TNI: Current Status and Future Plans

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LIGO Executive Committee Meeting

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Current Objectives

Small, tightly-focused program to directly measure displacement noise arising from a variety of sources, most of which are thermal in origin.

- Brownian noise in coatings (Initial and Advanced LIGO)
- Evaluating new coating technologies for AdvLIGO
  - Doping
  - Optimized (aperiodic) structure
- Thermoelastic-damping noise in Sapphire substrates (Complete)
- Thermoelastic-damping noise in coatings
  - Photothermal experiment to measure relevant parameters
- Parametric Instabilities
  - Effect of ring dampers on the thermal noise floor
- Non-Gaussian noise
  - Bond-noise experiment
  - Direct measurement in the TNI to identify non-Gaussian noise in optics and suspensions

AdvLIGO noise floor requirement cannot be met with current state of the art in coatings.

Person-Power

- Faculty
  - Kenneth Libbrecht (part-time)
- Staff
  - Eric Black (1/3 FTE)
- Graduate Students
  - Akira Villar (Senior)
  - Greg Ogin (Junior)
  - Ilaria Taurasi (Visiting)
- Undergraduates
  - 2-4 SURF Students per year

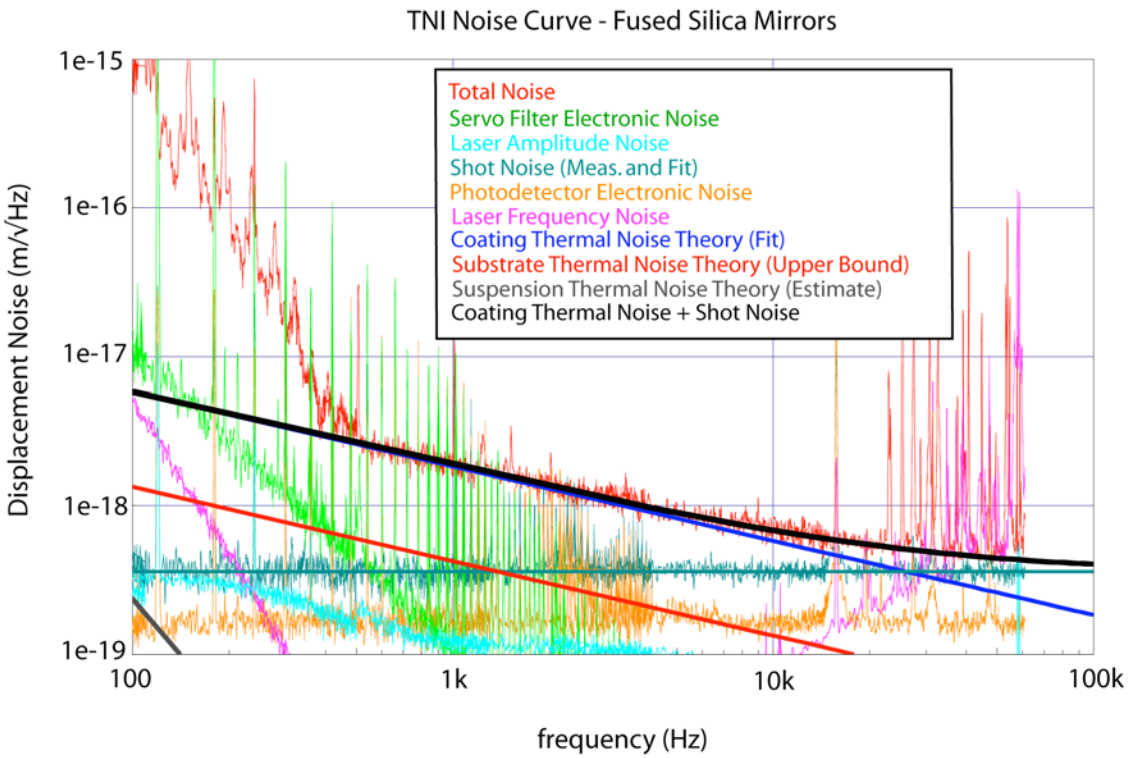
- Collaborators
  - Gregg Harry (MIT)
  - Andri Gretarsson (Embry-Riddle)
  - Innocenzo Pinto (Benevento)
  - Vincenzo Galdi (Benevento)
  - Dennis Coyne (Caltech)
  - Jay Heefner (Caltech)
  - Seiji Kawamura (Tokyo/TAMA)

- Alumni
  - Shanti Rao (graduated 2003)
  - Luca Matone (former postdoc)
  - Undergraduates: Casey Stevens, Matt Seaberg, Michael Goldman, Kate Dooley, Richard Kirian, Chinyere Nwabugwu, Jason Sussman, Michael Zhang, Adam Bushmaker, Kyle Barbary, Fumiko Kawazoe, Sharon Meidt, Ryan Gutenkunst, Kim Page, Sinead Quin, Sam Makonnen, Antal Gyori, Kaiwen Xu

Funding

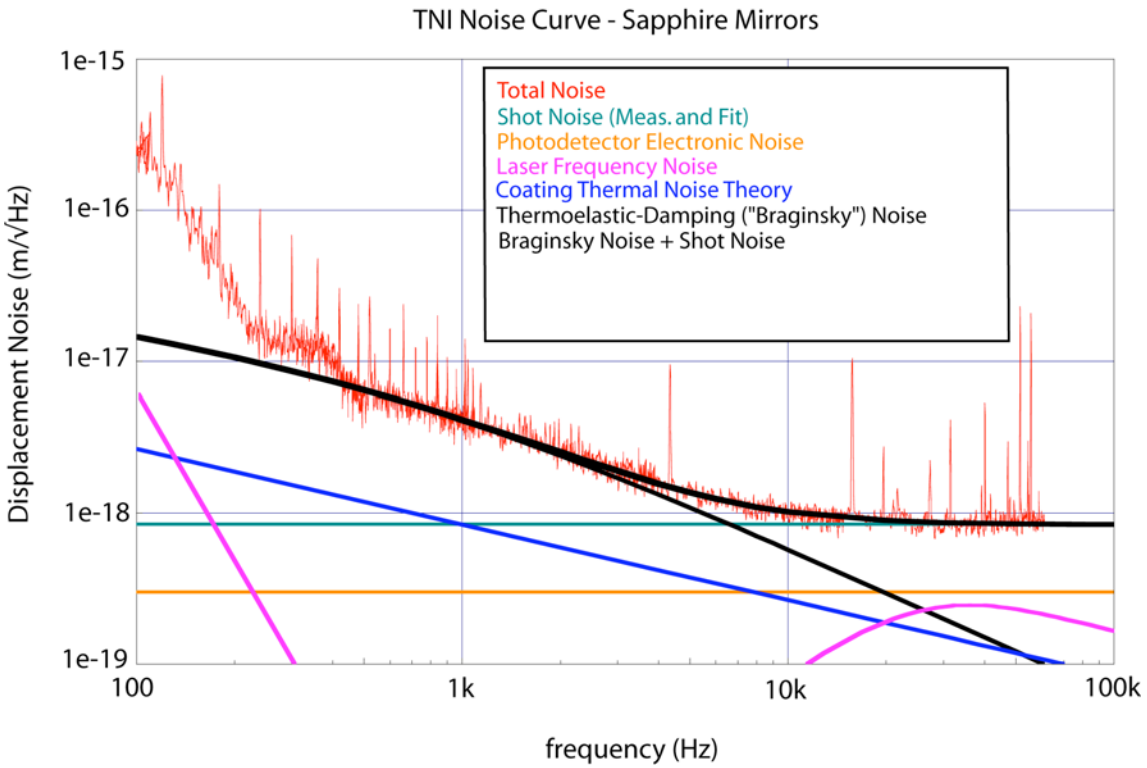
- Equipment:
  - 30k$/yr.
- Salaries:
  - 1/6 FTE faculty
  - 1/3 FTE staff
  - 2 Caltech grad students
  - 1 visiting grad student
  - Much work done by SURF students, REU funding

Results 1: Thermal Noise in Initial-LIGO Coatings



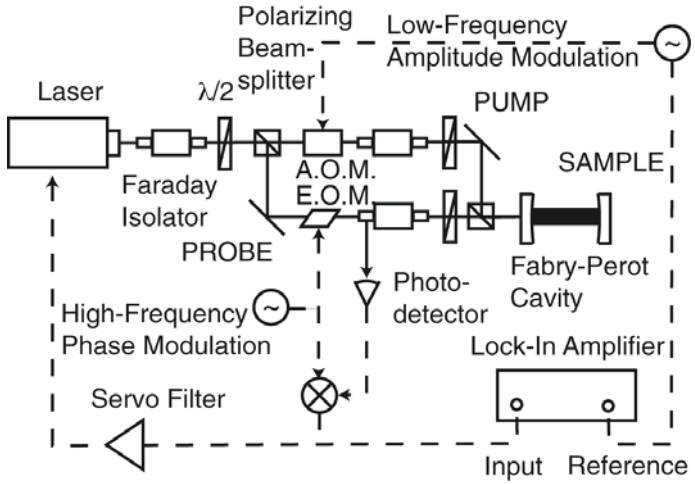
- First result
- Measured noise floor in undoped silica-tantala coatings
- Instrument characterization
- Verified scaling properties: noise floor really is displacement noise inside the cavities
- Result validated predictions based on Q measurements

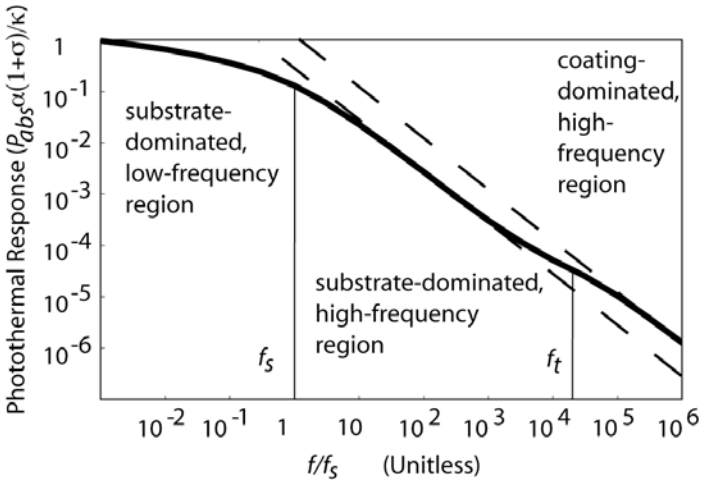
Results 2: Thermoelastic-damping noise in Sapphire Substrates



- Validated model of Braginsky, et al.
- No fitted parameters
  - $\alpha = 2.7\text{e-}6\ K^{-1}$
  - $\kappa = 44\ W/mK$
- Sapphire was later rejected as a substrate material, so this program was ended.

Results 3: New method to measure thermal properties of coatings

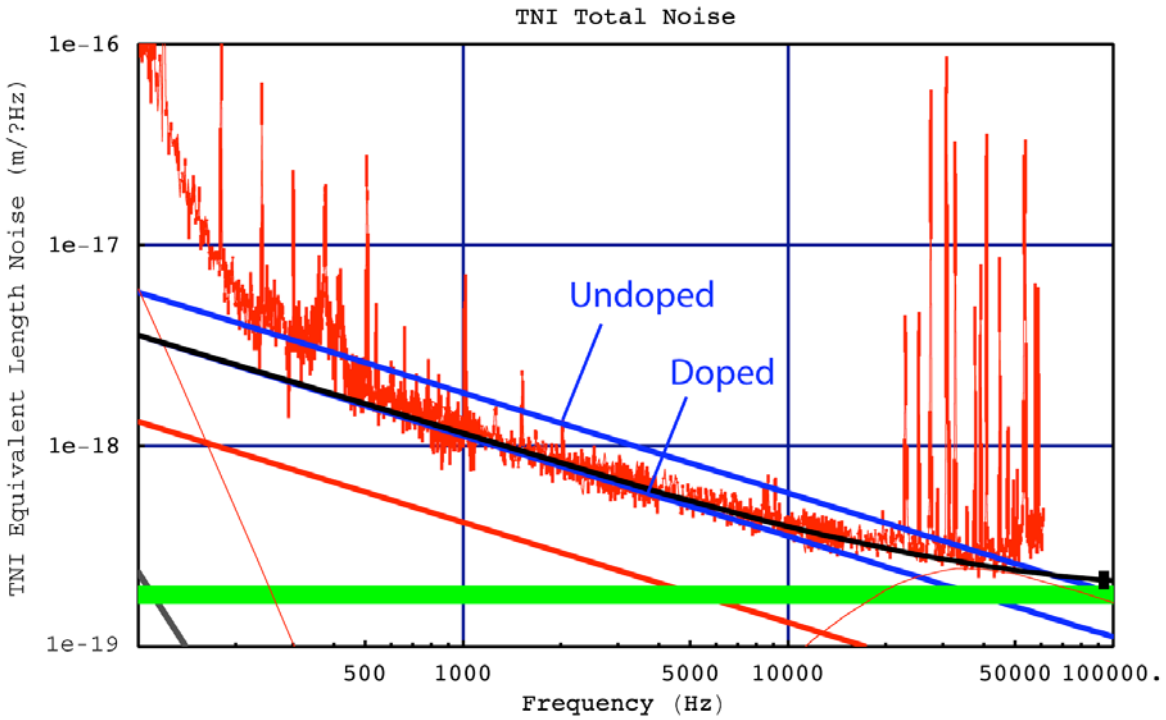




- Cavity-enhanced photothermal displacement spectroscopy method.
- Measures thermal properties of substrate or coating, depending on modulation frequency.
- Allows us to predict thermoelastic-damping noise in coatings.
- Measures thermoelastic-damping noise separate from thermo-refractive noise.

- Currently only way to measure κ in coatings?

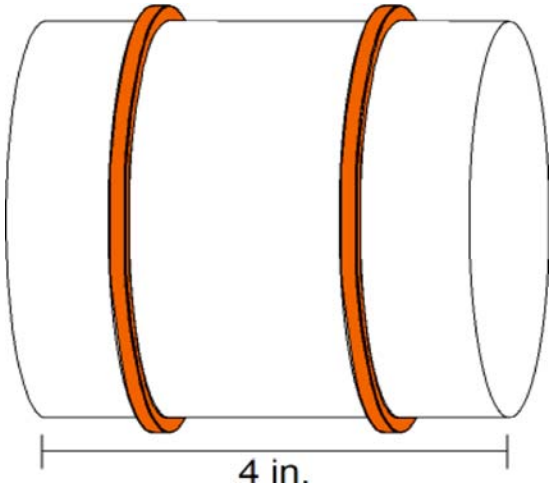
Results 4: Thermal Noise in Doped Coatings

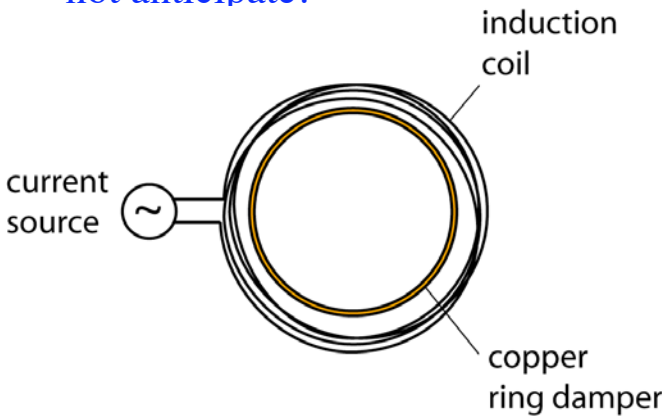


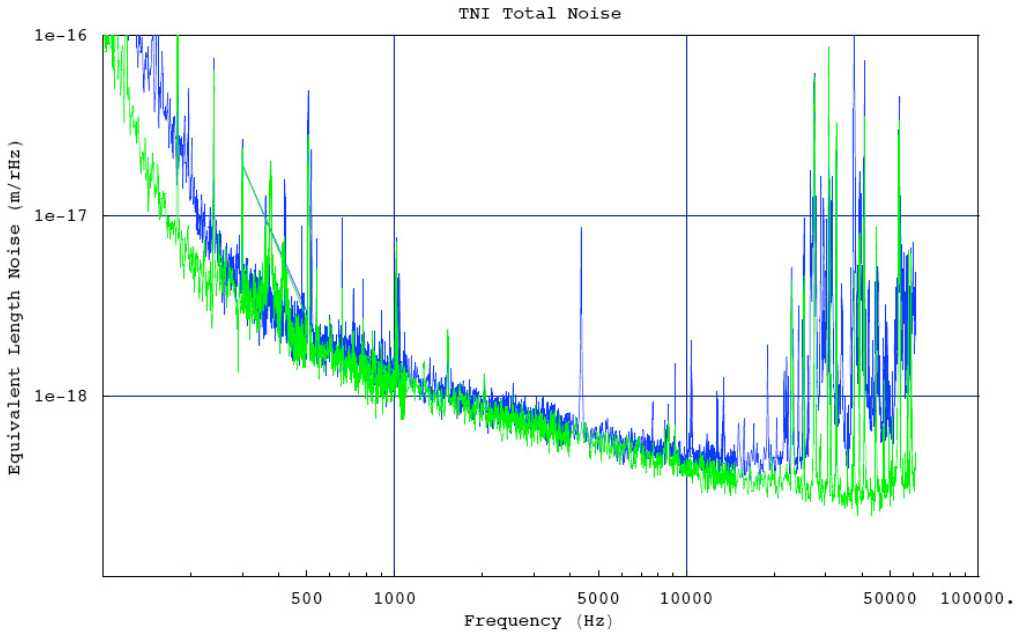
- AdvLIGO required noise floor not achievable with initial-LIGO optical coatings.
- Dominant source of coating thermal noise is intrinsic loss in the tantala layers.
- Doping the tantala layers with titanium substantially reduces the noise floor.
- Predictions from Q measurements validated at new, lower noise levels

Results 5: Ring dampers for suppressing parametric instabilities

- Parametric oscillations may be a problem for AdvLIGO
- 3 schemes for mitigation
  - Thermal detuning
  - Suppression of individual modes by active feedback
  - Q reduction by addition of localized mechanical loss, *must not affect the noise floor*
- Tried several kinds of rings, most of which did not work. FEA models did not anticipate!







Selected publications

- Gregg M. Harry, et al., *Titania-doped tantala/silica coatings for gravitational-wave detection,* Class. Quantum Grav. 24 405-415 (2007).
- Harry, G.M., Armandula, H., Black, E., et al., *Thermal noise from optical coatings in gravitational wave detectors,* Applied Optics 45 (7), 1569-1574 (2006).
- Eric D. Black, Akira Villar, and Kenneth G. Libbrecht, *Thermoelastic-damping noise from sapphire mirrors in a fundamental-noise-limited interferometer,* Phys. Rev. Lett. 93, 241101 (2004).
- Eric D. Black, et al., *Direct observation of broadband coating thermal noise in a suspended interferometer,* Phys. Lett. A 328, 1-5 (2004).
- Eric D. Black, et al., *Enhanced photothermal displacement spectroscopy for thin-film characterization using a Fabry-Perot resonator,* J. Appl. Phys. 95 (12), 7655-7659 (2004).
- Kenneth G. Libbrecht and Eric D. Black, *Toward quantum-limited position measurements using optically levitated microspheres,* Phys. Lett. A 321, 99-102 (2004).
- Eric D. Black and Ryan N. Gutenkunst, *An introduction to signal extraction in interferometric gravitational wave detectors,* Am. J. Phys. 71 (4), 365-378 (2003).
- Eric D. Black, *An introduction to Pound-Drever-Hall laser frequency stabilization,* Am. J. Phys. 69 (1), 79-87 (2001).

Future Objectives

- All current research programs continue *except* thermoelastic-damping noise in sapphire substrates.
- Direct measurement of thermo-optic (thermoelastic + thermorefractive) noise
- Direct measurement of charging noise and evaluation of charge-mitigation system

Future Science Directions

- Direct measurement of suspension thermal noise
  - Collaborate with Steve Penn, et al. on wire clamps? Possible contribution to Enhanced LIGO
  - Fused-silica fibers
- Electrostatic drive noise
- Thermal noise as a function of position
  - look for inhomogeneities in coatings
- Residual-gas noise

Instrument Science and Improvements

- Lower the shot-noise floor by increasing the finesse of the arm cavities
  - Necessary (and probably sufficient) to measure thermo-optic noise
  - 1e-20 m/√Hz has never been seen before
- Lock acquisition - underlying physics
  - Why can't we acquire lock at full power?
  - Radiation-pressure effects not well understood.

Future plans assuming existing group size

- 2007
  - Aperiodic coating measurement (Q2 if LMA delivers samples - Ilaria, Greg)
  - Bond-noise first results (Q3 - Akira, Greg, Ilaria fallback)
  - Charging-noise design, review (Q3 - Eric, Greg); experimental construction (Q3); measurement (Q4)
  - 100,000 Finesse mirror fabrication, installation (Q4 - Greg)
  - Suspension thermal noise experiment design (Eric)
  - Akira transitions to Enhanced-LIGO commissioning effort
  - Ilaria completes Benevento thesis, graduates
  - Hire 2 new graduate students to replace Akira, Ilaria (in negotiation now)
- 2008
  - Shakedown, noise reduction with 100,000 Finesse arm cavities (Eric, Greg)
  - Measure thermo-optic noise OR set new, lower bounds on thermo-optic noise level
  - Non-Gaussian noise measurement in the TNI, silicate bonds, application to AdvLIGO (Greg)
  - Suspension thermal-noise experiment construction, first results (Eric, new grad student)

Future plans assuming existing group size

- 2008-2010
  - Greg transitions to AdvLIGO commissioning
  - Hire new graduate student to replace Greg
  - Evaluate improved coatings for thermo-optic noise?
  - Evaluation of final AdvLIGO coatings?
  - Suspension thermal noise in fibers
  - Electrostatic-drive noise experiment design, construction, measurement, mitigation (Eric, new graduate student)
  - Radiation-pressure effects in lock acquisition, application to AdvLIGO
- 2011-2015
  - Low-frequency noise reduction, application to LIGO
  - Non-Gaussian noise mitigation in suspensions and optics
  - AdvLIGO commissioning (All) ?

Wish List

- TNI is not currently utilized to its full potential.
- Ideal case: dedicated graduate students for each of the following programs
  - Development and evaluation of AdvLIGO coatings
  - Non-Gaussian noise, both in TNI and silicate bonds
    - Uses both existing silicate-bond-noise experiment and main TNI IFO
  - Thermo-optic noise and photothermal experiment
    - Uses existing photothermal experiment and main IFO
  - Charging noise and mitigation, electrostatic-drive noise
    - Uses separate, tabletop experiment and main IFO
  - Suspension thermal noise in wires and fibers
    - Separate, tabletop experiment
    - Would apply to both Enhanced LIGO and AdvLIGO
  - Instrument science: noise floor reduction and lock acquisition
- Total: 5-6 graduate students, or 4-5 and 1 post doc
- Each graduate student would start out full-time at the TNI, then transition to commissioning at the sites after 2-3 yrs.