Assessing Thermal Noise From Optical Coatings

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Context

- **Previously measured coating loss:**
  - SiO_2/Ta_2O_5 on silica substrate $\phi=1.0 \pm 0.3\ 10^{-4}$
  - AL_2O_3/Ta_2O_5 on silica substrate $\phi=6.4 \pm 0.6\ 10^{-5}$
- **Theory to predict thermal noise from ϕ_{coat}**
- **FEA code to compute energy in coating**
- **Implications for advanced LIGO**
  - silica mirrors BNS range 115 Mpc $\rightarrow$ 80 Mpc
  - sapphire mirrors BNS range 185 Mpc $\rightarrow$ 110 Mpc

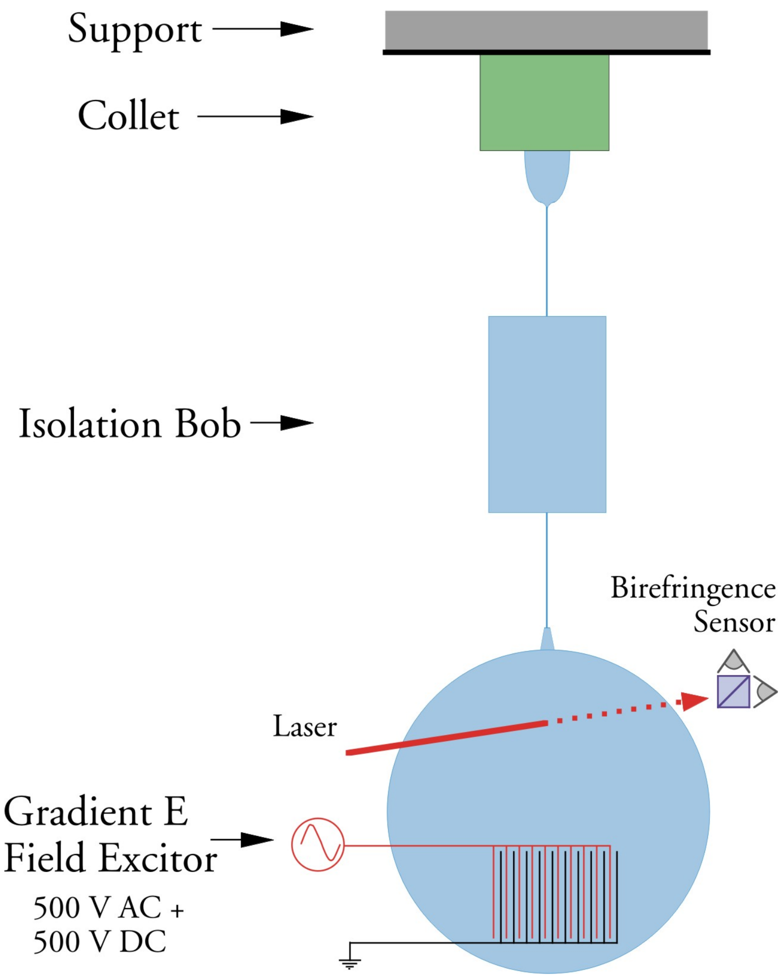
See DRM Crooks et al, CQG 19, 5(2002) 883; GM Harry et al, CQG 19, 5(2002) 897.

Measurement

- **Thin fused silica samples**
  (3 inch diameter by 0.1 inch thick)

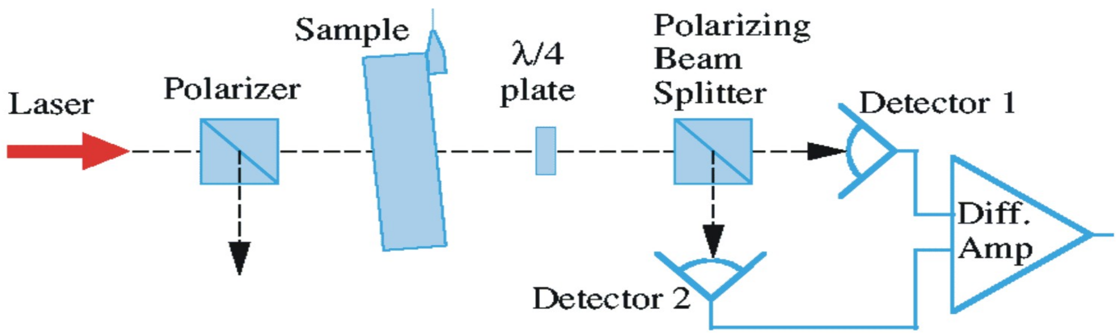
- **Samples suspended from monolithic, double−bob suspensions (*see Steve Penn's presentation*)**

- **Q of normal modes measured before and after coating**
  - **two butterfly modes (n=0, l=2)**
  - **single drumhead (n=1, l=0)**



Measurement, *cont'd*

- Birefringence sensor used to readout oscillating strain in normal mode



- Data fit to full damped sinusoid to get Q
- FEA results used to determine energy in coating for each mode
- ϕ_{coat} deduced from Q's and FEA

Finite Element Analysis (FEA)

- Make Algor model of samples
  - $f_{butterfly}$ = 2659Hz
  - $f_{drumhead}$ = 4038 Hz
- Use Ocean to get energy ratio in coating (for 8 μm coating)
  - butterfly 1.19×10^{-2}
  - drumhead 1.26×10^{-2}

Analyses

- Determine if loss due to factor other than coating
  - uncoated sample annealed
- Determine if loss scales with coating thickness or with number of layers
  - 2 layers, $\lambda/4$ SiO_2 and $\lambda/4$ Ta_2O_5
  - 30 layers, $\lambda/4$ SiO_2 and $\lambda/4$ Ta_2O_5
  - 60 layers, $\lambda/8$ SiO_2 and $\lambda/8$ Ta_2O_5
- Determine if SiO_2 or Ta_2O_5 is lossier
  - 30 layers, $\lambda/8$ SiO_2 and $3\lambda/8$ Ta_2O_5

Annealing Results

Sample annealed at 900° C

Mode	Annealing	Frequency	Q
Butterfly 1	Unannealed	2720	11 million
	Annealed	2717	42 million
Butterfly 2	Unannealed	2720	14 million
	Annealed	2718	54 million

Sample annealed at 600° C

Mode	Annealing	Frequency	Q
Butterfly 1	Unannealed	2779	15 million
	Annealed	----	----
Butterfly 2	Unannealed	2781	12 million
	Annealed	2781	44 million

Coating Results – *2 layers*

Samples coated with 2 layers of $\lambda/4$ SiO_2 and $\lambda/4$ Ta_2O_5

Mode	Frequency	Q
Butterfly +	2679	5.4 million
Butterfly x	2681	6.5 million

Mode	Frequency	Q
Butterfly 1	2711	8 million
Butterfly 2	2722	9 million

Coating Results – *30 layers even*

Samples coated with 30 layers of $\lambda/4$ SiO_2 and $\lambda/4$ Ta_2O_5

Mode	Frequency	Q
Butterfly +	2708	528,000
Butterfly x	2840	1.9 million

Mode	Frequency	Q
Butterfly 1	2732	536,000
Butterfly 2	2735	549,000

Coating Results – *30 layers uneven*

Samples coated with 30 layers of $\lambda/8$ SiO_2 and $3\lambda/8$ Ta_2O_5

Mode	Frequency	Q
Butterfly 1	2721	400,000
Butterfly 2	2723	403,000
Drumhead	4107	285,000

Mode	Frequency	Q
Butterfly 1	2700	409,000
Butterfly 2	2694	404,000

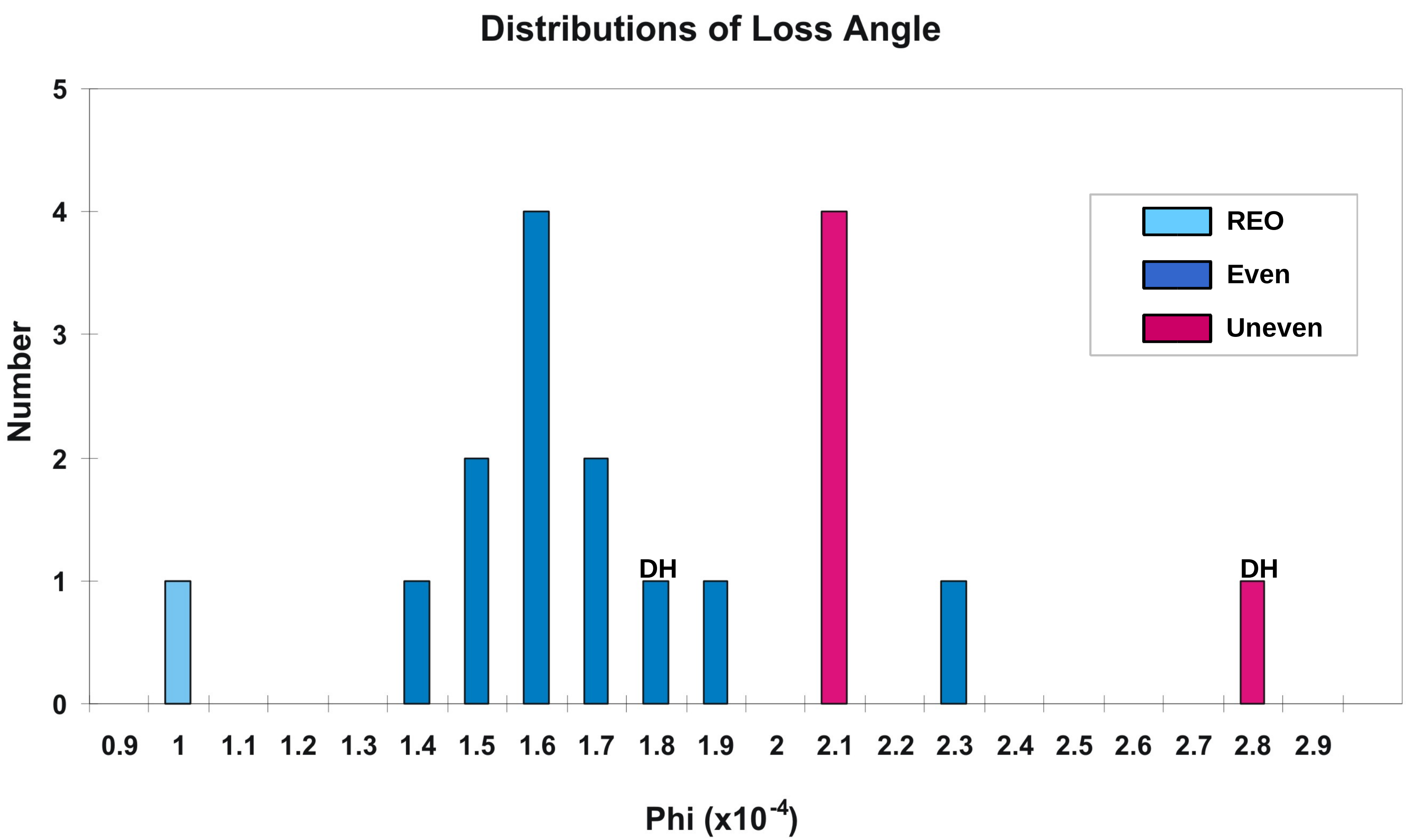
Coating Results – *60 layers*

Samples coated with 60 layers of $\lambda/8$ SiO_2 and $\lambda/8$ Ta_2O_5

Mode	Frequency	Q
Butterfly +	2712	548,000
Butterfly x	2690	487,000
Drumhead	4057	439,000

Mode	Frequency	Q
Butterfly +	2786	502,000
Butterfly x	2782	520,000

Coating ϕ's



Interpretation

- Annealing can reduce silica loss, even for thin samples
- $\phi_{coat} = 1.7 \pm 0.2 \times 10^{-4}$
- Loss scales with coating thickness
- No significant effect from first or subsequent layers
- Ta_2O_5 is lossier than SiO_2
- $\phi_{Ta_2O_5} = 2.7 \pm 0.7 \times 10^{-4}$
- $\phi_{SiO_2} = 4.2 \pm 4.4 \times 10^{-4}$

Next Steps

- Anneal current coated samples
  - limited maximum temperature due to Ta_2O_5
  - adjust cooling rate
- Try other materials and combinations
  - SiO_2 /Al_2O_3 (need ~80 layers to get HR)
  - Nb_2O_5 , HfO_2 , ZrO_2 (optically lossy)
- Changes to coating process
  - adjust purity of target materials
  - change substrate temperature
  - change ion beam energy

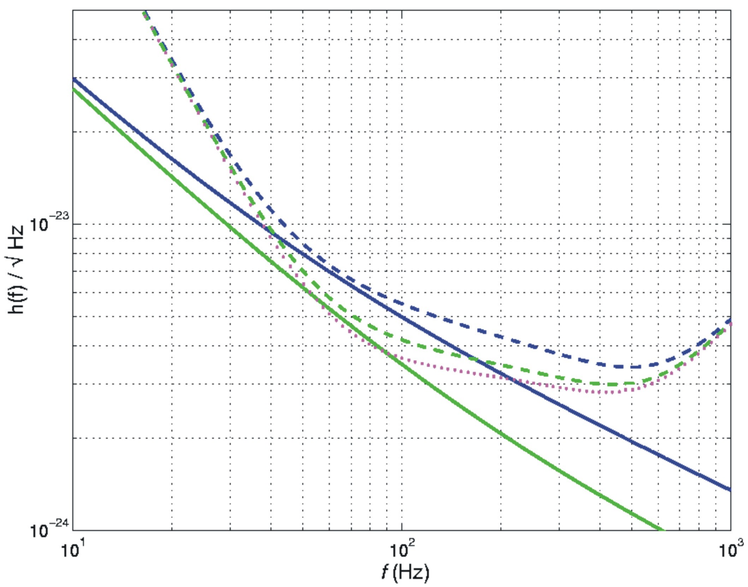
Predicting Thermal Noise from Coating ϕ

$$\phi_{readout} = \phi_{bulk} + \frac{1}{\sqrt{\pi}} \frac{(1-\sigma_{sub})}{(1-2\sigma_{sub})} \frac{d}{w} \left(\frac{Y_{coat}}{Y_{sub}} \phi_{coat\,||} + \frac{Y_{ub}}{Y_{coat}} \phi_{coat\,+} \right)$$

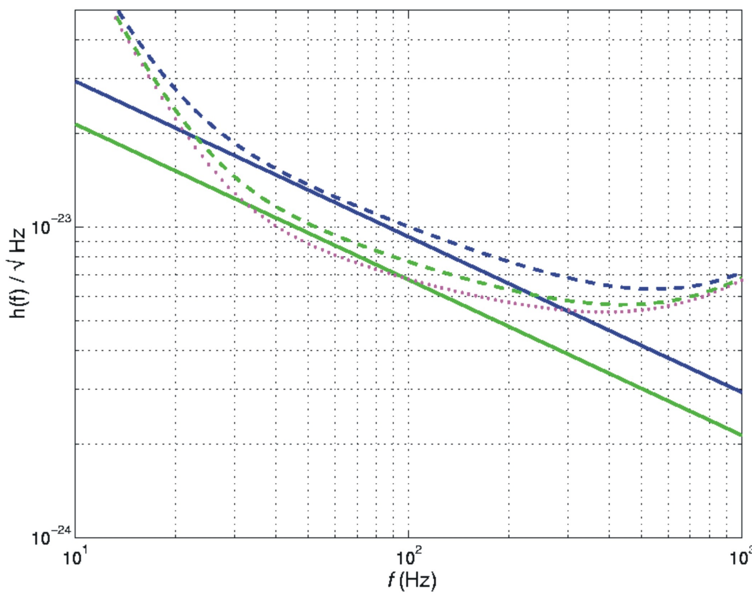
Still needed …

- **value for ϕ_{coat+}**
- **more complete accounting for coating anisotropy** ***(could have similar problem/solution in sapphire)***
- **accounting for finite size of mirrors**

Implications for Advanced LIGO



sapphire mirrors



fused silica mirrors

- Comparison of $\phi_{coat} = 1 \times 10^{-4}$ and $\phi_{coat} = 4 \times 10^{-4}$
- 5.5 cm beam spot, 30 kg masses

Goals

- How large can ϕ_{coat} be without affecting the astronomical reach of advanced LIGO?
- Choose reduction of 5 Mpc for BNS as limit
- Fused silica mirrors $\phi_{coat} < 3 \times 10^{-5}$
  Sapphire mirrors $\phi_{coat} < 1 \times 10^{-5}$
- How realistic is this? (*while maintaining low optical loss*)