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Thermal Noise from Coatings

What is needed for a solution?

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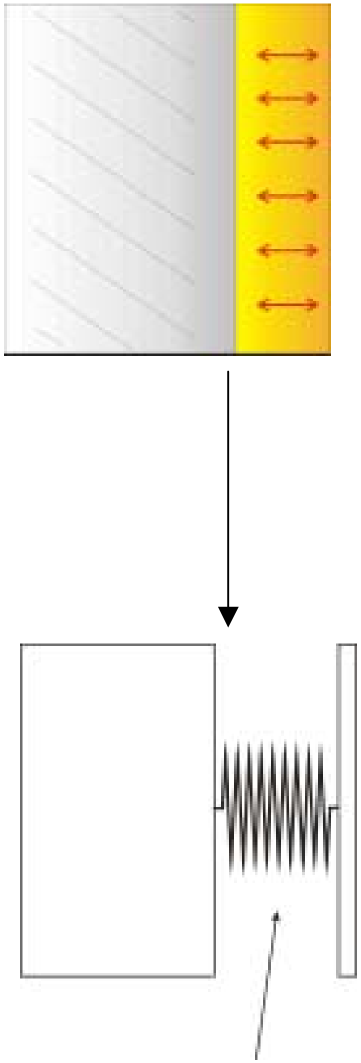
Stanford: Marty Fejer, Eric Gustafson, Roger Route, Sheila Rowan;
Glasgow: Geppo Cagnoli, David Crooks, Jim Hough;
Iowa State: Norio Nakagawa.

Simplest coating model



$$k = \frac{Y'\pi w^2}{d}$$

$$S_x(f) \approx \frac{2k_B T}{\pi k f}\phi_\perp = \frac{2k_B T}{\pi^2 f}\left(\frac{d\,\phi_\perp}{Y' w^2}\right)$$

$$\Rightarrow \sqrt{S_h(200\ \text{Hz})} \approx 10^{-22}\sqrt{\phi_\perp}$$

$$\text{Need: } \phi_\perp \le 10^{-4}$$

Result using Levin's method

$$S_x = \frac{2k_B T}{\pi^{\frac{3}{2}} f} \frac{1-\sigma^2}{wY} \left\{ \phi_{\text{substrate}} + \frac{1}{\sqrt{\pi}} \frac{d}{w} \frac{1}{YY'(1-\sigma'^2)(1-\sigma^2)} \right.$$

$$[Y'^2(1+\sigma)^2(1-2\sigma)^2\phi_{\parallel} + YY'(1+\sigma')(1+\sigma)(1-2\sigma)(\phi_{\parallel} - \phi_{\perp})$$

$$\left. + Y^2(1+\sigma')^2(1-2\sigma')\phi_{\perp}] \right\}$$

Limit $\phi_{\parallel} = \phi_{\perp}$ *agrees w/Nakagawa (private comm.)*

$$\xrightarrow{\sigma,\sigma'\to 0} \quad \frac{2k_B T}{\pi^{\frac{3}{2}} f} \frac{1}{wY} \left\{ \phi_{\text{substrate}} + \frac{d}{w\sqrt{\pi}} \left(\frac{Y'}{Y}\phi_{\parallel} + \frac{Y}{Y'}\phi_{\perp} \right) \right\}$$

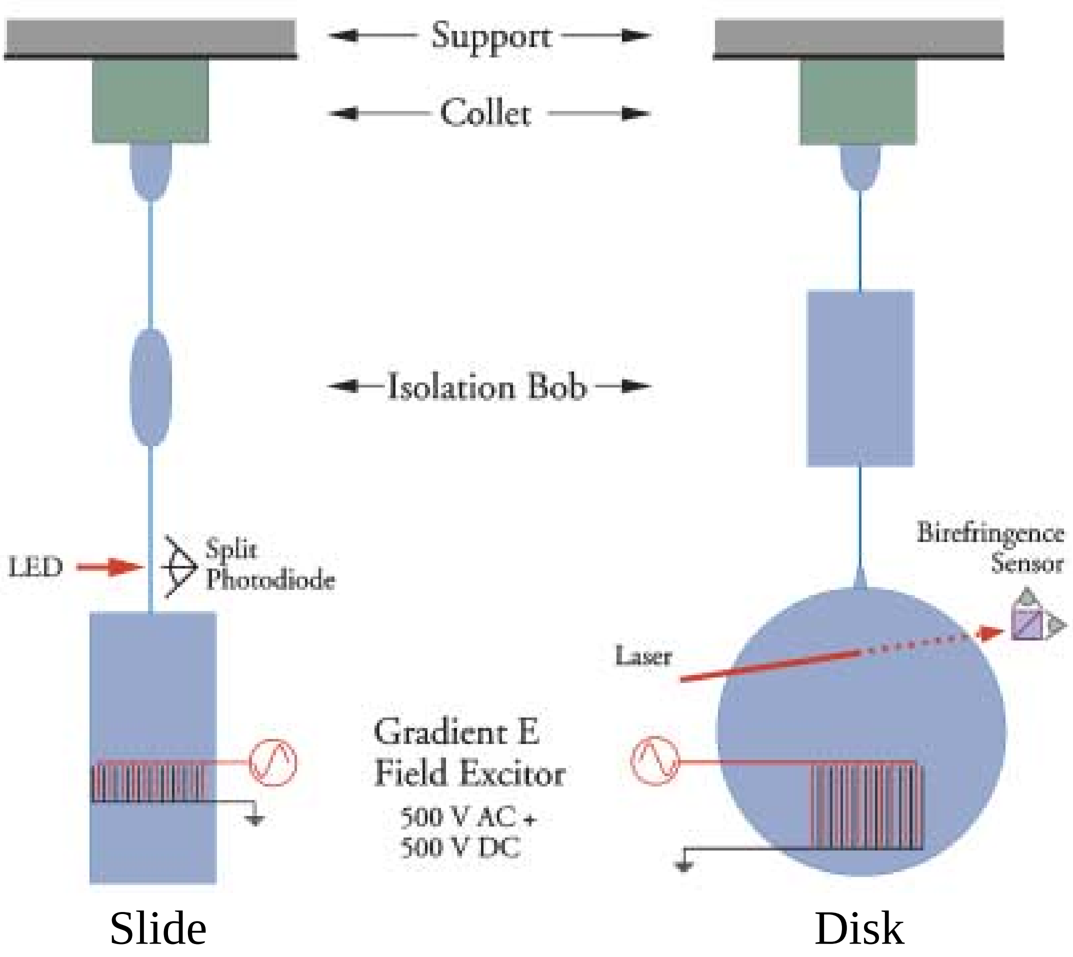
Need to measure: $\phi_{\parallel}$, $\phi_{\perp}$, and Y'.

So far, have only measured $\phi_{\parallel}$.

(For thermal noise estimates set $\phi_{\perp} = \phi_{\parallel}$, guess Y'.)

(MIT/Syracuse)

Ringdown experiments using thin fused silica substrates



(MIT/Syracuse)

Results

Pre-coat Q   Post-coat Q   Coating energy analysis

⇨ Loss angle, $\phi_{\parallel}$.

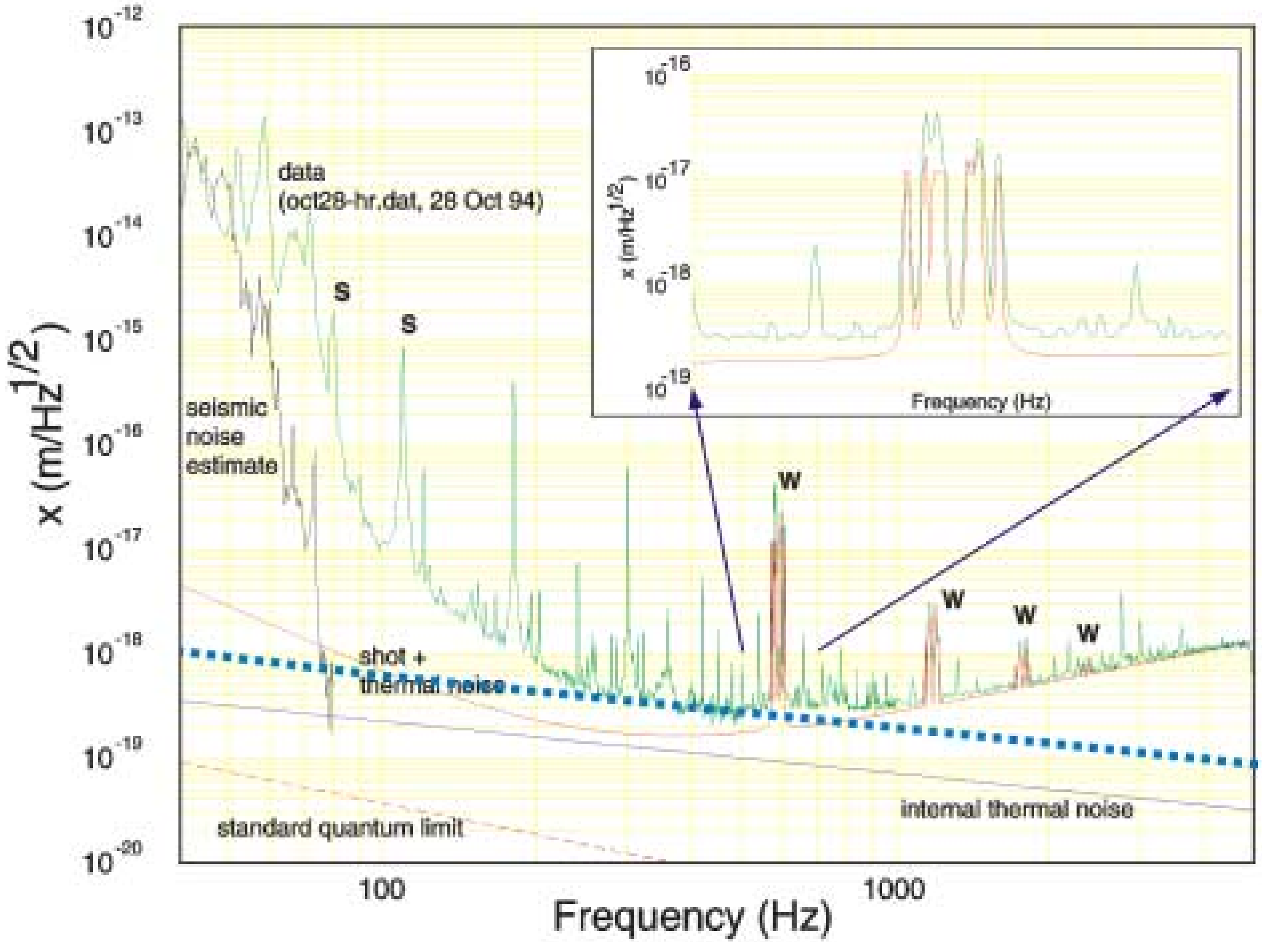
Ta$_2$O$_5$/SiO$_2$ coatings from R.E.O.

Commercial polish slides: $\phi_{\parallel} = 4.2 \pm 0.3 \times 10^{-4}$

"Superpolished" disk: $\phi_{\parallel} \approx 1 \times 10^{-4}$ (shear?)

Caltech 40 m

(Ta_2O_5/SiO_2, R.E.O. coatings)

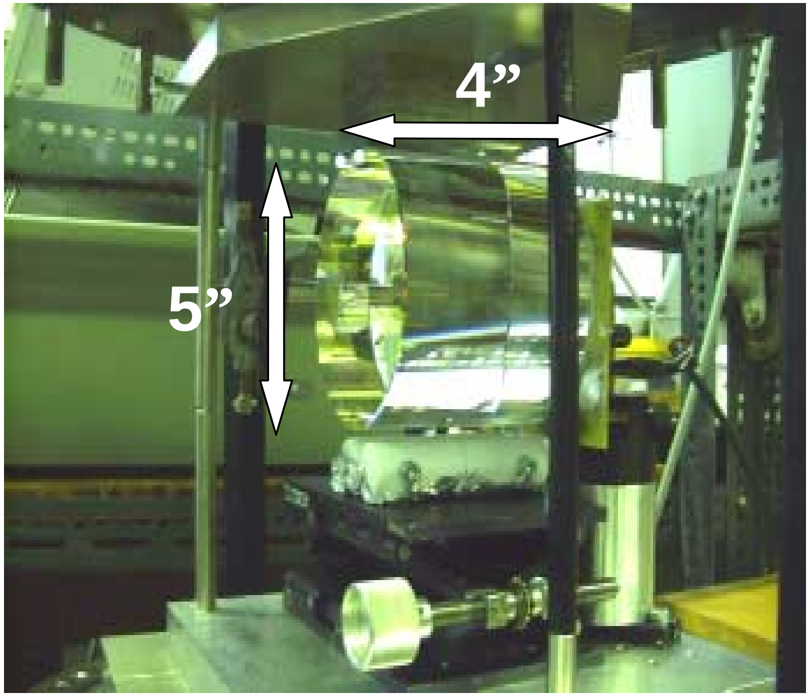


(Glasgow/Stanford)

Thick fused silica substrates

- Corning 7940 (3G)
- Corning 7980 (OC)
- Dimensions 5”dia x 4” thick
  (size of mirrors in Glasgow 10m prototype)
- 2 samples coated by G.O.
- AL_2O_3/TA_2O_5

7940:
HR @1064nm <20ppm 5.9µm thick
(AR @ 1064nm)
7980:
HR @1064nm ~300ppm 8.1µm thick
(AR @ 1064nm)



Test mass in Q measurement apparatus

Q’s measured for 7 modes of each mass

(Glasgow/Stanford)

Measured loss factors

Mode (*)	Corning 7980 Frequency (Hz) Modeled	Corning 7980 Frequency (Hz) Measured	Corning 7980 Measured loss ($x 10^{-7}$)	Corning 7940 Frequency (Hz) Measured	Corning 7940 Measured loss ($x 10^{-7}$)
1. Bending (8, n=1)	22401	22105	1.37 +/- 0.04	22361	1.6+/-0.01
2. Asymmetric Drum (1, n=0)	23238	22977	1.16 +/- 0.02	23004	1.23+/-0.05
3. Fundamental (1, n=2)	24671	25378	0.65 +/- 0.01	25404	0.5+/-0.02
4. Clover 4 (16, n=2)	25490	26176	1.61 +/- 0.03	26193	1.89+/-0.04
5. Symmetric Drum (4, n=0)	27723	28388	3.1 +/- 0.12	28395	3.6+/-0.29
6. Expansion	31397	31710	1.09 +/- 0.01	31731	1.01+/-0.01
7. 2nd Asymmetric Drum (3, n=0)	35133	36045	0.86 +/- 0.01	36072	0.94+/-0.03

For each sample a significant variation in measured loss factor was seen. For an uncoated mass of the same dimensions the variation in loss factor between modes was significantly smaller - we believe the variation seen for the coated masses is a result of the coatings applied

(Glasgow/Stanford)

Analysis of results

Assuming all other losses are of a negligible level, total measured loss may be expressed as the sum of the loss of the substrate plus any loss associated with the coating:

$$\phi(\omega_0)_{\text{coated}} = \phi(\omega_0)_{\text{substrate}} + \phi(\omega_0)_{\substack{\text{associated}\\\text{with coating}}}$$

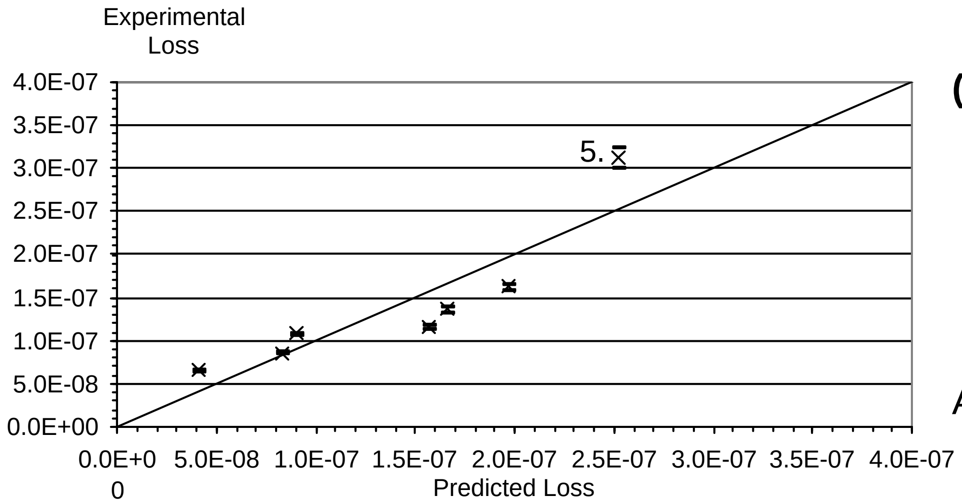
More fully:

$$\phi(\omega_0)_{\text{coated}} \approx \phi(\omega_0)_{\text{substrate}} + \frac{E_{\text{coating on face}}}{E_{\text{substrate}}}\,\phi(\omega_0)_{\substack{\text{coating}\\\text{on face}}} + \frac{E_{\substack{\text{barrel}\\\text{coating}}}}{E_{\text{substrate}}}\,\phi(\omega_0)_{\text{eff}}$$

Where $\phi(\omega_o)$eff includes the effect of loss assocated with coating which had spilled onto the barrel of the samples.

For each mode, finite element analysis was used to calculate the relevant energy ratios, and $\phi(\omega_o)$ was measured.
A multiple linear regression algorithm was then used to find the best fit values for $\phi(\omega_o)_{\text{substrate}}$, $\phi(\omega_o)_{\text{coating on face}}$ and $\phi(\omega_o)_{\text{eff}}$

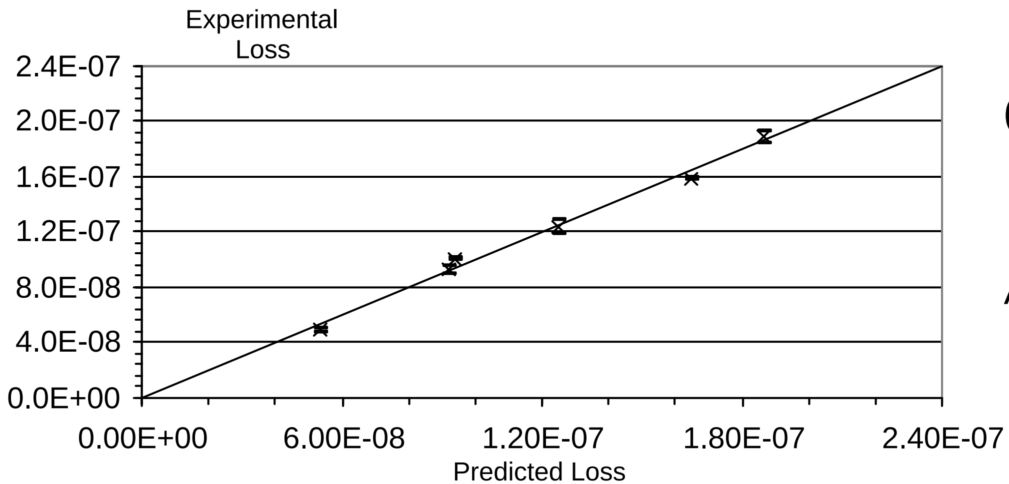
Results - 7980 mass



(a) Comparison of the experimental loss with that predicted using the 3 parameter regression analysis using results from all modes.

It can be seen that the fit is good, but is better if one point (mode 5. - symmetric drum mode) is removed

Analysis ⟶ $\phi(\omega_o)_{coating}$ = **(1.6 +/- 0.7) x 10^{-4}**



(b) Comparison of the experimental loss with that predicted using same analysis omitting mode 5

Analysis ⟶ $\phi(\omega_o)_{coating}$ = **(7.1 +/- 1.8) x 10^{-5}**

Results for 7940 mass - v. similar (a) $\phi(\omega_o)_{coating}$ = **(1.4 +/- 0.5) x 10^{-4}** **(b)** $\phi(\omega_o)_{coating}$ = **(7.1 +/- 0.8) x 10^{-5}**

(Glasgow/Stanford)

Conclusions

Consider interferometer $\rightarrow$ using same materials for substrates/coatings as studied here

using the analysis by Nakagawa et al, expected thermal noise would increase by

~1.3 in power spectral density,

or ~1.14 in amplitude

due to the effects of coating loss, (assuming **$\phi(\omega_o)_{coating}$ = (7.1 +/- 1.8) x 10^{-5})**

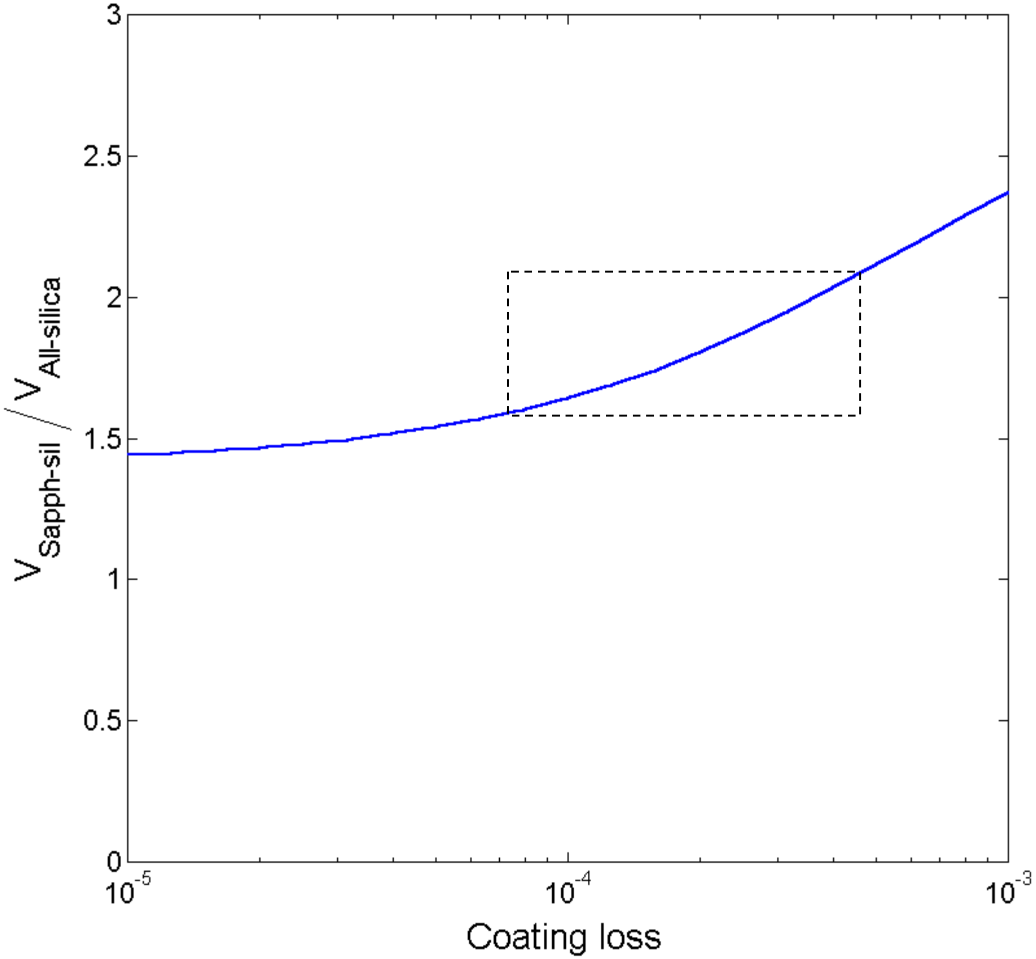
G.O. – R.E.O. comparison: Current Adv. LIGO design *

Substrate Material	*Coating Type*	*Normalized Volume*
Sapphire	None	1.0
Sapphire	G.O.	0.86
	R.E.O	0.36
Silica	G.O.	0.20
	R.E.O.	0.11
Mixed	G.O.	0.37
	R.E.O.	0.22

Still Preliminary!

* Using Bench (factor of 2 error corrected).

Mixed (sapph-sil) versus all-silica

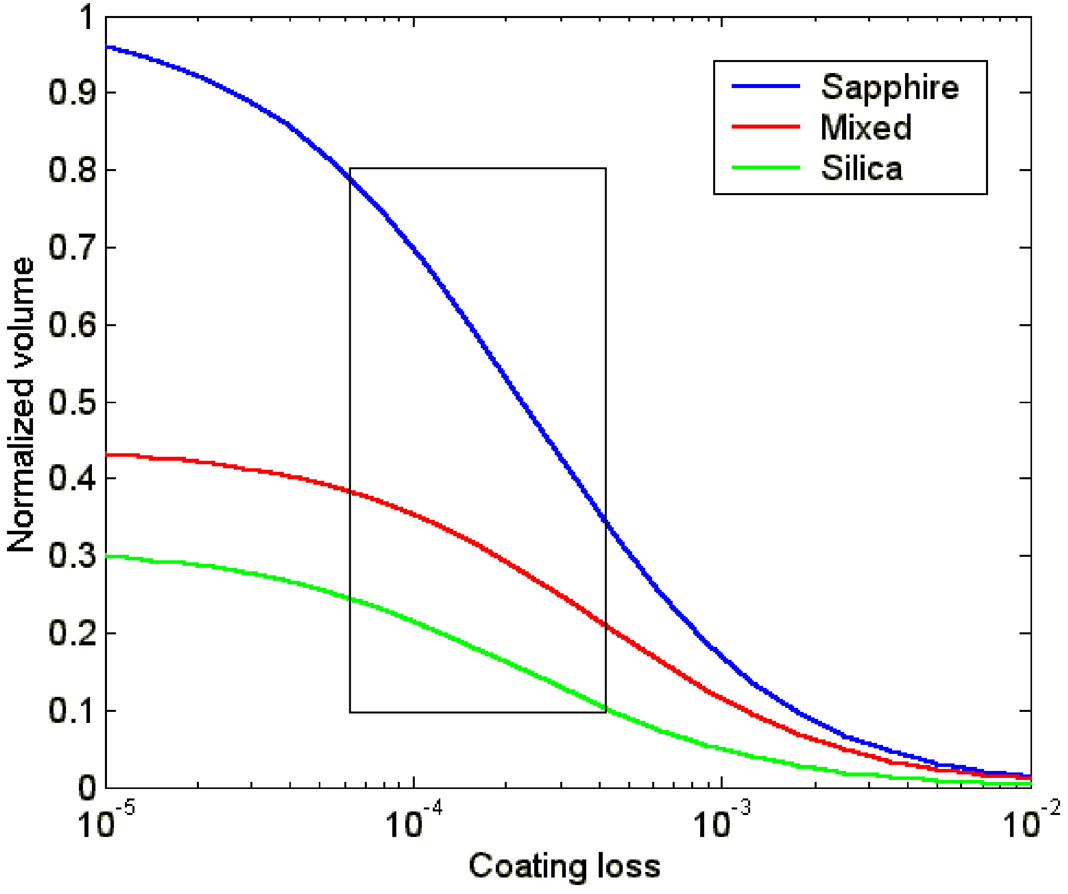


If Sapphire cannot be made with sufficiently low absorbtion/ biref., need to go to silica ITM's and BS's.

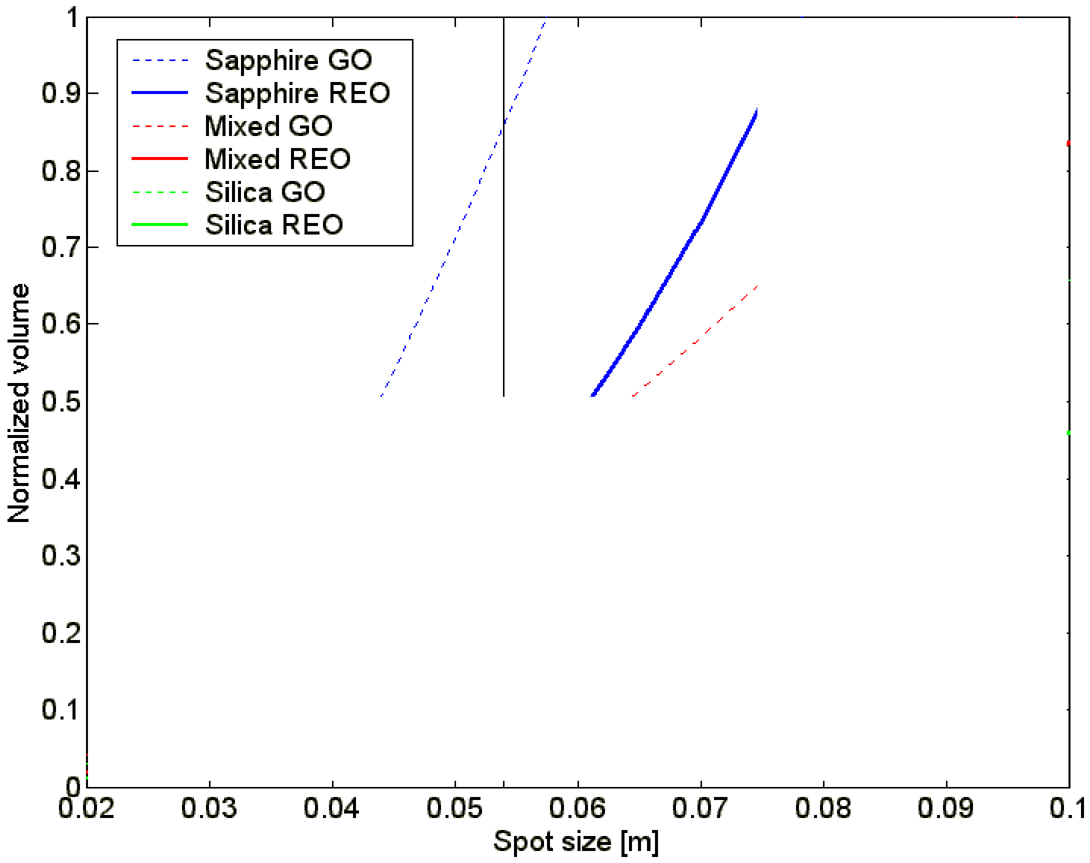
Th. n. from coatings is dominated by the thick ETM coatings.

Gain by using sapphire ETM's because of high Young's modulus.

Sensitivity as a function of coating loss
(spot size = 5.4 cm)



Sensitivity vs. spot size



Materials work

- Finish characterizing currently available coatings
  - Optical studies of the G.O. coatings
  - More measurements of $\phi_{\|}$ (Stanford, MIT, Glasgow, Syracuse)
  - Measurement of $\phi_{\perp}$ (Caltech)
  - Measurement of coating Young’s moduli
- If current coatings don’t cut it, need new methods
  - Deposition process
  - Effect of annealing
  - New materials

Planned measurements of $\phi_{||}$

Table 1: Coating Mechanical Loss Program Technical Summary

Run #	Coating Design	Test	Comments
0	no coating	Effect of cleaning and annealing on loss	
1	SiO_2 Ta_2O_5 30 layer $\lambda/4$ $\lambda/4$	Effect of surface layer +30 layer coating on loss,	
2	SiO_2 Ta_2O_5 2 layer $\lambda/4$ $\lambda/4$	Effect of surface layer + 1st coating layer on loss	
3a	SiO_2 Ta_2O_5 30 layer $3\lambda/8$ $\lambda/8$	Which material has effect on loss	assumes run 1 is dominant effect
3b	SiO_2 Ta_2O_5 60 layer $\lambda/8$ $\lambda/8$	does material thickness or # interfaces affect loss	assumes run 1 is dominant effect

Summary

- Coating measurements still at an early stage.
- Current results indicate coatings are a serious concern, but…
- Only modest improvements in coating loss are needed.
- Can spot size be increased further?
- In the presence of coatings, a sapph-sil interferometer's performance is further enhanced relative to an all-silica interferometer.