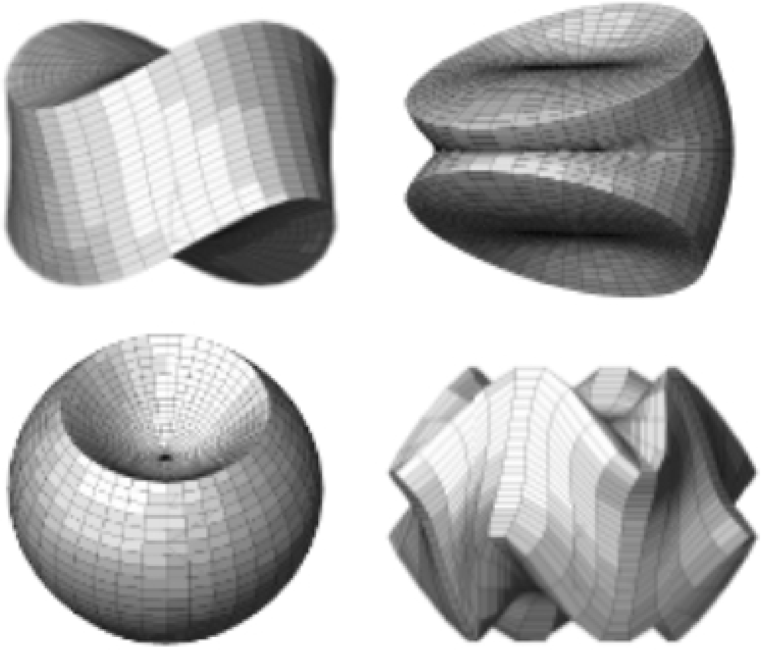
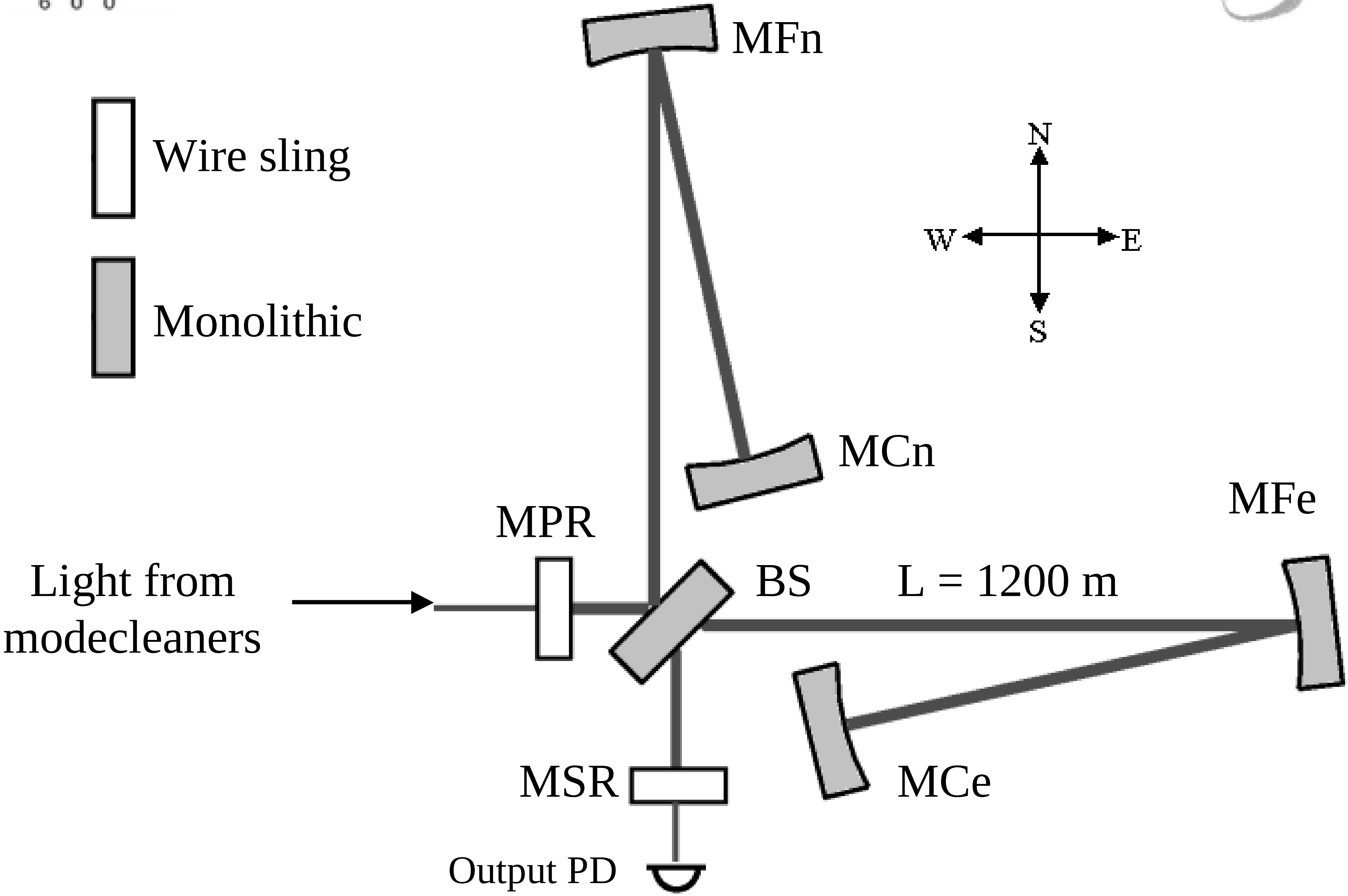
Internal Mode Qs of Monolithically Suspended Test Masses in GEO600



Joshua Smith, Harald Lück, Stefan Goßler, Gianpietro Cagnoli, David Crooks, Sheila Rowan, Jim Hough and Karsten Danzman

LIGO-G030473-00-Z

Simplified GEO600 Optical Layout



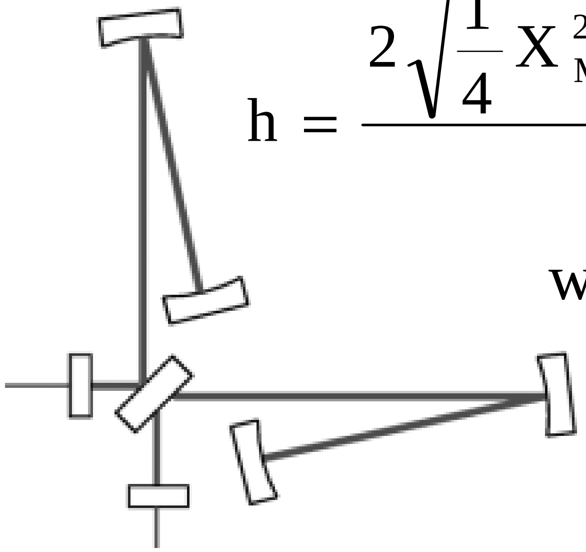
Mirror Contributions to Strain

For GEO we have:

$$h = \frac{2\Delta L}{L}$$

Where L is arm length (1200 m) and 2👎L is the differential arm length change.

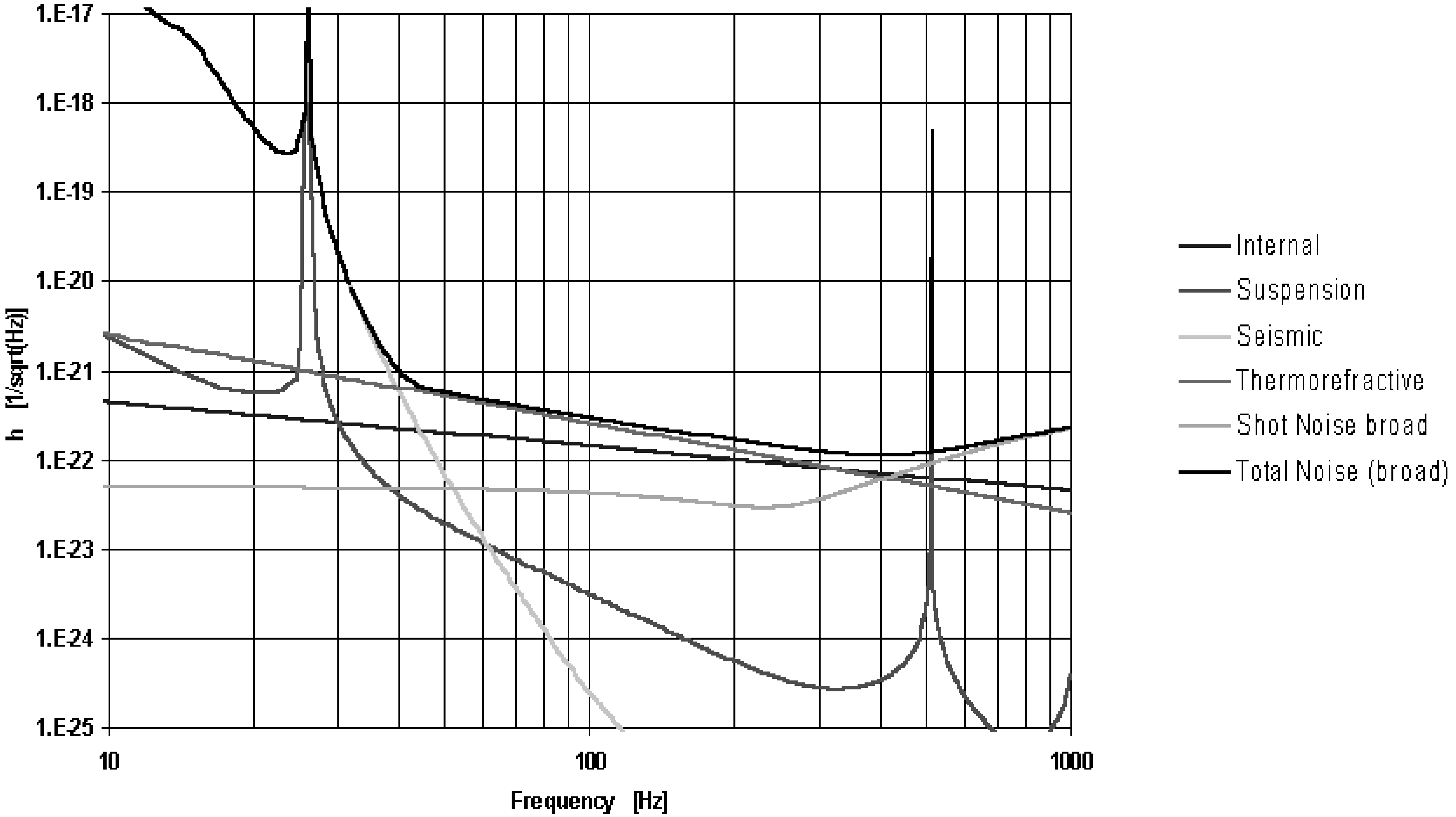
Considering contributions from each test mass:



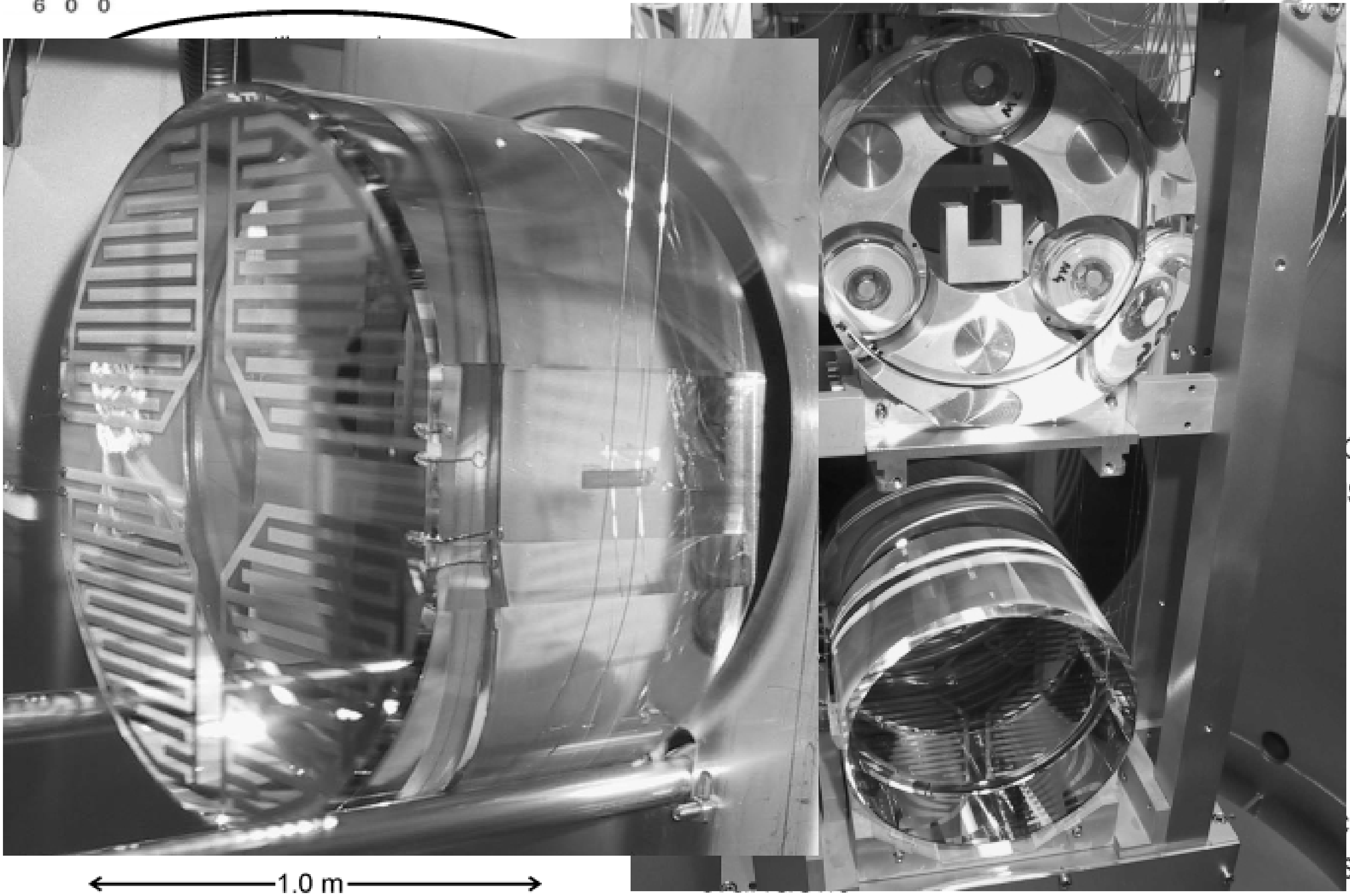
$$h = \frac{2\sqrt{\frac{1}{4}X_{MCn}^{2} + \frac{1}{4}X_{MCe}^{2} + X_{MFn}^{2} + X_{MFe}^{2} + \frac{1}{2}X_{BS}^{2}}}{L}$$

where X is mirror motion in m.

Theoretical Noise Curves (Broadband)



Monolithic Suspensions



ca
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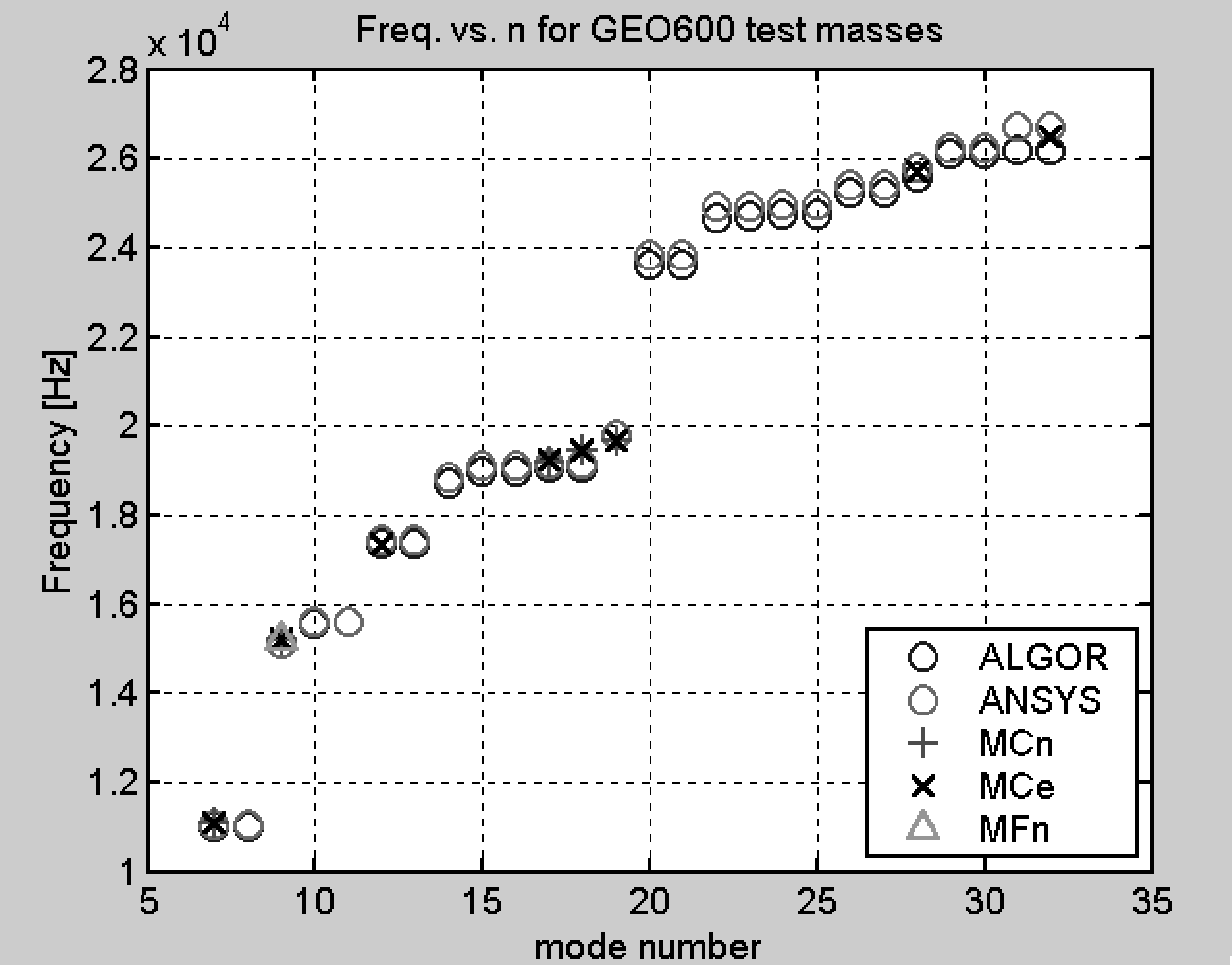
Internal Modes



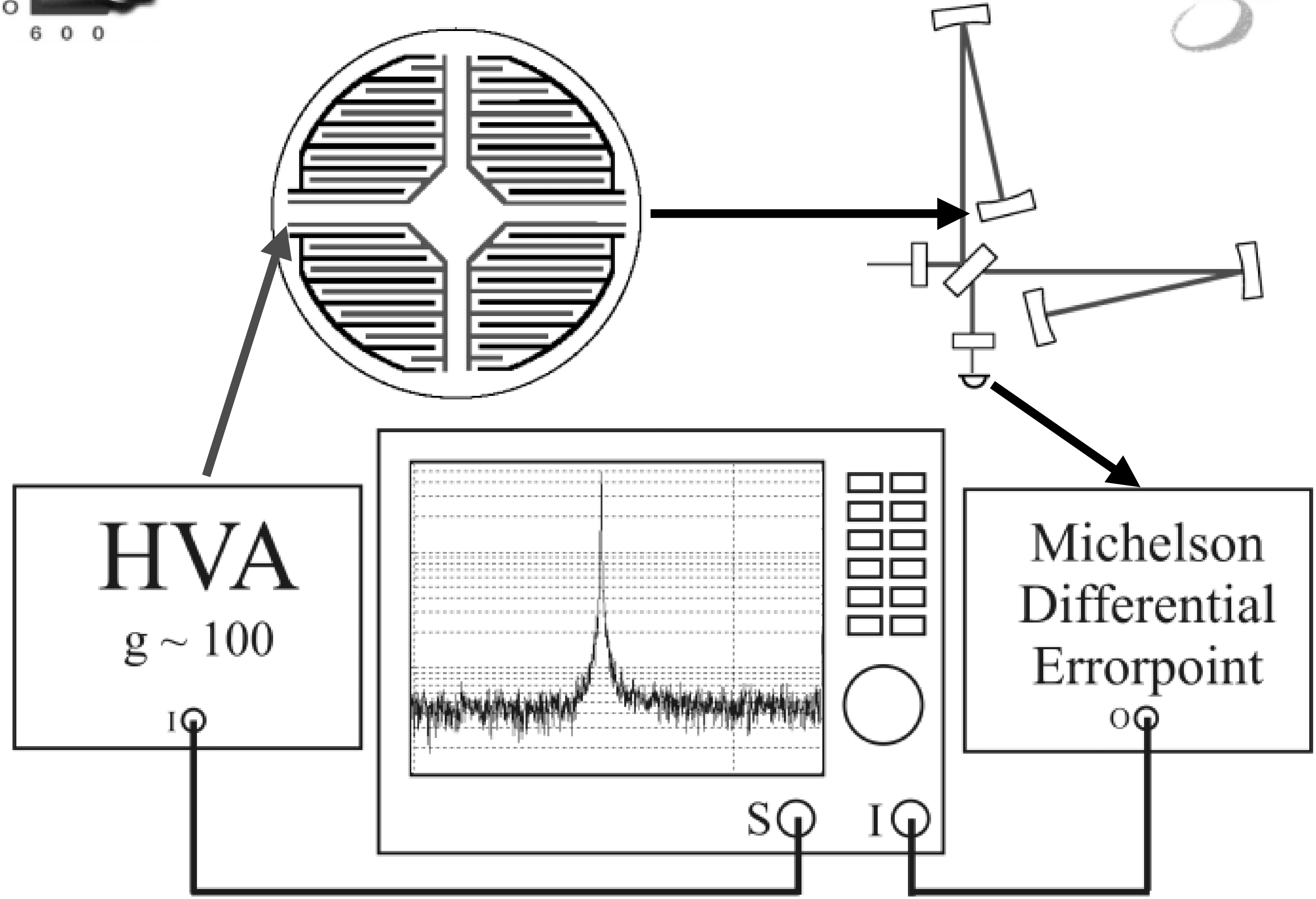
- Mode shapes, freq’s determined using ALGOR. Cross-checked using ANSYS (Jena).

See poster: A. Zimmer, S. Nietzsche, W. Vodel, M. Thürk, F. Schmidl, P. Seidel "FE analysis of the structural dynamics of mirror substrates"

- Agreement between calculated and measured frequencies ~ 0.1 to 1 %. (ANSYS and ALGOR), that’s ~ 10 to 100 Hz

- More precision not expected as models without flats, standoffs

Measurements

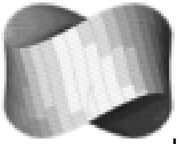
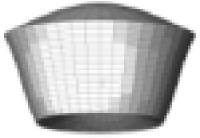
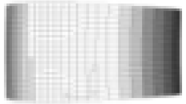
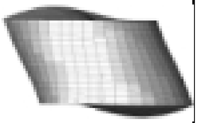
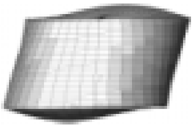
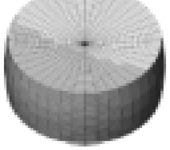
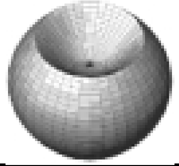
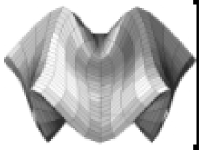


HVA

$g \sim 100$

Michelson Differential Errorpoint

Q Results

mode:	7	9	12	17	18	19	28	32
shape:								
kHz	11.1	15.2	17.4	19.2	19.4	19.7	25.7	26.5
MCe	3.8	0.5	1.2	0.4	3.4	0.4	1.0	0.1
MCn	0.4	0.9		0.6	1.8	0.7		
MFn		1.9						

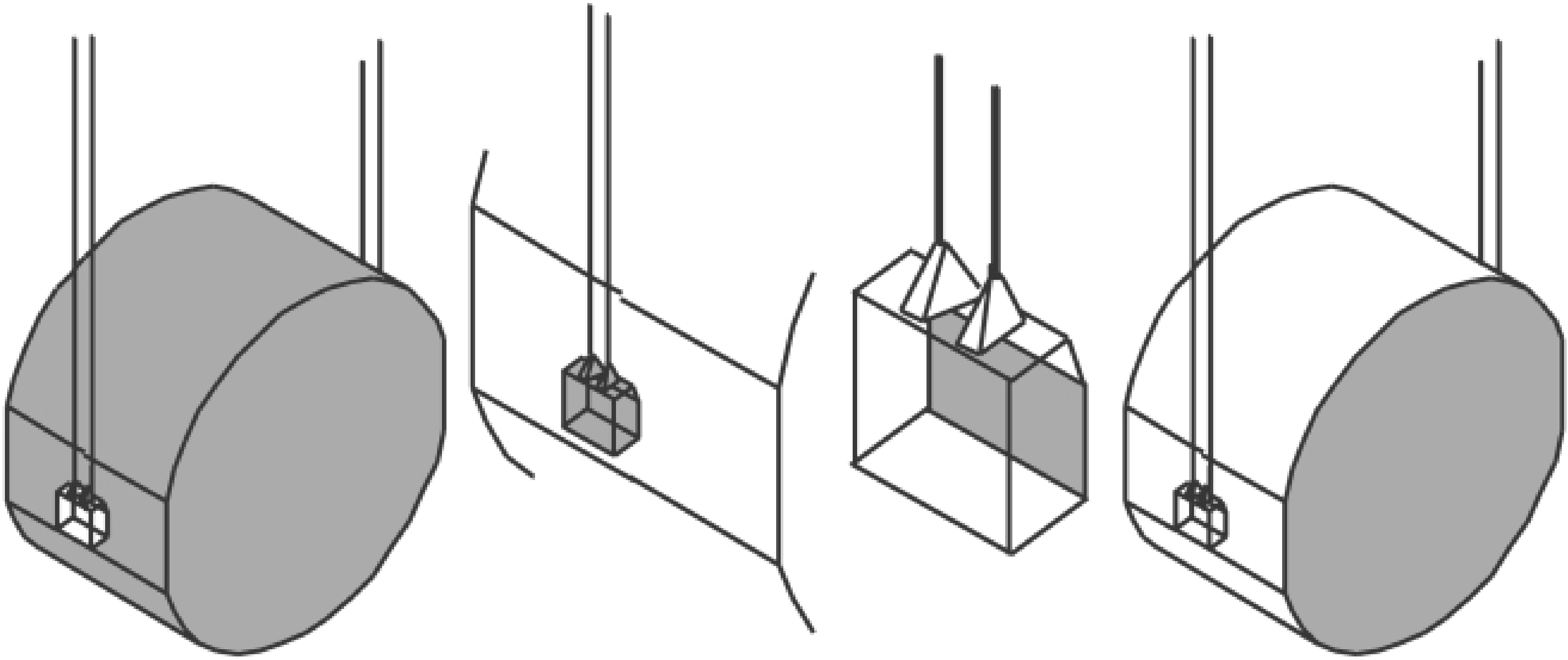
All Qs are in millions

$Q_{max} = 3.8 \times 10^6$

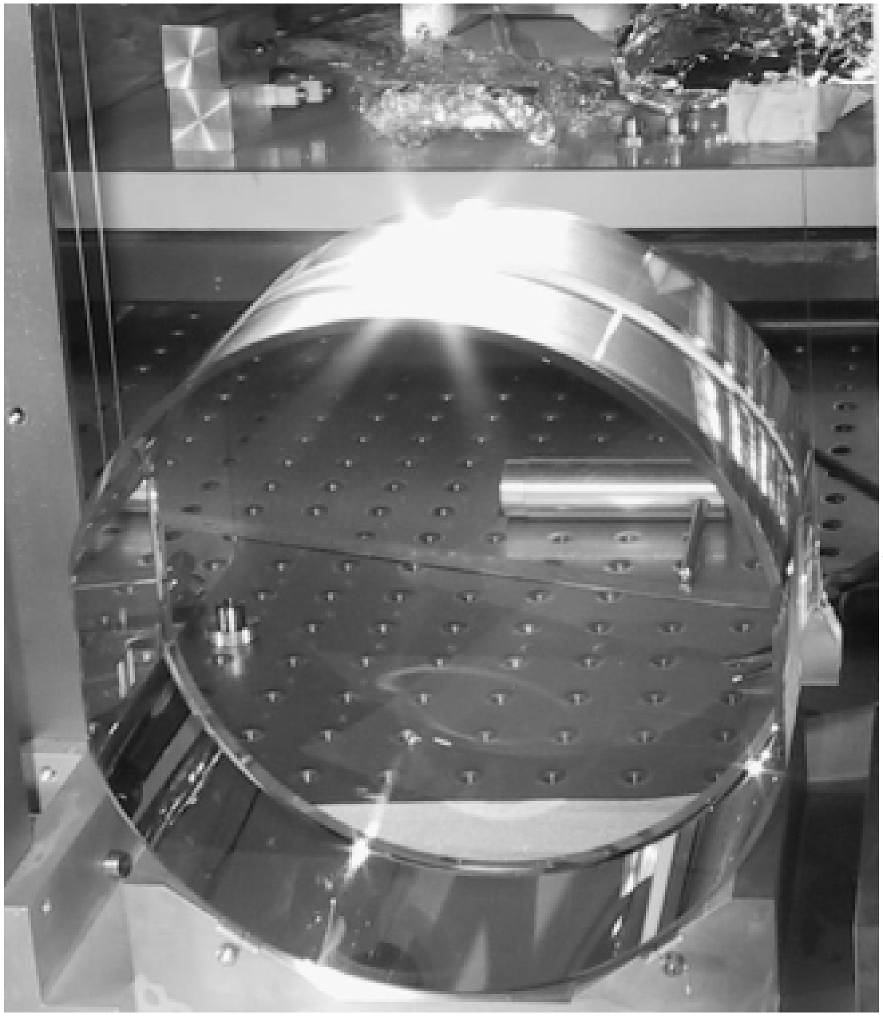
Test Mass Internal Losses

Loss of a GEO test mass for a given mode can be expressed as a sum of the effective losses (loss factors scaled by energy ratios) of its constituent materials:

$$\phi_{\mathrm{eff}} = \phi_{\mathrm{bulk}} \frac{E_{\mathrm{bulk}}}{E_{\mathrm{total}}} + \phi_{\mathrm{standoff}} \frac{E_{\mathrm{standoffs}}}{E_{\mathrm{total}}} + \phi_{\mathrm{bond}} \frac{E_{\mathrm{bonds}}}{E_{\mathrm{total}}} + \phi_{\mathrm{coating}} \frac{E_{\mathrm{coating}}}{E_{\mathrm{total}}} + \ldots$$



Bulk Effective Loss: ϕ_{effbulk}

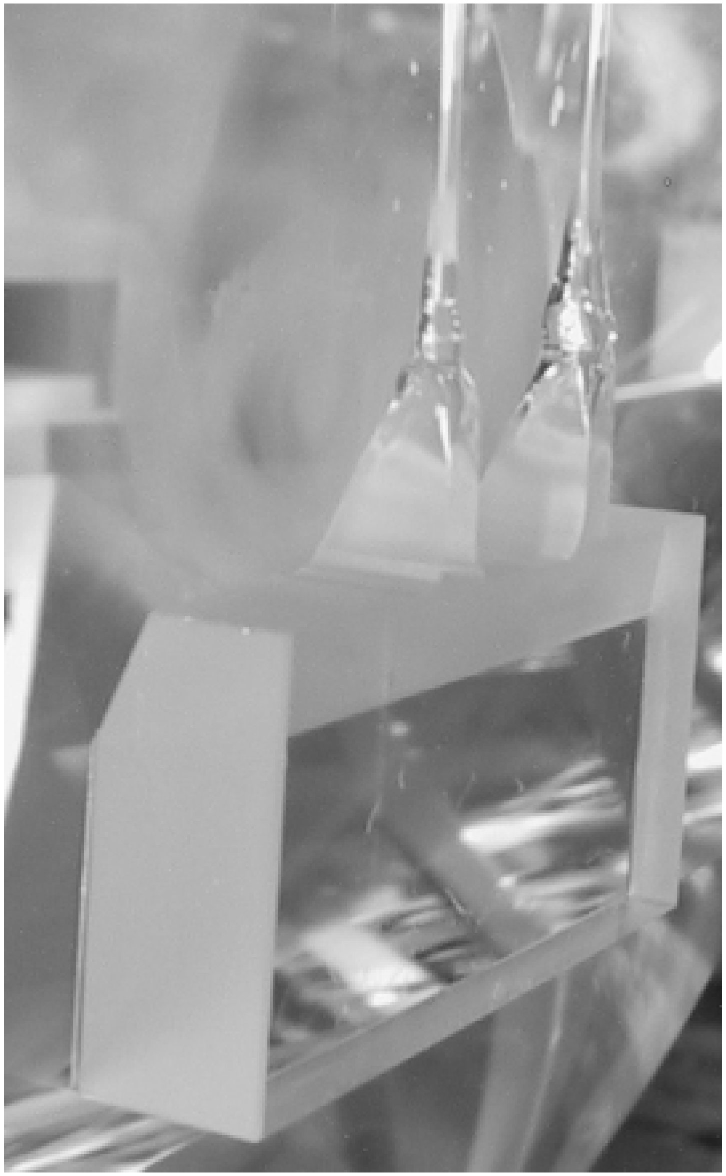


$$\phi_{\text{effbulk}} = \phi_{\text{bulk}} \frac{E_{\text{bulk}}}{E_{\text{total}}} \cong \phi_{\text{bulk}}$$

- $\phi_{\text{bulk}} \approx 2\text{x}10^{-8}$ (Penn et al)
- $\phi_{\text{standoff}} \approx \phi_{\text{bulk}}$, while $E_{\text{standoffs}} \ll E_{\text{bulk}}$, so loss from standoffs is negligible.

$$\boxed{\boldsymbol{\phi_{\text{effbulk}} + \phi_{\text{effstandoffs}} \approx 2\text{x}10^{-8}}}$$

Effective Loss of the Bonds: ϕ_{effbonds}



$$\begin{aligned}\phi_{\text{effbonds}} &= \phi_{\text{bond}} \frac{E_{\text{bonds}}}{E_{\text{total}}} \\ &\cong \phi_{\text{bond}} \frac{V_{\text{bonds}}}{V_{\text{total}}} \\ &\cong \phi_{\text{bonds}} \frac{2\, A_{\text{bond}}\, t_{\text{bond}}}{\pi r^2 t}\end{aligned}$$

Measurements of other GEO-like bonds:
(Sodium silicate bond sol’n containing SiO_2)

- ϕ_{bond} = 1.8×10^{-1} to 5.4×10^{-1} (Glasgow)
- t_{bond} = 81 nm (Glasgow)

These Give:

$\phi_{\text{effbonds}} \approx 3.4 \times 10^{-9}$ to 1.0×10^{-8}

Effective Loss of the Coating: ♐$_{\text{effcoating}}$

$$\phi_{\text{effcoating}} = \phi_{\text{coating}} \frac{E_{\text{coating}}}{E_{\text{total}}}$$

$$\cong \phi_{\text{coating}} \frac{V_{\text{bonds}}}{V_{\text{total}}}$$

$$\cong \phi_{\text{coating}} \frac{t_{\text{coating}}}{t}$$

GEO test mass coatings:

- 30 layers of silica/tantala ●/4: ●/4
- t_{coating} = 4.3 ❍m (Penn et al)
- ♐$_{\text{coating}}$ = 2.8x10^{-4} (Crooks et al)

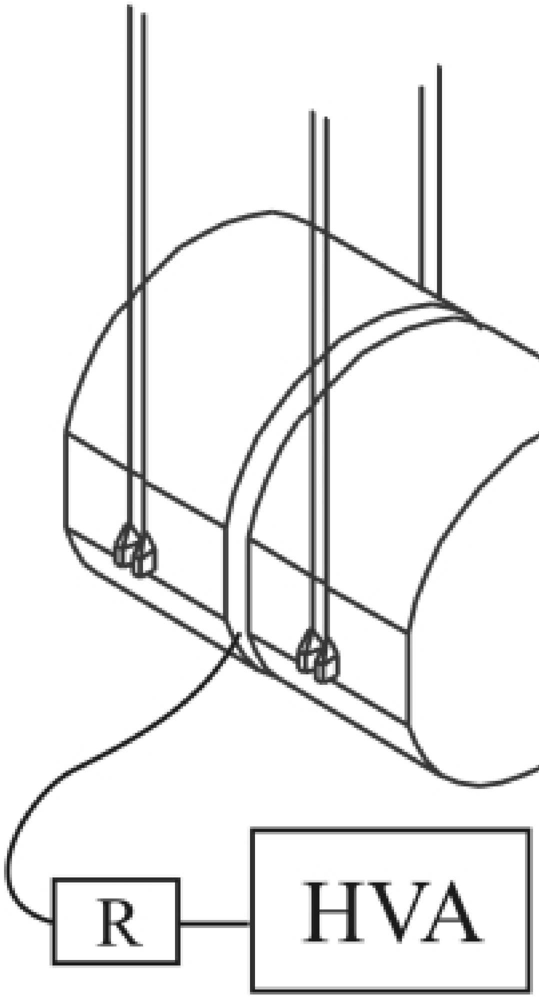
This gives:

♐$_{\text{effcoating}}$ ✍ 1.2x10^{-8}

FEA for BF and drum modes (Crooks):

♐$_{\text{effcoating}}$ ✍ 5x10^{-8}

ESD Damping



👎 d → 👎 C → I → dissipation in real impedance (R) (Mitrofanov, Strain)

With 40 k⌖ output resistor, for f > 10 kHz,

$$\boxed{\mathbf{Q_{ESD} \sim 10^{9}}}$$

Feedback from control loop also negligible as UGF ~ 100 Hz

Loss Conclusions

♐$_{\mathrm{eff}}$ = ♐$_{\mathrm{effbulk}}$ + ♐$_{\mathrm{effstandoffs}}$ + ♐$_{\mathrm{effbonds}}$ + ♐$_{\mathrm{effcoating}}$ ✍ **4x10^{-8}**

Q$_{\mathrm{eff}}$ ✍ 2x10^{7}

- **Measured Qs cannot be entirely explained by loss of TM constituent materials.**

- **Energy distribution will not be uniform, will vary mode to mode**

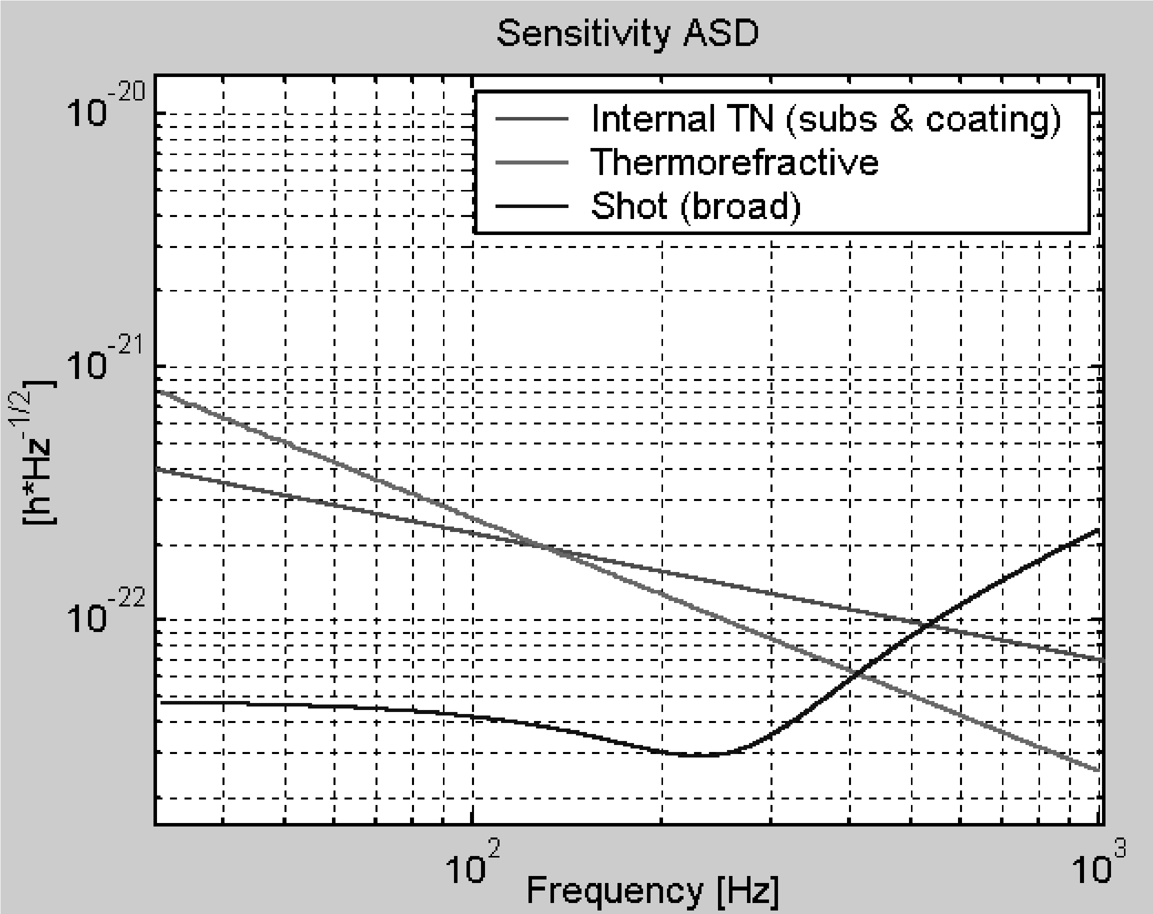
- **Does not take surface loss from barrel polish or back surface polish into account (but should be < coating).**

- **Could also be non-negligible energy lost to intermediate mass**

- **Erratic Qs suggest energy dissipated in fibers (Logan et al, Braginsky et al)**

- **This should not degrade TN away from violin modes (Logan et al)**

Thermal Noise Calculations



- **Use corrected Levin method (Liu, Thorne, Nakagawa)**
- **Take inverse Q_{max} as upper limit for substrate loss for each mirror.**
- **Use measured beam radius for each mirror: (1 to 2 cm (E_0/e^2)).**
- **Model coating as thin surface layer (Nakagawa et al) with:**
- **$t_{coating} = 4.3\mu m$**
- **$\phi_{coating} = 2.8 \times 10^{-4}$**
- **at 100 Hz we have**

$$h_{int} \approx 2.2 \times 10^{-22}\ [\mathrm{Hz}^{-1/2}]$$

Summary

- **calculations represent a preliminary estimate based on measured values (Q, r_0)**
- **measured Qs only lower limits**
- **not all mirrors measured (BS, MFe)**
- **FEA needed for more precise calculations:**

Allows to apply Levin Pressure directly, calculate energy ratios in each volume use these to scale measured loss factors to determine TN

- **GEO should reach internal thermal noise for narrowband operation above 300 Hz (thermorefractive noise slightly higher at lower f's)**
- **Await measurements from the interferometer !**