Predicting Thermal Noise in Initial LIGO Interferometers

*Gregory Harry**, Dennis Coyne**, Rana Adhikari *%,
Joe Betzweiser*, Bill Butler#, Andri Gretarsson%,
Dave Ottaway*

*MIT, **Caltech, %LLO, #LHO and U Rochester

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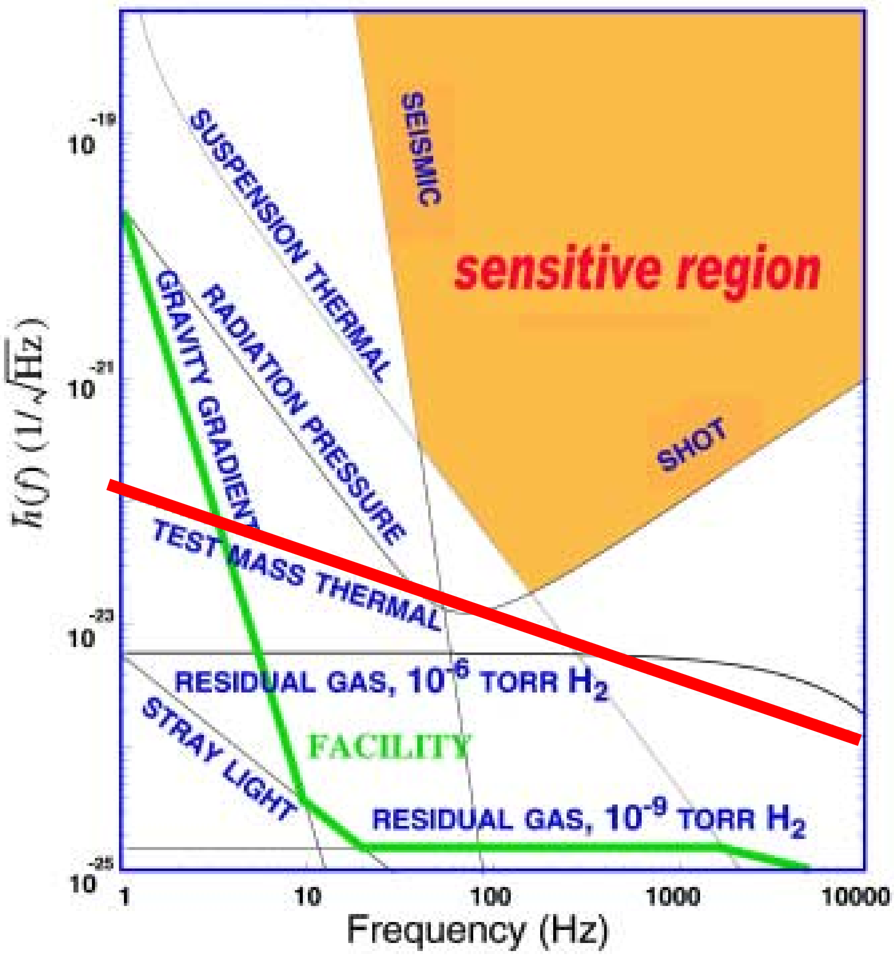
Requirement for internal mode thermal noise

- SRD requires internal mechanical Q of 1×10^6
- Thermal noise limit at 100 Hz $S_h^{1/2} = 4 \times 10^{-23} / Hz^{1/2}$
- Should not be a limiting noise source in any band



Predicting thermal noise
Levin's theorem

- Modal expansion used to test requirements
  - Does not account for inhomogeneity correctly
- Yuri Levin developed direct method for prediction
  - Treats inhomogeneities correctly
  - Predicts large effect from optical coatings
  - Verified by K. Yamamoto experiments
- Apply DC pressure with profile same as Gaussian beam
- Calculate energy distribution
- Use energy ratios to scale loss in different regions

Strategy
Applying Levin's theorem

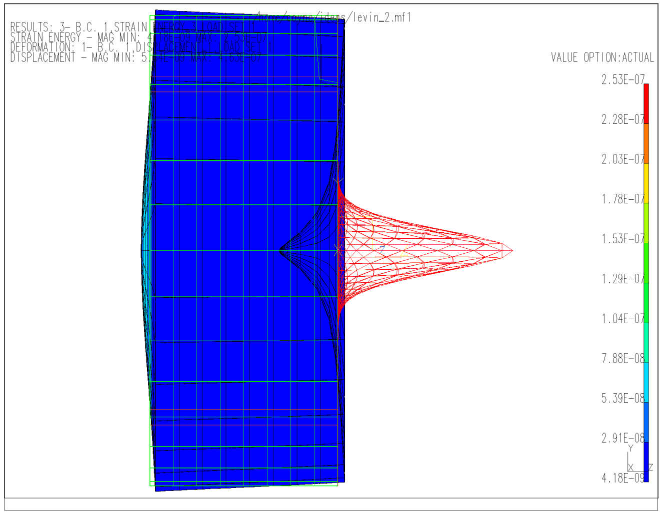
- Use FEA to determine energy in mirror for Levin pressure
- Regions of different loss
  - Silica substrate
  - Optical coatings, HR and AR (REO tantala/silica)
  - Magnet standoffs
  - Wire standoffs
  - Support wire
- Use FEA to determine energy ratios for various modes
- Measure modal Q's
- Determine loss in each region from measured Q's
- Use FEA model and loss model to predict thermal noise

FEA results
Levin pressure

- Apply Gaussian pressure
- Different beam widths
  - ITM 2K – 2.5 cm 4K – 3.8 cm
  - ETM 2K – 2.5 cm 4K – 4.4 cm

(3.8 cm beam waist)

Loss region	Energy ratio
Substrate	100
HR coating	2.1×10^{-4}
AR coating	6.1×10^{-6}
Magnet standoffs	2.3×10^{-7}
Wire standoffs	2.1×10^{-8}
Wire	**



- Sum total strain energy in each lossy region
- Ignores any anisotropy
- Assume frequency independent structural damping
- ** Wire loss probably rubbing
  - Tricky to get correct

Modal Q results

Probe the system

Mode	7	8	9	10	14	15	16	17	18	19	20	32
L1: ITMx	0.457	0.415	0.913	6.416	6.07		12.44	6.85	6.34	10.91	13.53	1.82
H2: ITMx	1.75	0.774	0.674	4.66	0.0078	0.203	13.4					
H2: ITMy	1.5	1.77	0.230	0.63	1.5	1.4	6.7					8.6

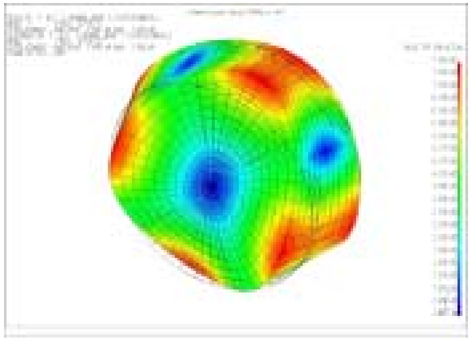
Modal Q's in millions

FEA results

Modal loss

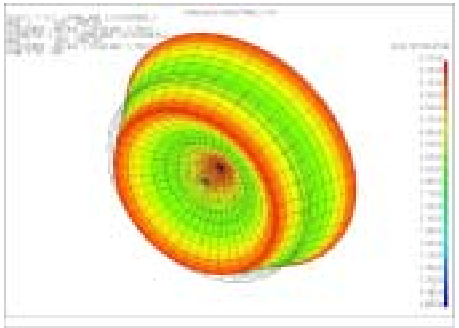
Butterfly X

Mode 7



Drumhead

Mode 9



Loss region	Energy ratio
Substrate	1
HR coating	9.65 10^{-5}
AR coating	1.20 10^{-5}
Magnet standoffs	1.91 10^{-9}
Wire standoffs	7.26 10^{-6}
Wire	**

Loss region	Energy ratio
Substrate	1
HR coating	1.05 10^{-4}
AR coating	1.32 10^{-5}
Magnet standoffs	2.42 10^{-9}
Wire standoffs	5.63 10^{-7}
Wire	**

All measured modes modeled

Loss model
Limits

- Use highest Q mode to limit substrate loss
- Use next highest Q mode to limit loss in region with highest energy

L1: ITMx
Substrate – mode 20
Coating – mode 16
Standoffs – mode 19

H2: ITMx
Substrate – mode 15
Coating – mode 10
Standoffs – mode 7

H2: ITMy
Substrate – mode 16
Coating – mode 15
Standoffs – mode 7

Loss region	Loss angle ϕ
Substrate	$7.4\ 10^{-8}$
Coatings	$1.6\ 10^{-4}$
Standoffs	$1.0\ 10^{-2}$

L1: ITMx results

Compare with other measurements

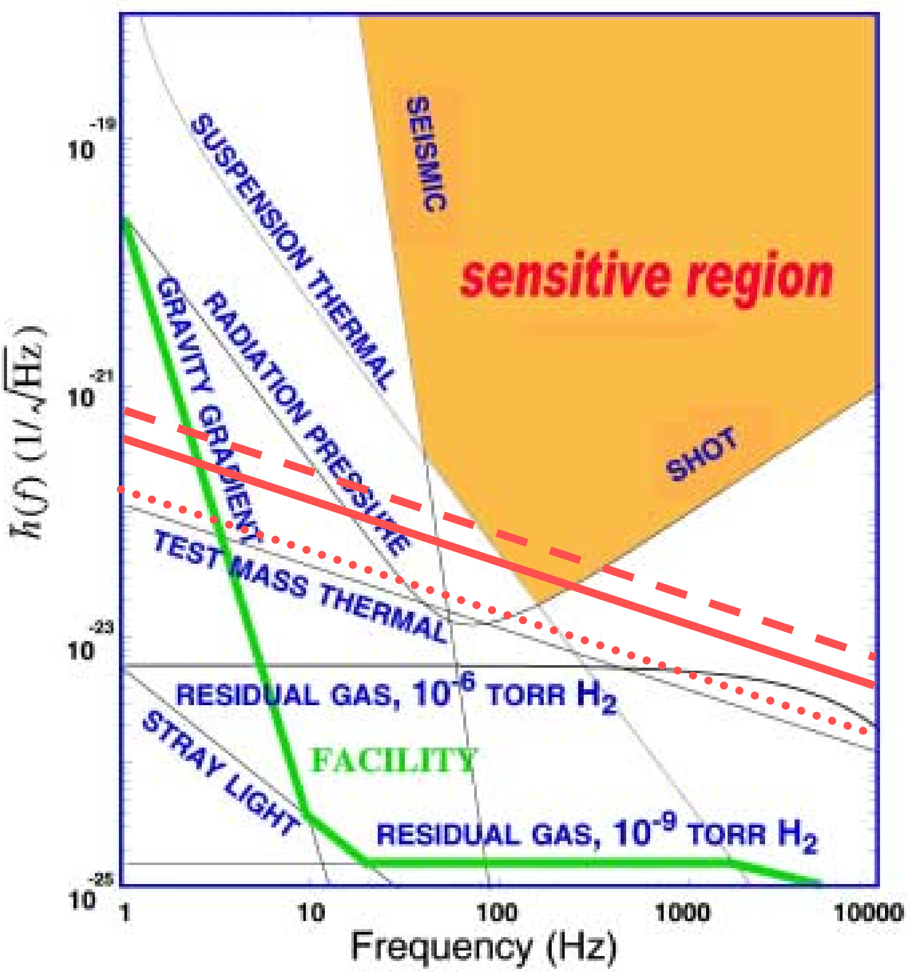
- Substrate $\phi \sim 3 \times 10^{-8}$ (Penn et al)
- Coating $\phi \sim 2 \times 10^{-4}$ (Crooks et al)
- Standoffs $\phi \sim 1 \times 10^{-2}$ (Gillespie)

Various models were tried for the wire, with limited success
- Rubbing friction
- Internal friction

Preliminary thermal noise prediction

- Q_{eff} = 9.0 X 10^6 (L1: ITMy)
  = 1.3 X 10^6 (H2: ITMx)
  = 2.3 X 10^5 (H2: ITMy)
  = 1.0 X 10^6 (SRD limit)
- Extrapolating from these Q's, can estimate thermal noise
- Limit of thermal noise at 100 Hz (scaled to 4 km)

  $S_h^{1/2}$ = 1.3 X 10^{-23} / $Hz^{1/2}$ (L1) ··········
  = 1.3 X 10^{-22} / $Hz^{1/2}$ (H2) – – –
  = 4.0 X 10^{-23} / $Hz^{1/2}$ (SRD) ———



Conclusions

- Looks like internal mode thermal noise will not be a limiting noise source
  - Not all mirrors measured
  - Don’t have a complete loss model
- Need a working model for wire loss
- Need to measure all mirrors on all IFOs
- Need to measure more modes for most mirrors
- Initial LIGO will probably set interesting limits on coating loss