LIGO

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LSC

Coating Research at Sannio - Status

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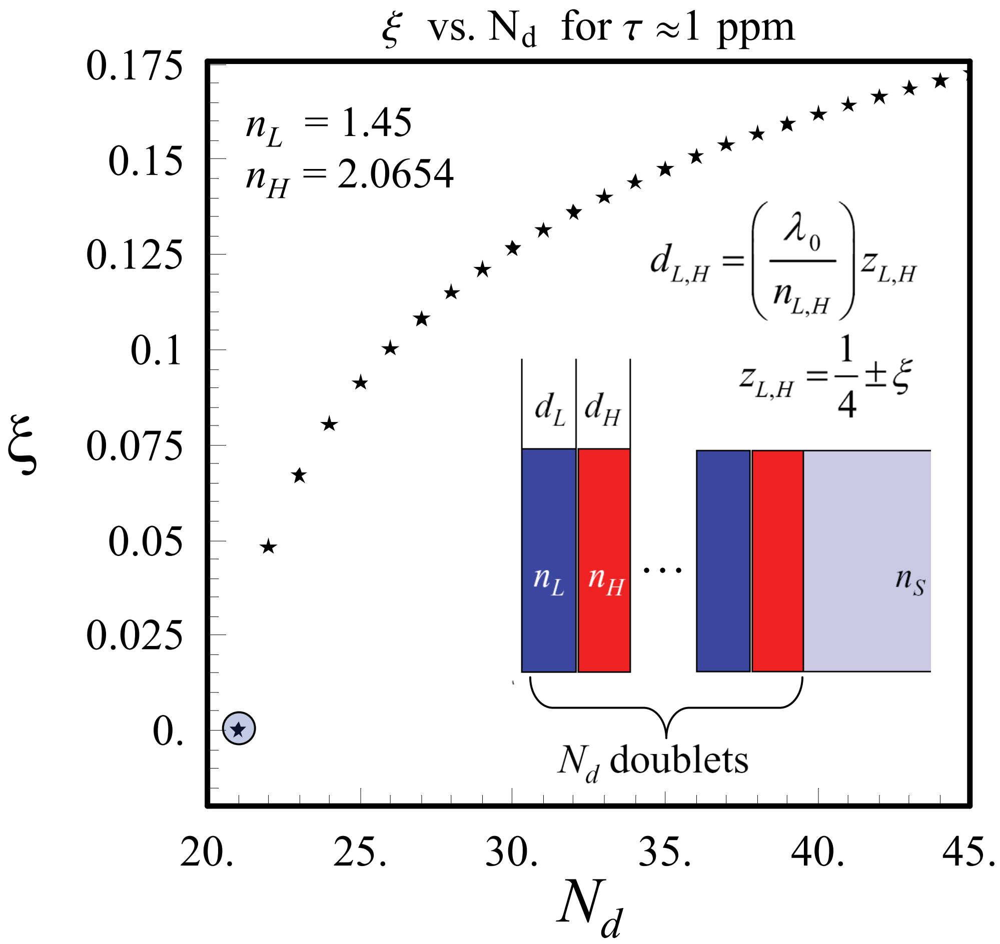
Outlook

- Status of Coating Optimization
  - Full Noise Budget – Doped Tantala
  - Plain Tantala Prototypes
  - Ongoing Work
- Beam Profile Optimization
  - Absolute/Realistic Bounds - Margins

Work done in cooperation with J. Agresti, R. De Salvo, E .Black (Caltech) within the LSC-OWG and Coating Groups.

Isoreflective Coatings



For

$$n_L = 1.45$$
$$n_H = 2.0654$$

the QWL (ξ=0) design which goes closest to the 1ppm Adv LIGO design goal has

$$N_D = 21$$
$$\tau = 0.9727 \text{ ppm}$$

Coating Brownian Noise

Boltzmann

Poisson ratio

Coating loss angle

$$S^{(B)}_{\Delta x}(f) = \frac{\sqrt{2} k_B T}{\pi^{3/2} f} \frac{(1-\nu_s^2)}{r_0 E_s} \phi_c \quad , \qquad \phi_c = N_d (b_L z_L + b_H z_H)$$

Beam spot radius

Young modulus

coating materials loss angles

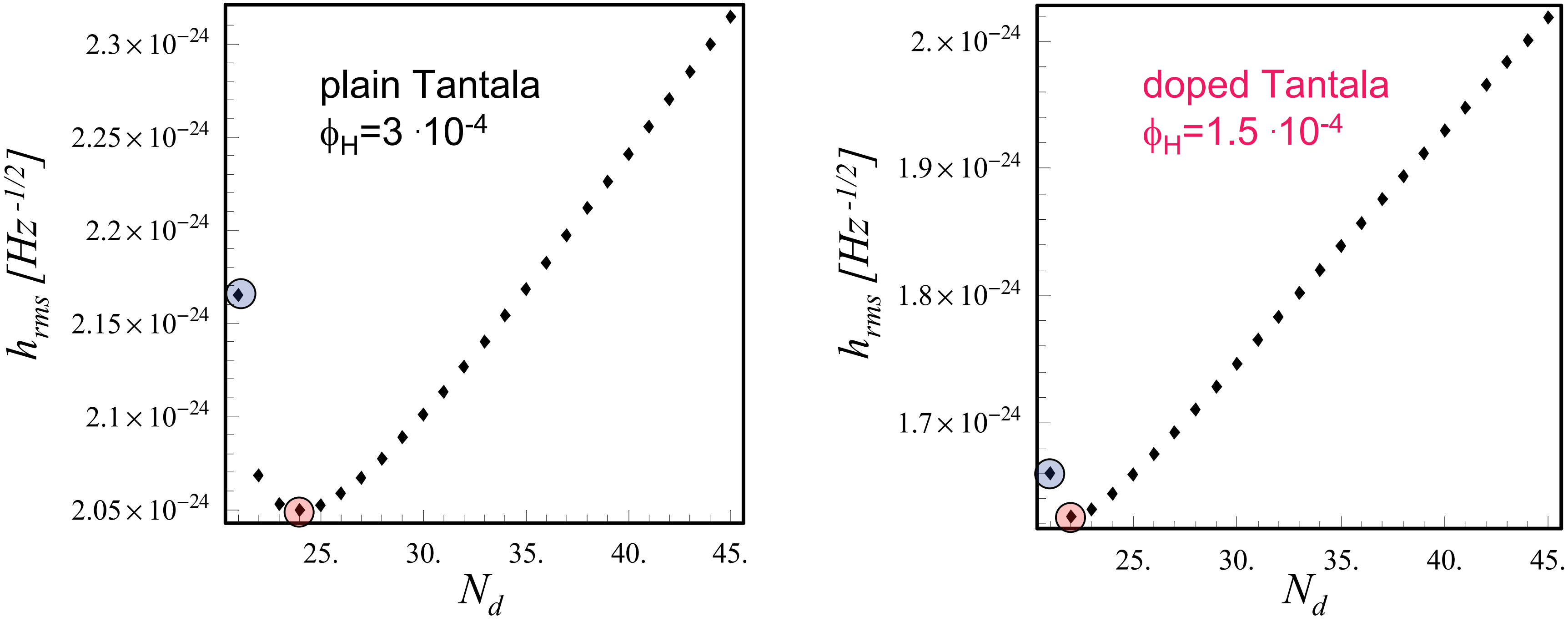
$$b_{L,H} \approx \frac{\lambda_0}{\sqrt{2\pi} r_0} \frac{\phi_{L,H}}{n_{L,H}} \left(\frac{E_{L,H}}{E_s} + \frac{E_s}{E_{L,H}} \right) \qquad \nu_{L,H} \ll 1$$

$b_H / b_L = 5.149$ [Tantala (plain) – Silica coatings]

Minimum Noise Design, Brownian Noise Only

Brownian Noise Only. τ = 0.9727ppm, f = 100Hz

○ QWL coating ○ Optimized coating



Thermal Fluctuations of Test Mass Face Position

Effective fluctuations of the test-mass (coated mirror) front - face position with respect to the mirror center of mass may occur as an effect of

-Thermal expansion of the coating layers (thermoelastic effect),

$$\Delta x^{(TE)} = \alpha_{eff} d_{tot} \Delta T$$

effective coating expansion coeff.

coating thickness

-Thermal variations of the refraction indexes $n_{H,L}$ of the coating materials (thermorefractive effect),

$$\Delta x^{(TR)} = \beta_{eff} \lambda_0 \Delta T$$

thermorefractive coefficient

optical wavelength (vacuum)

Temperature Fluctuation Driven Displacement Noises

Power spectral density (PSD) :

Wiener-Khinchin th.

$$S_{\Delta x}(f) = \mathcal{F}_{\tau \to f} \langle \Delta x(t) \Delta x(t+\tau) \rangle_t = \left(\frac{\Delta x}{\Delta T} \right)^2 \mathcal{F}_{\tau \to f} \langle \Delta T(t) \Delta T(t+\tau) \rangle_t =$$

$$= \left(\frac{\Delta x}{\Delta T} \right)^2 S_{\Delta T}(f)$$

PSD of T - fluctuations
in the coating

$$S_{\Delta T}(f) = S_{\Delta T}^{(\Theta)}(f) + S_{\Delta T}^{(\Phi)}(f)$$

Intrinsic fluctuations of
thermodynamic origin

add
in-coherently

Photo-thermal fluctuactions
arising from laser shot noise
through optical absorption

Temperature Fluctuations in the Coating

$$S_{\Delta T}^{(\Theta)}(f) = \frac{k_B T^2}{\pi^{3/2} r_0^2 \sqrt{f \kappa_s C_s \rho_s}}$$

[V. Braginsky, Phys. Lett A264 (1999) 1]

mass density
specific heat capacity
thermal conducivity
} of substrate

single photon energy
power abs. in coating

$$S_{\Delta T}^{(\Phi)}(f) = \frac{P_{\mathrm{abs}} E_\lambda}{4\pi^3 r_0^4 \kappa_s \rho_s C_s f}$$

[S. Rao, PhD Thesis, Caltech, 2003, etd-05092003-153759]

$E_\lambda \cong 1.867 \cdot 10^{-19} J \; @ \; \lambda = 1064 nm$

$P_{abs} = 0.4\, W$ for Adv LIGO

(a *different* formula for $S_{\Delta T}^{(\Phi)}$ applies for sapphire substrates)

Coating Thermal Noise Budget

Total Coating Noise PSD

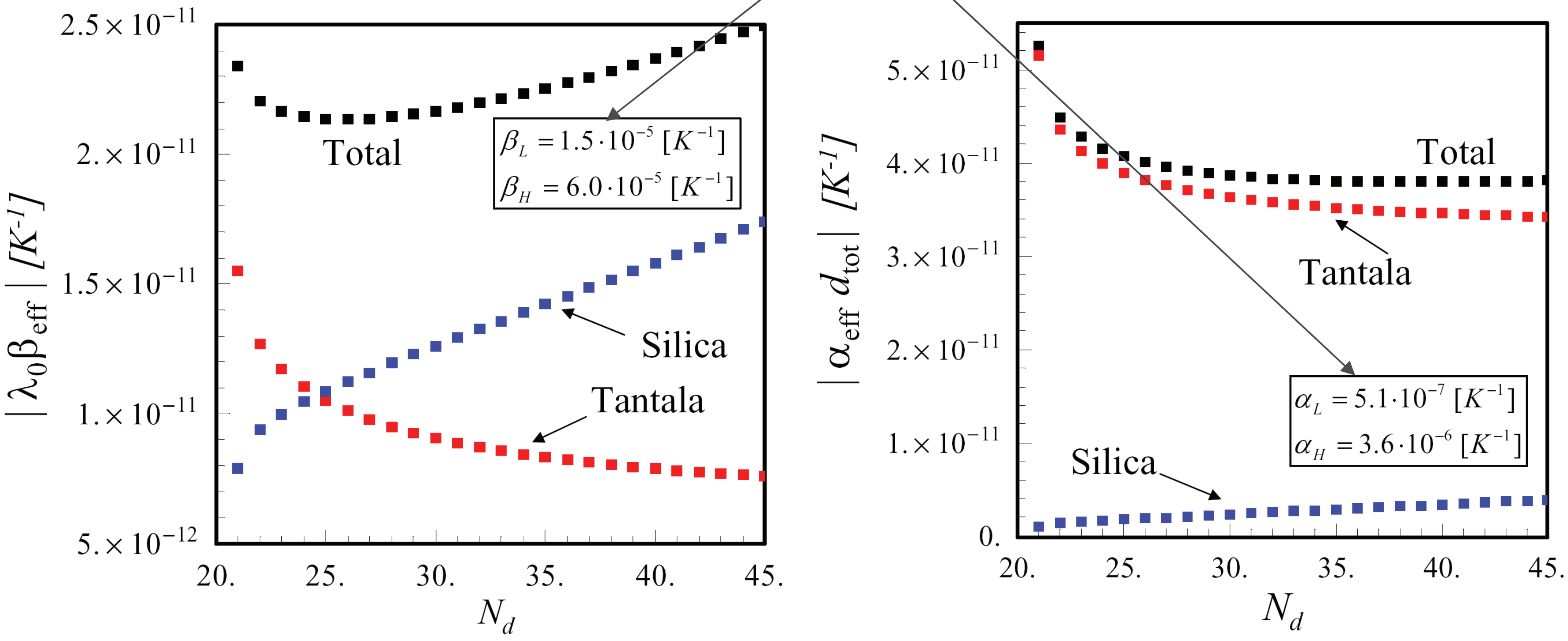
$$S^{(tot)}_{\Delta x}(f) = S^{(B)}_{\Delta x}(f) + \left(\frac{\Delta x^{(TE)}}{\Delta T} + \frac{\Delta x^{(TR)}}{\Delta T} \right)^2 S_{\Delta T}(f)$$

The thermal - driven elastic and refractive fluctuations *should add coherently .* Indeed, the temperature in the coating does *not* fluctuate

- on the space-scale (thickness) of the coating,
- on the time scales whereby the field in the coating builds up.

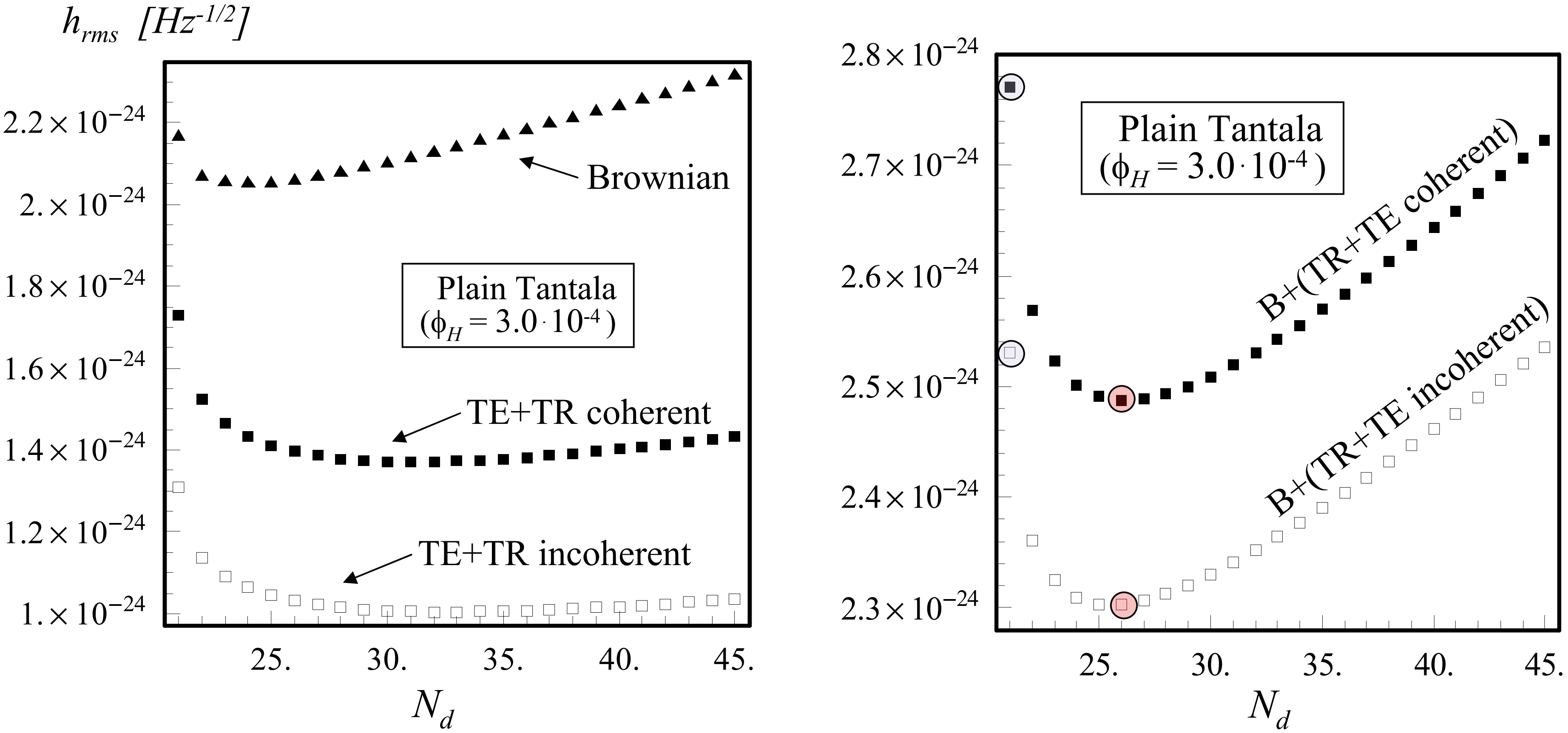
Thermo-Optic Noise Coefficients

Gretarsson values



Coating Noise Budget Plain Tantala

$\tau = 0.9727\text{ppm}, \; f = 100\text{Hz}$



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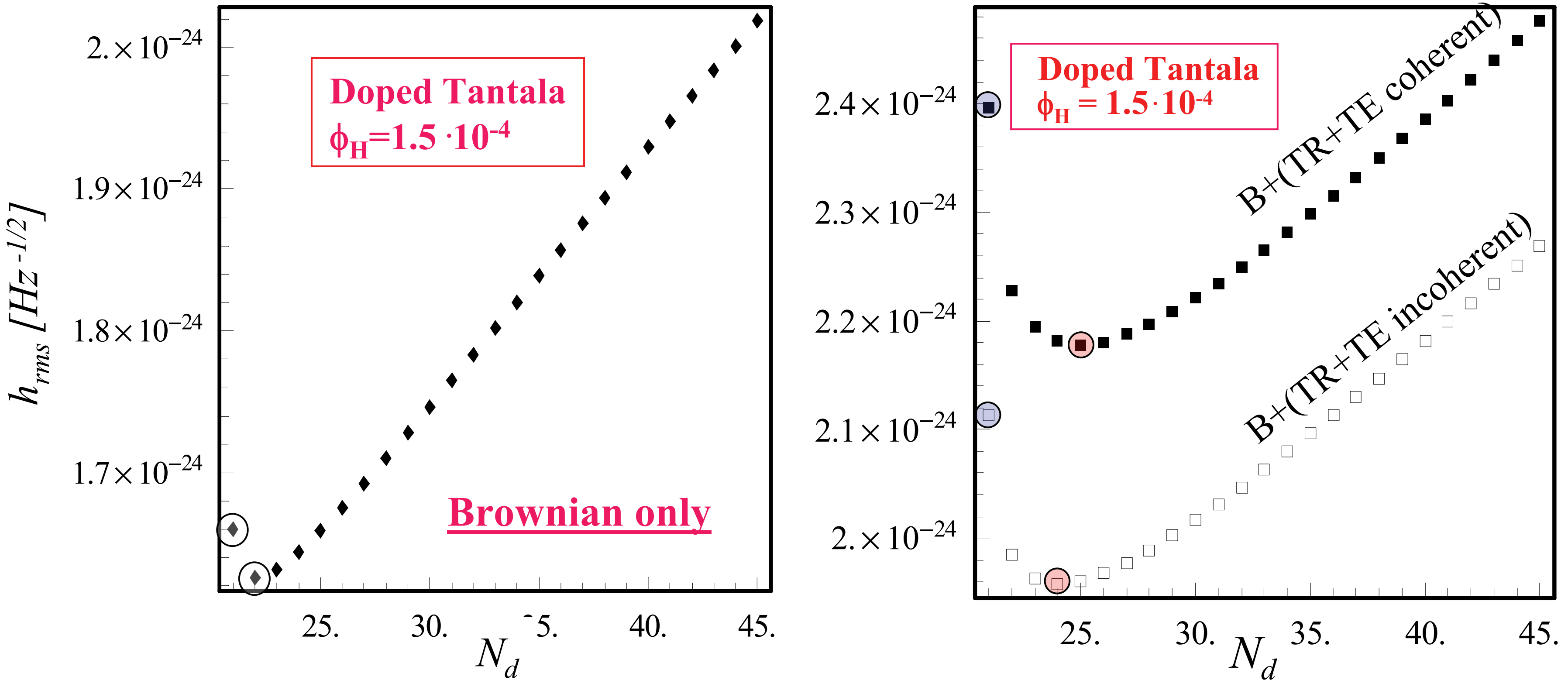
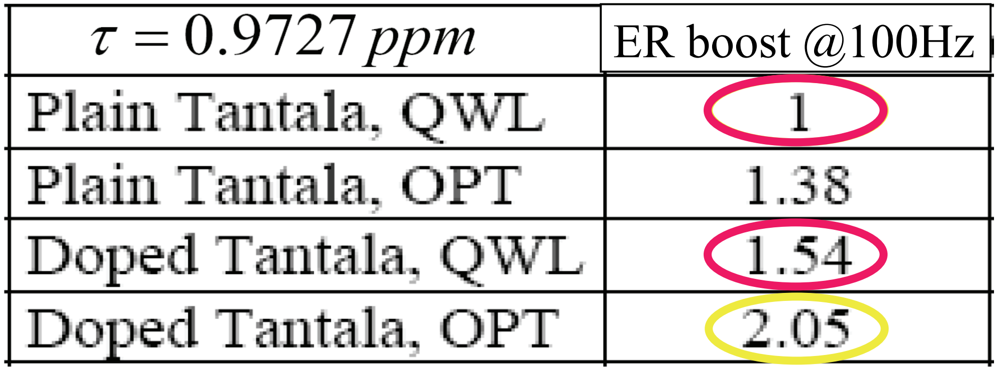
Non-Brownian vs Brownian Coating Noise Components TiO_2 - Doped Tantala

$\tau = 0.9727\text{ppm}, \; f = 100\text{Hz}$



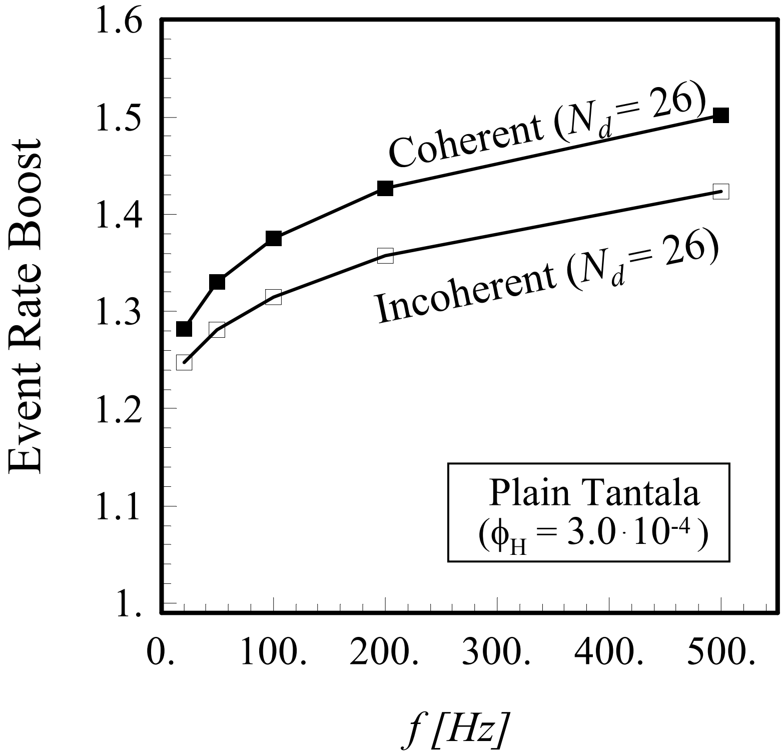
Event Rate Boost (Isotropic/Homogeneous Source Distribution)

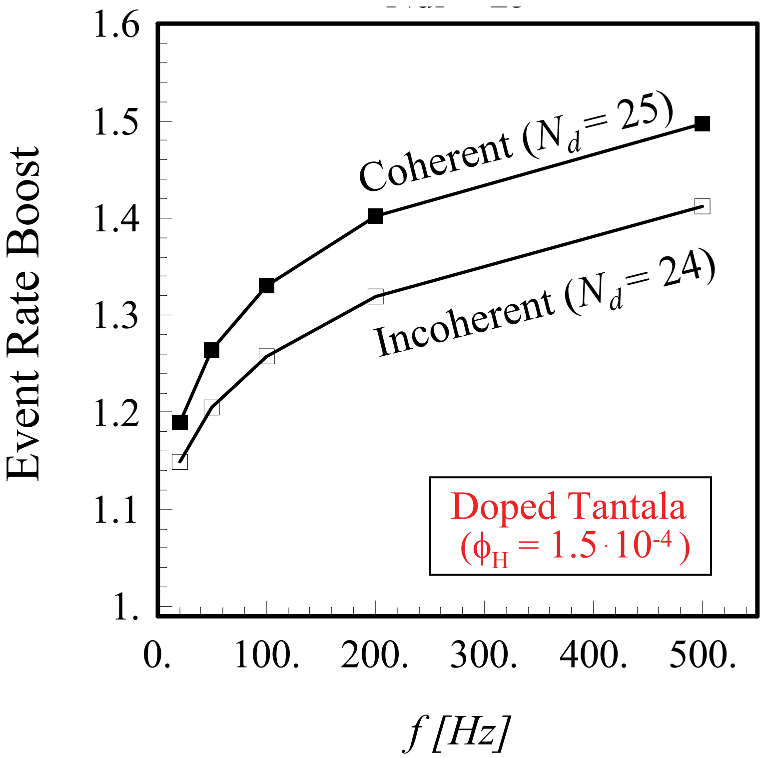
(Total Noise Budget))



$\tau = 0.9727\, ppm$	ER boost @100Hz
Plain Tantala, QWL	1
Plain Tantala, OPT	1.38
Doped Tantala, QWL	1.54
Doped Tantala, OPT	2.05

Optimized Coatings
Event Rate Boost vs. f



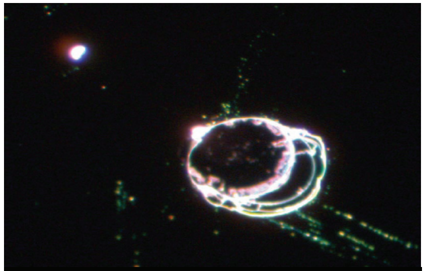


Summary (Technical)

- Coating thickness optimization *almost mandatory* to minimize coating noise when using doped Tantala, yielding a substantial increase (> 30%@ 100Hz) in the expected event rate, as compared to QWL design.
- Optimal design *almost the same for both* the incoherent and the coherent thermooptic noise formula.
- Among all proposed coating noise reduction techniques (new materials, cryogenic mirrors, flat-top beams) thickness optimization is the *cheapest option*
- Coating thickness optimization is *effective* in reducing the total coating noise even when using the controversial Inci's values for α_H, β_H.

Prototypes

- Plain Tantala optimized coatings for testing at TNI designed Nov. 2006;
- Delivery of prototypes delayed by (Ar) bubbling problem at LMA, causing high-scattering and non adhesivity. Same problem also affected (though to a lesser extent) the $\lambda/4$ LASTI mirror prototypes made at LMA;



dark field microscope 10x, FOV = 0.85mm; $\varnothing \approx 0.2$mm

- Bubbling problem eventually fixed using different (lower T) annealing schedule; prototypes tested at LMA within specs; delivered to Caltech July 2007;
- TNI re-installed in a new location; TNI re-alignment completed; a few problems fixed; testing will become soon (see Eric Black's talk);
- SiO_2 and Ta_20_5 and loss angles used in design obtained from (cantilever) samples made using a *different* annealing schedule. This may affect the final result.

Ongoing Work

- MATHEMATICA code for (stacked-doublet, tweaked end-layers) coating optimization including full noise budget completed (May 2007);
- Doped-Tantala prototyping for testing at TNI scheduled. Reliable measurements of thermoelastic and thermorefractive coeffs of proposed doped-Tantala formulas needed for design (plain Tantala results used so far);
- Porting of code to BENCH (Matlab) scheduled (TBD asap);
- Three technical papers completed (coating optimization; extension of Braginsky's formula for the thermorefractive coefficient to non-QWL coatings; analytic model for loss angle measurements on multi-layer clamped diving-board samples) will be posted on the LSC web soon;
- More general design options (dual wavelength operation, using more than two refracting materials) under investigation.

Beam Optimization Margins

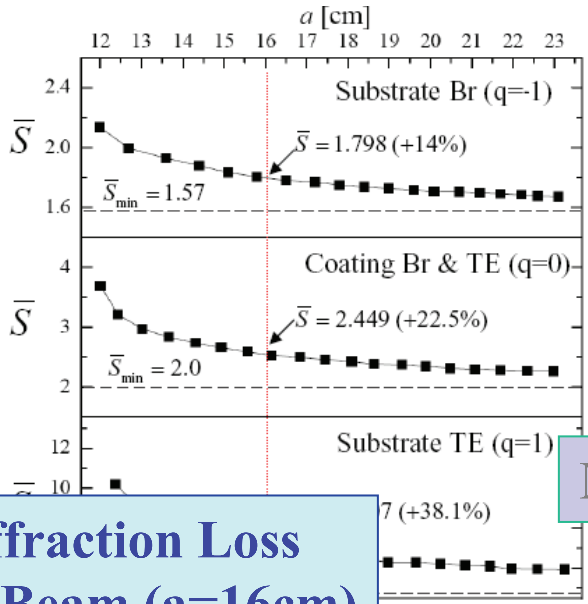
- Main results:

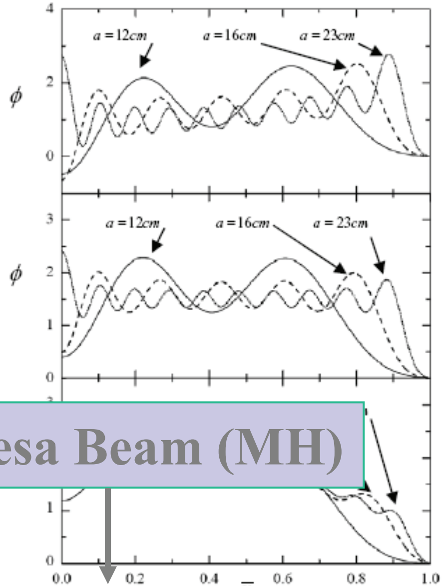
  - Absolute (variational closed-form) lower bounds for coating & substrate noises under the (unphysical) 0-diffraction loss approximation;
  - Shannon dimension of the space of all diffraction-loss admissible fields no greater than $a^2/L\lambda$ (arm cavity Fresnel number),
  - Within the current Adv-LIGO baseline design ($a=16cm$), one could do better than mexican-hat by a factor ~ 2.6 (in terms of coating noise) while satisfying the 1ppm diffraction loss constraint.

- Consistent with independent results by Bondarescu & Chen on optimized mirror-shapes (Caltech, PhD thesis, 2007)

- Full paper (LIGO P-070066-01-Z) to appear on PRD (review process completed).

Beam Optimization Margins, contd.





Mesa Beam (MH)

Gaussian Beam

1ppm diffraction Loss compliant Beam (a=16cm)

number of modes = $N_T \approx N_D = 2a^2/\lambda L$

	$\bar{S}_{SLP}/\bar{S}_{\min}$	$\bar{S}_{MB}/\bar{S}_{\min}$	$\bar{S}_{GB}/\bar{S}_{\min}$
Substrate (Br)	1.145	2.044	2.97
Coating (Br+TE)	1.225	3.227	6.92
Substrate (TE)	1.381	4.455	13.66

$a = 16cm$ ($N_D = 14$) ; $\mathcal{L}_T = 1ppm$; $w_{MB} = (N_D)^{-1/2}$ (minimum spreading)

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