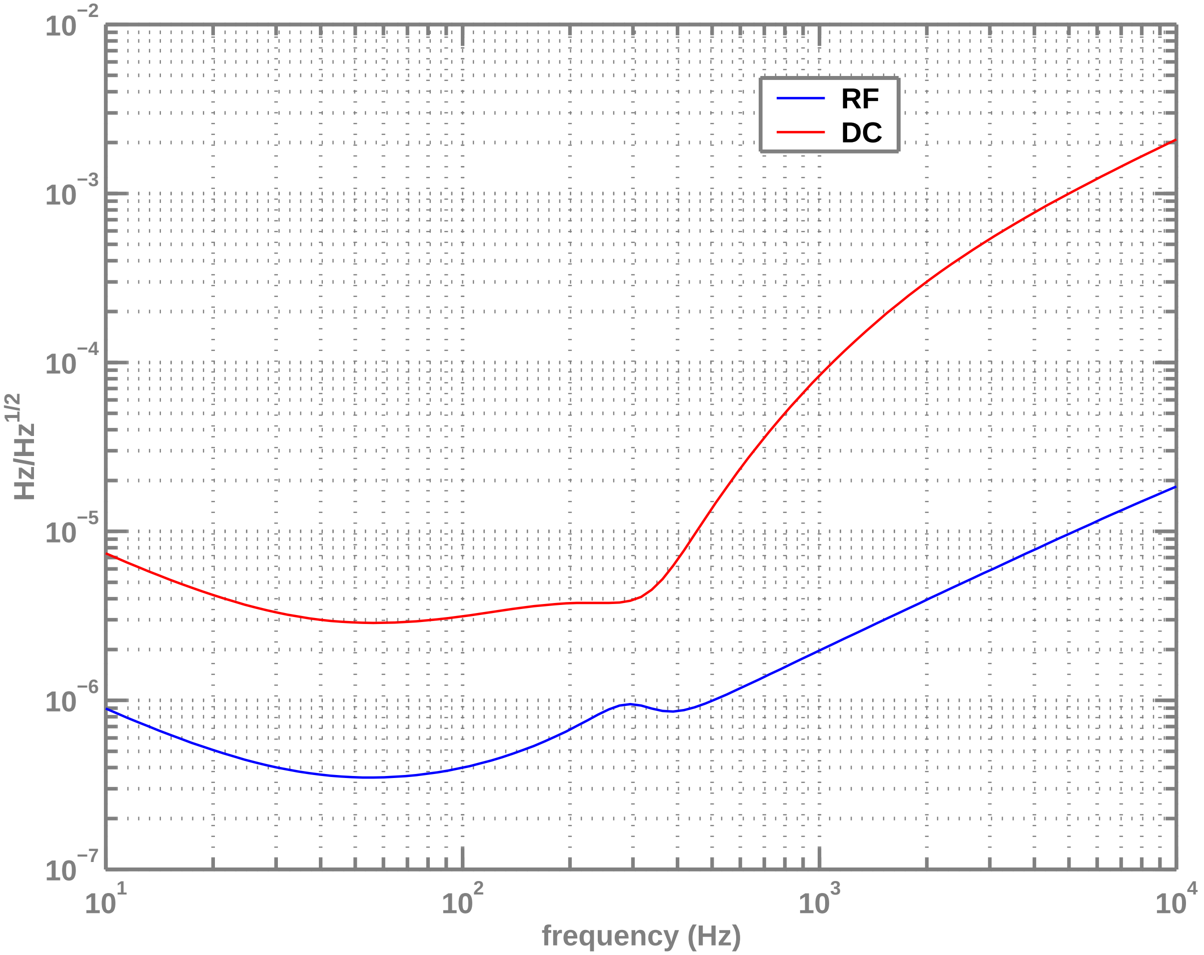
loss difference = 5, 20, & 45 ppm

Laser amplitude sensitivity



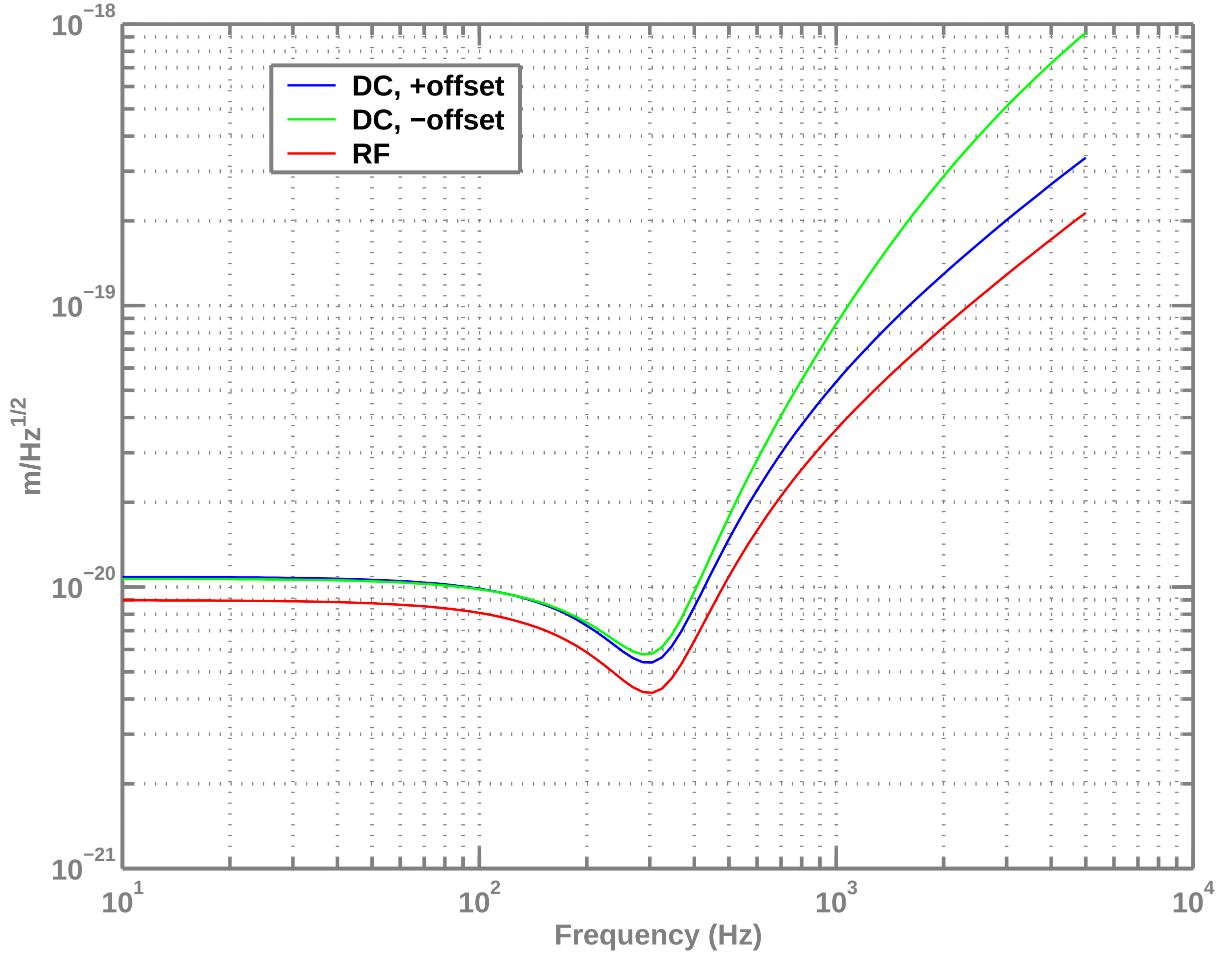
Requirement for RIN to be 10x below Bench strain sensitivity

Laser frequency sensitivity



Requirement for frequency noise to be 10x below Bench strain sensitivity

Sensitivity hit?



Sensitivity & control

- Two control issues strongly affect required sensing noise of auxiliary d.o.f.

  > excellent seismic isolation permits achievement of $10^{-10} – 10^{-11}$ m rms with a ~1 Hz control bandwidth

  > eddy current damping of test mass suspensions: avoidance of interferometric TM damping gives much greater isolation of GW channel from auxiliary d.o.f.

- In the presence of these 2 factors, the sensing requirement could be as lax as $\sim 10^{-14}$ m/Hz$^{1/2}$

LIGO II – Some requirements

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Note ‘requirements’ stated in this talk are illustrative estimates. Most are conservative but not all parameters are approved system parameters. Some results were obtained using relatively untested versions of software. Sensing parameters have not been finalised.

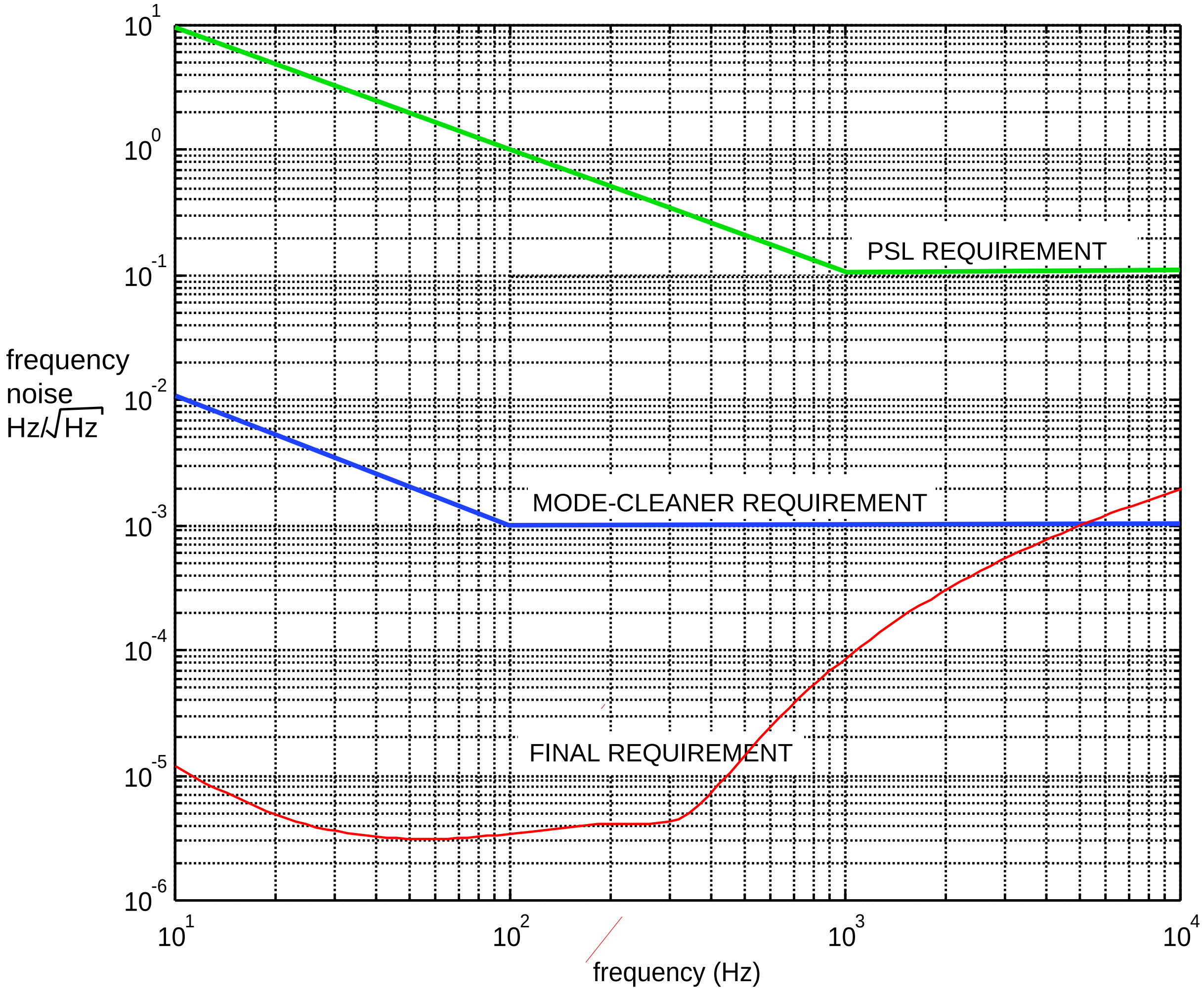
Contents

- Noise couplings
- Mode-cleaners
- Photodiode requirements
- Thermal loading and configuration parameters

Frequency noise requirements

- Frequency noise should contribute no more than 1% of the total noise power.
- Frequency noise — Φ_- coupling calculated using "rsenoiseDC.m" (Mason) and "bench" with reference parameters.
- A conservative estimate of achievable loop gain was used to set the requirement residual frequency noise for light stabilised to the mode-cleaner length
- A conservative estimate of achievable loop gain was used to set the requirement residual frequency noise for the PSL.
- Fall-back sensing scheme would require ~ 10 times lower final frequency noise, obtained by improvements to the references and/or redistribution of loop-gain between the 3 loops

Frequency noise specifications



Input mode-cleaner

- Input mode-cleaner $\sim 16\,\mathrm{m}$ long
- All RF modulations resonant (and an attempt will be made to keep them under $\sim 200\,\mathrm{MHz}$)
- Key displacement noise specification $\sim 3 \times 10^{-16}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at $10\,\mathrm{Hz}$ (Most stringent requirement found $3 \times 10^{-17}\mathrm{m}/\sqrt{\mathrm{Hz}}$ for fall-back RF scheme)

Thermal effects and configuration parameters 1

- Target arm power $\sim 0.8\,\mathrm{MW} \rightarrow 0.4\,\mathrm{W}$ coating heating per ITM
- Keep total heating as close to this as possible
- Sapphire: finesse as high as possible ~ 1300, few W absorbed in substrates
- Suprasil SV: finesse of at least LIGO I value. Can then neglect substrate heating. Suggest use of same parameters as for sapphire in mean time

Thermal effects and configuration parameters 2

- Active compensation of thermal distortion.
- Distorted beams still lead to residual higher order modes which must be non-resonant in SR cavity.
- There is a minimum SR finesse, and hence arm cavity finesse.
- The minimum arm cavity finesse seems to be $\sim 50\%$ higher than that used in LIGO I.

Note: for constant frequency response, arm cavity and SR cavity finesse scale proportionally over a wide range.

Thermo-elastic distortion

- 0.4 W in silica ($\alpha = 5.1 \times 10^{-7}$/K) produces relatively minor effect (subject to confirmation)
- 2.4 W in sapphire produces a much larger effect ($\sim \lambda/10$ distortion)
- Sapphire may not ‘cold start’.
- Melody/MATLAB results needed before effect is understood in combination with thermal lensing and compensation methods

Photodiode requirements

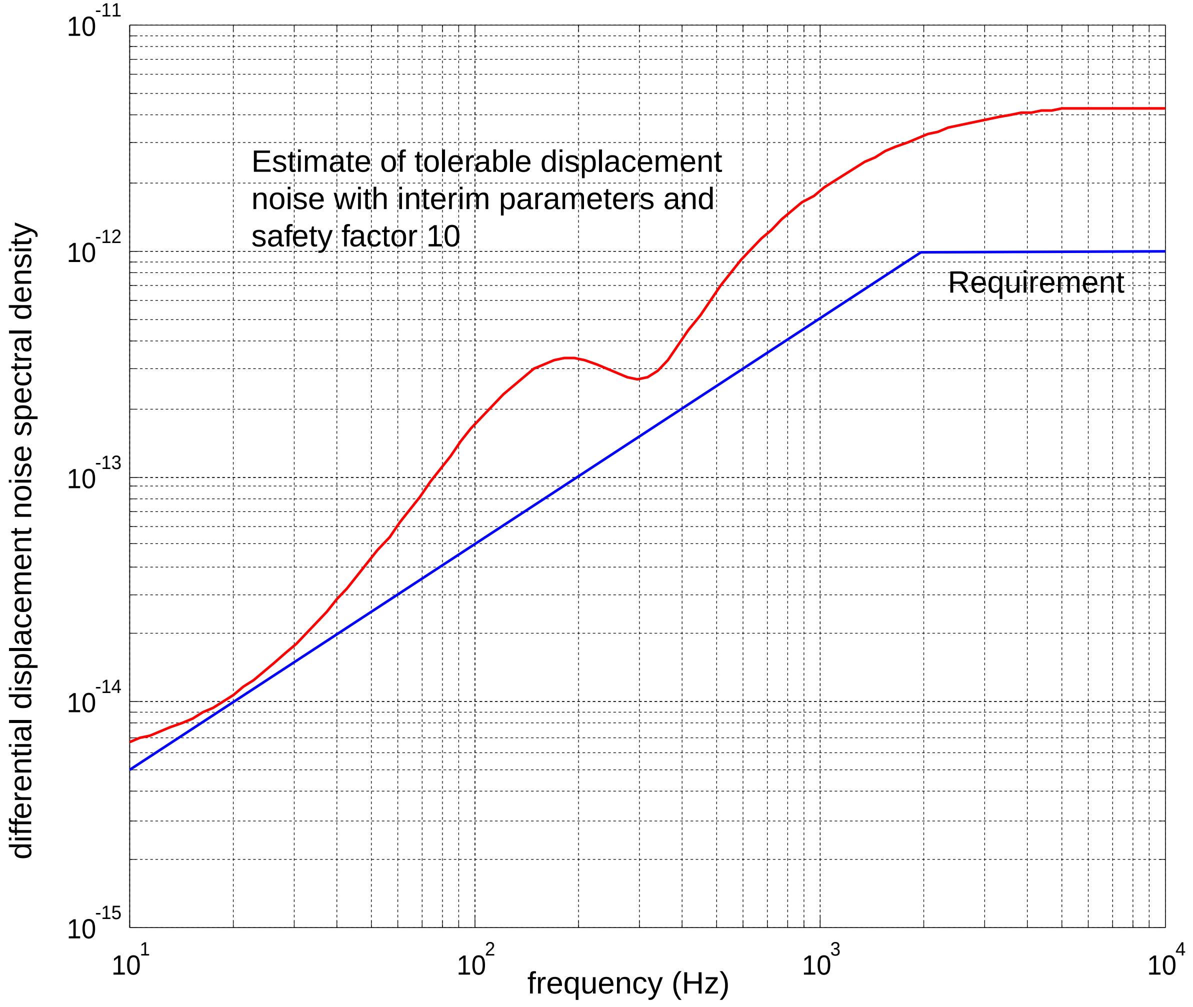
- Two types of diode needed
  1. for Φ_- sensing: $\leq 1\,\mathrm{W}$, DC – 10 kHz, Q.E.~ 0.9, low scatter, good uniformity
     - $*$ this is, in any case, needed for laser power stabilisation!
  2. for other sensing 9 MHz or 180 MHz centre frequencies, 100 kHz minimum bandwidth, 100 mW typical power, may need more bandwidth for double demodulation at 180 MHz then 9 MHz

All numbers to be confirmed

Output mode-cleaner (preliminary)

- Suggest short (0.2 m) monolithic ring cavity with a long (10 m) matching telescope (OPMC in HAM 6)
- RF reflection locked and aligned to well defined LO mode.
- To pass 99% of correct mode. Assume 20 ppm loss per mirror, $T_{\mathrm{coupler}} = 0.01$. (Finesse about 300.)
- Must pass DC with good amplitude stability. Thus length stability requirement can be derived from AM requirement.

OP-MC displacement noise requirement



Output mode-cleaner actuation

- Thermal tuning of a silica spacer ($0.2\,\mathrm{m}$ needs $5\,\mathrm{K/FSR}$) is very slow (hours, cooling is almost entirely by radiation).
- A PZT with $\sim 0.5\,\mu\mathrm{m}$ range would provide the faster actuator needed to lock the mode cleaner quickly

Short output mode-cleaner isolation requirement

- mount cavity on a single 2 Hz DC isolator (blade spring pendulum)
- length change depends on stiffness of cavity compared to stiffness of isolator, and suspension point motion.
- Assume 0.2 m cavity has 10 kHz lowest mode, isolation is *at least* $(10000/2)^2 > 2 \times 10^7$ (at $\geq$ 10 Hz, except at suspension and mechanical cavity modes).
- Suspension point seismic requirement is then $\sim 10^{-7}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 10 Hz.

Long output mode-cleaner option

- Require $\sim 10^5$ isolation at 10 Hz
- Achieved using triple pendulum with little or no pre-isolation
- Control more complicated (but also more flexible)
- Should probably work with short matching telescope