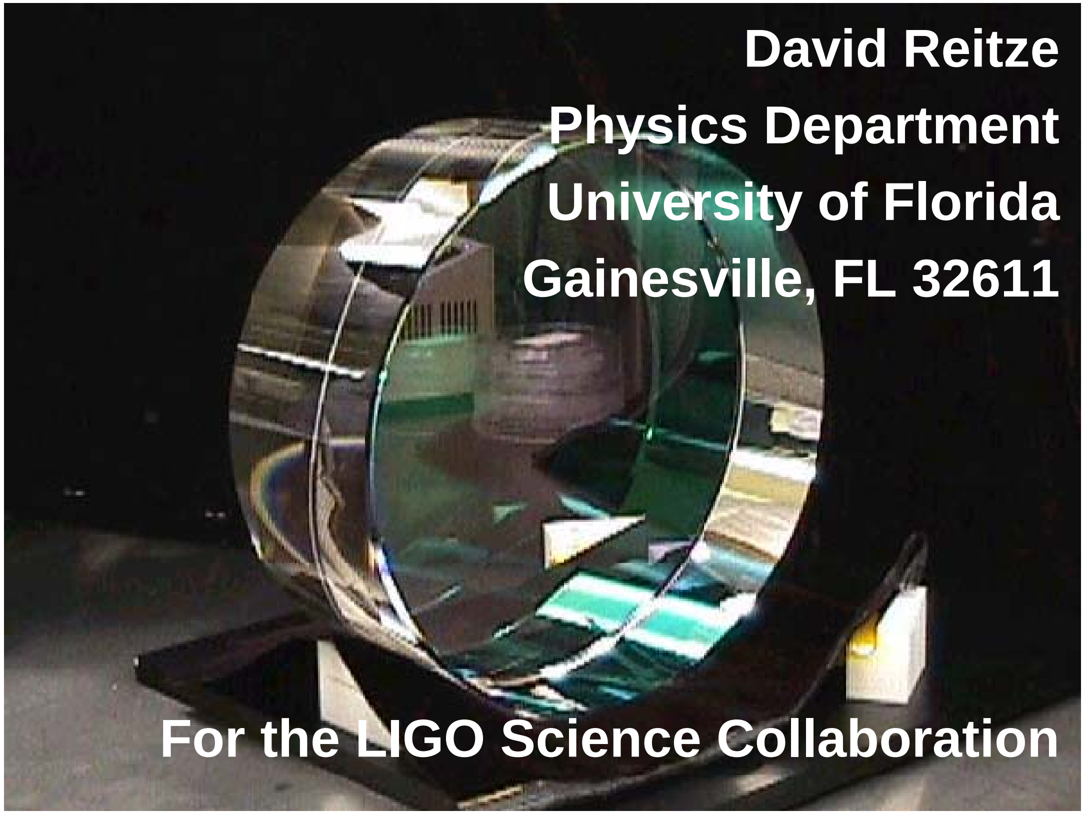
G070380-00-Z

Optics for Interferometers for Ground-based Detectors



David Reitze

Physics Department

University of Florida

Gainesville, FL 32611

For the LIGO Science Collaboration

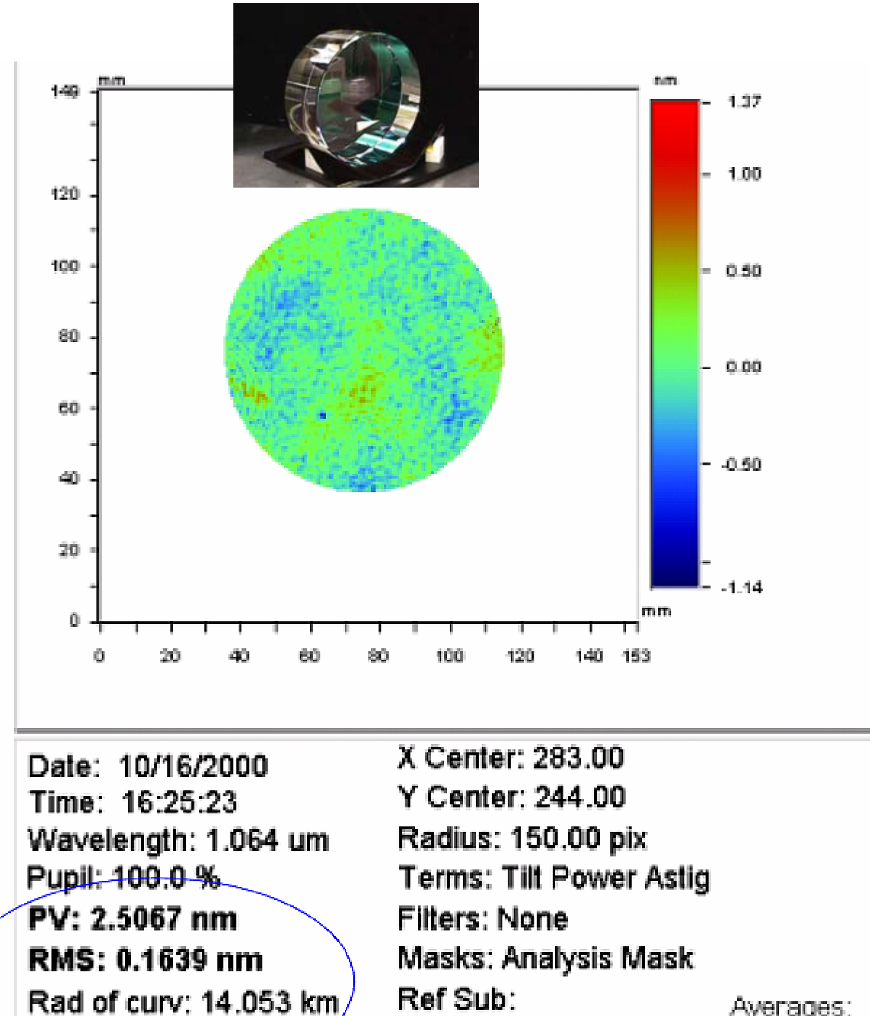
DFG-NSF Astrophysics Workshop 10-12 Jun 2007

Outline

- Optics in the current LIGO detectors
  - » Requirements and performance
  - » Thermal effects in LIGO
- Optics for Advanced LIGO
  - » Requirements
  - » The importance of optical coatings
  - » Thermal effects in Advanced LIGO
    - – Test masses and interferometer components
    - – Ancillary transmissive optical components
- Some thoughts on optics for third generation terrestrial detectors
  - » Substrate materials and masses
  - » Reflective optics and cryogenics

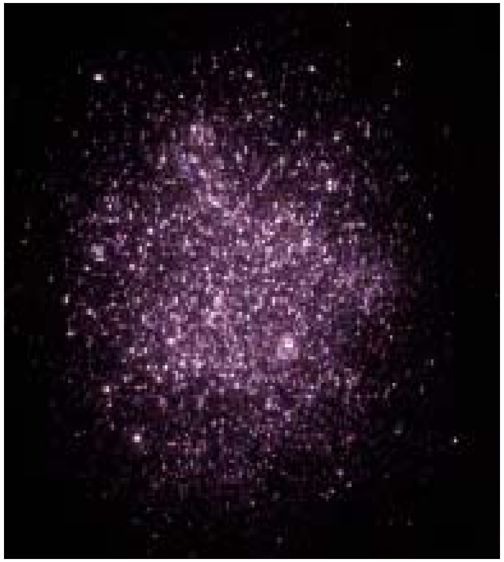
Requirements and performance in LIGO Optics

- Initial LIGO detectors had challenging requirements for test mass mirrors
  - » Mass: 11 kg; Physical dimensions: ϕ = 250 mm, d = 100 mm
  - » Surface Figure: ~ λ/1000
  - » Microroughness: 0.6 nm rms
  - » Coating Absorption: ~ 1 ppm
  - » Bulk Absorption: < 10 ppm
  - » Surface Scattering: 50 ppm
- At or beyond state-of-the-art at the time of beginning initial LIGO
  - » Metrology was a significant challenge

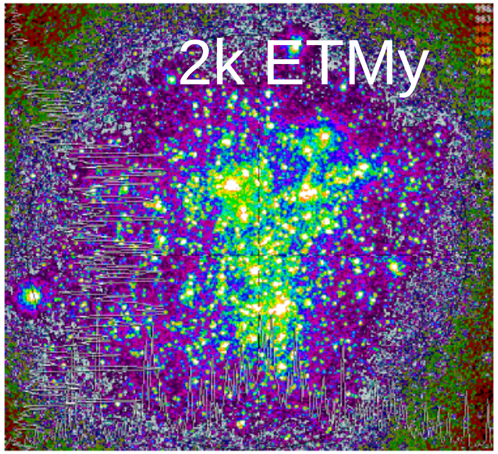


Performance: Cleanliness is next to…

- So how did we do?
  - Bulk Absorption:
    - 2 ppm/cm – 10 ppm/cm; varies with individual mirror
  - Coating absorption:
    - 1 – 5 ppm; varies with individual mirror
  - Scatter loss (arm cavity):
    - 70 ppm; also a bit variable
- Impact on performance
  - Thermal compensation system developed to combat variable absorption
  - *In situ* cleaning of the some of the ‘dirtiest’ test mass mirrors
    - in one case, a mirror was replaced due to a defective AR coating; likely the result of cleaning which etched AR coating

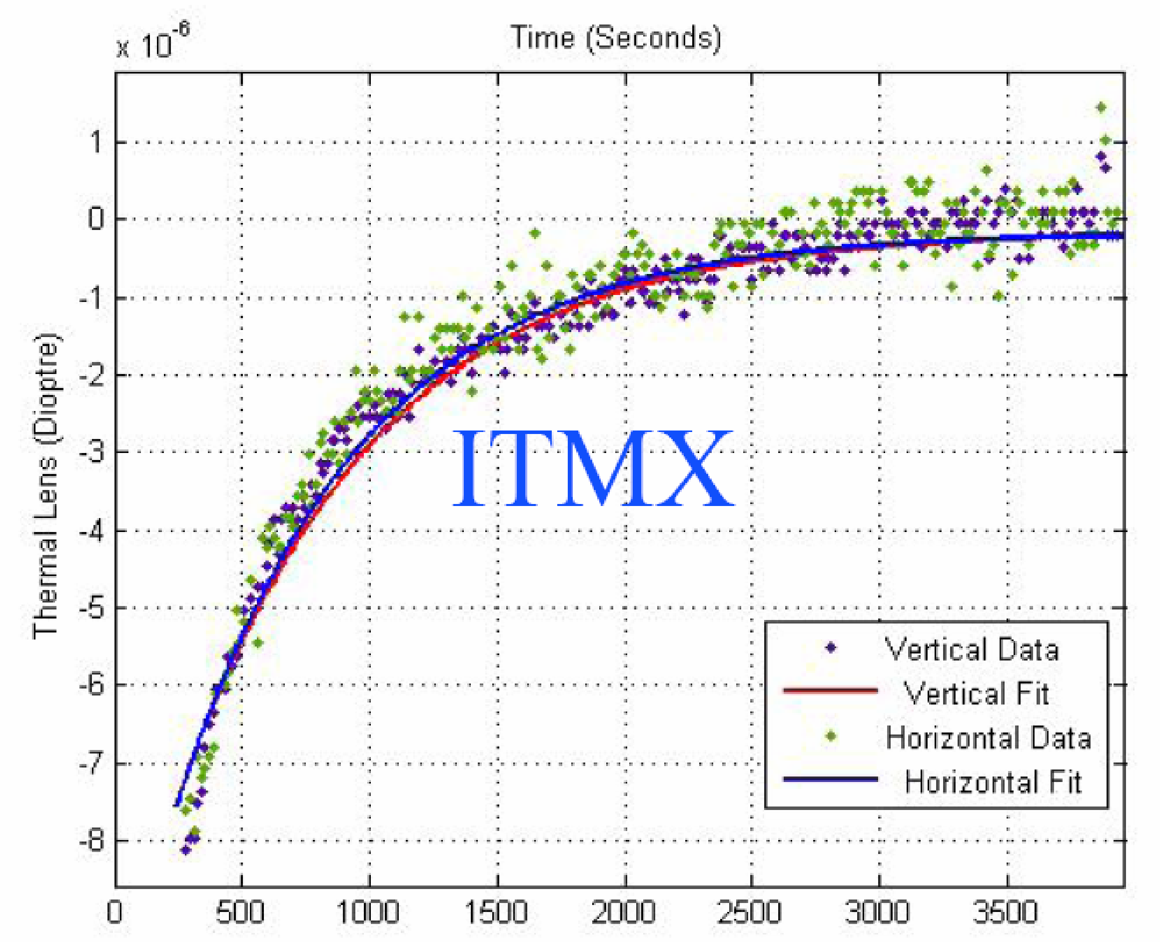


Resonant arm, Gaussian illuminated ETM



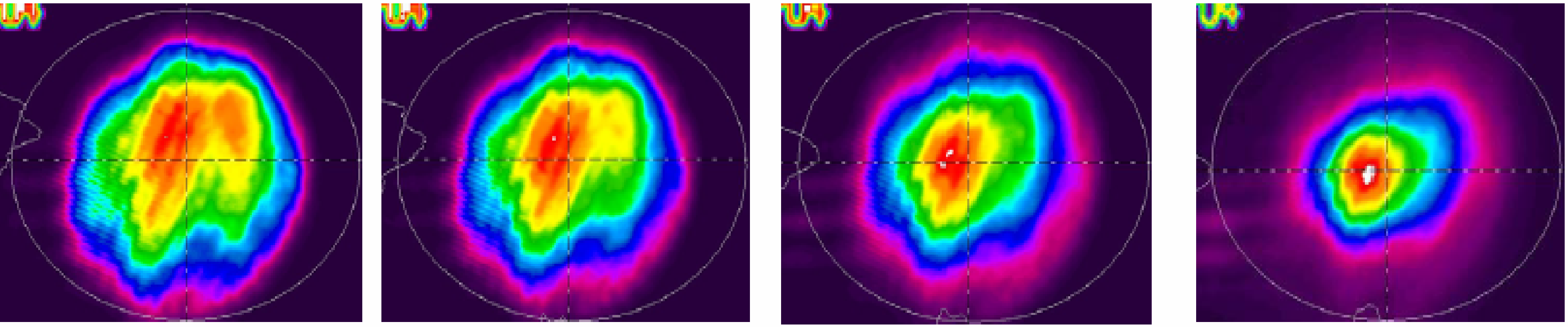
Thermal effects in LIGO optical components

- ‘High quality low absorption fused silica substrates’
  - » Heraeus 312 (ITM)
  - » All mirrors are different
- ~100 mW absorption in current LIGO interferometers
  - » Effects are noticeable: ***Unstable recycling cavity***
- Requires *adaptive* control of optical wavefronts
  - » Thermal compensation system (TCS)



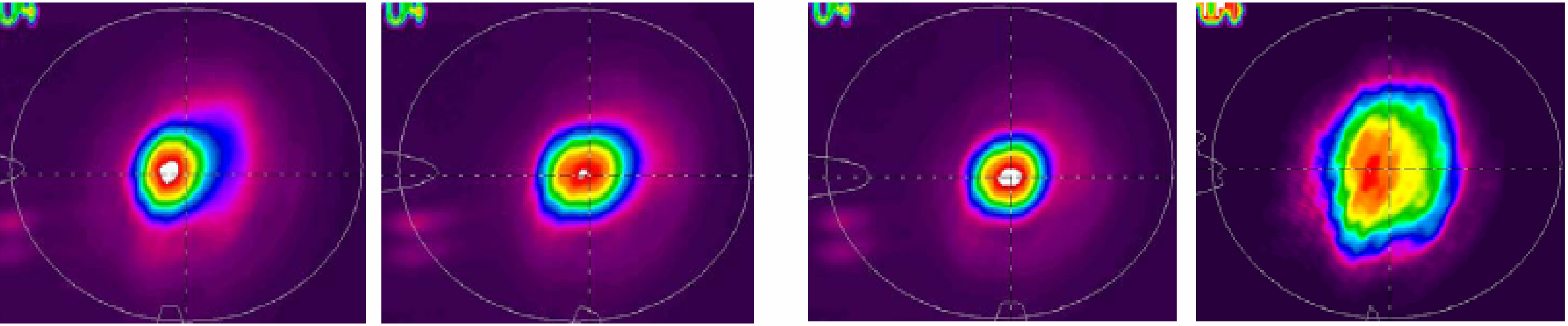
Thermal compensation

RF sidebands-->|



no heating | 30 mW | 60 mW | 90 mW

RF sidebands--->| Carrier



120 mW | 150 mW | 180 mW | (thru unlocked IFO)

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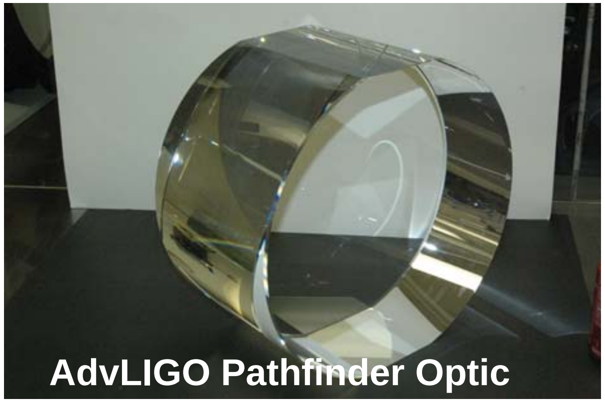
Advanced LIGO – a new standard for performance

- All requirements are tougher than initial LIGO
  - » Mass: 40 kg; Physical dimensions: ϕ = 340 mm, d = 200 mm
  - » Surface Figure: ~ λ/1200
  - » Microroughness: 0.1 nm (rms)
  - » Bulk Homogeneity: 20 nm (p-v)
  - » Coating Absorption: < 1 ppm
  - » Bulk Absorption: < 3.5 ppm
  - » Arm Cavity Scatter loss: 20 ppm


AdvLIGO Pathfinder Optic

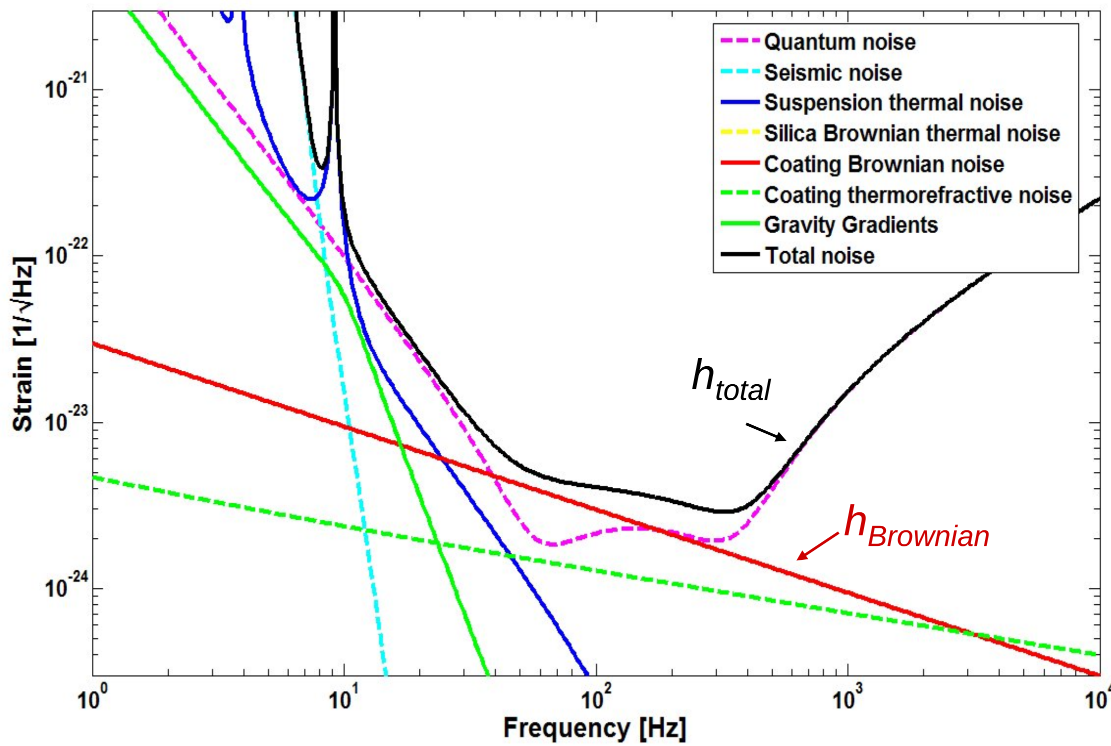
- Thermal effects are more severe in AdvLIGO
  - » ~ 1 W absorbed power into input test masses
  - » Affects interferometer architecture
    - – Stability of recycling cavity is problematic

Coating thermal noise

- Advanced LIGO performance is limited by *Brownian thermal noise of the mirror coatings*

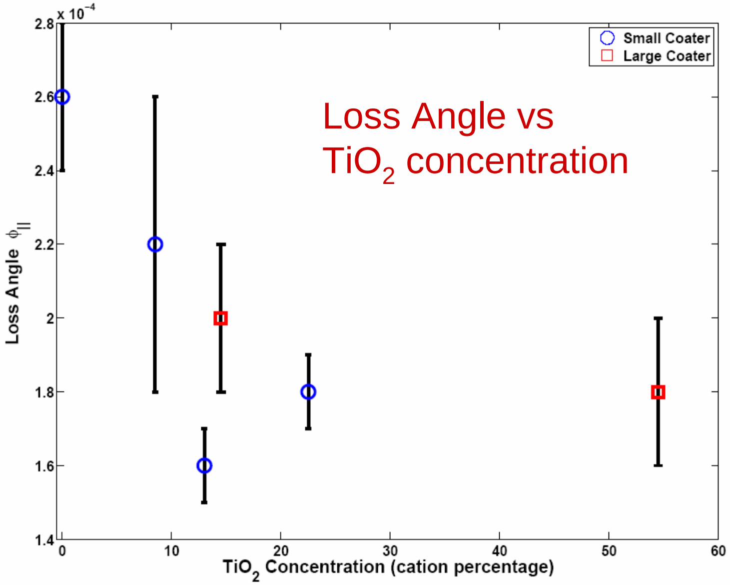
$$h_{Brownian} = \sqrt{2k_B T \phi_{eff} \frac{1-\sigma^2}{\pi^3 f\, wY}}$$

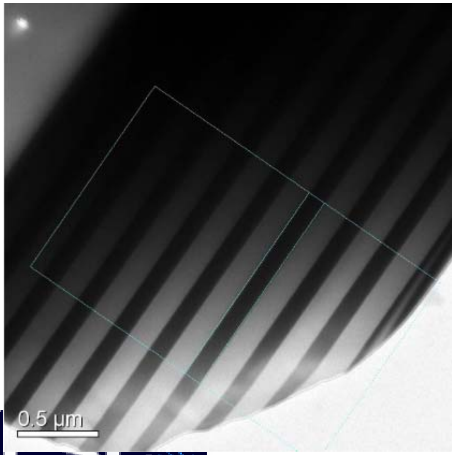
- Effort under way to develop better coatings for Advanced LIGO
  - » 30% reduction in Brownian coating noise via doping of HR coatings with TiO_2



Coating research and development

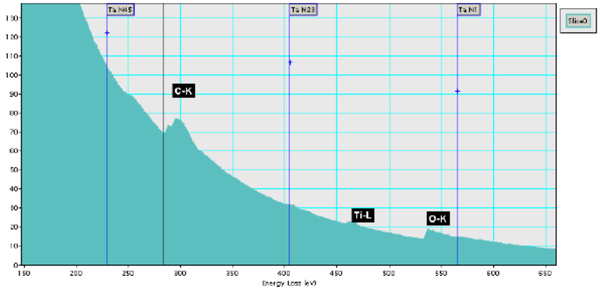
- Efforts in coating development, coating characterization
  - » Mechanical loss (reduction of thermal noise)
  - » Optical absorption (thermal effects)
- Focus on mechanical loss
  - » Efforts focused on incorporation of dopants to relieve coating stress
  - » TiO_2-doped Ta_2O_5 has shown promise



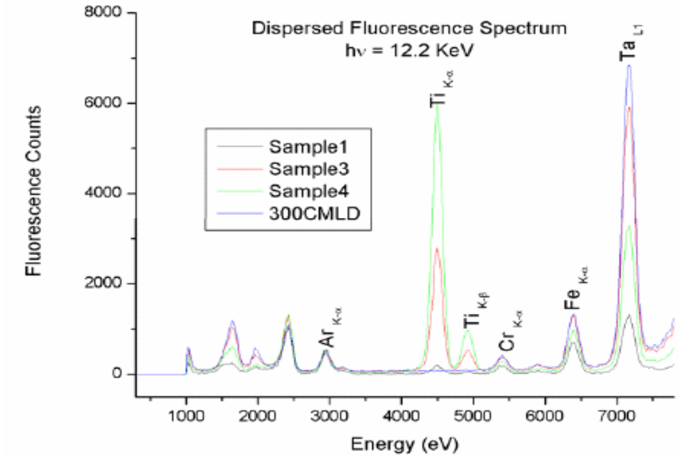


Harry, et al, CQG **24**, 405 (2007)

Electron Energy Loss Spectroscopy



X-Ray Florescence Results



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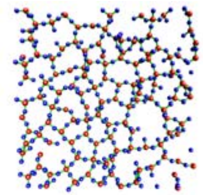
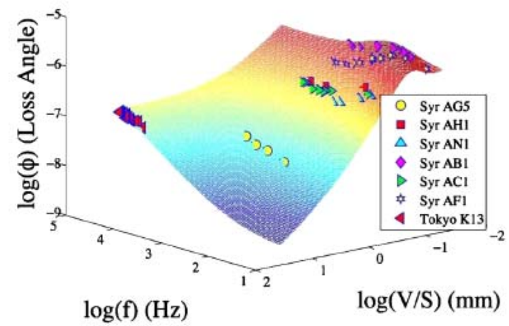
Microscopic mechanisms of mechanical loss

Goal: A description of mechanical loss in thin film amorphous oxides

- Molecular dynamics calculations beginning at University of Florida

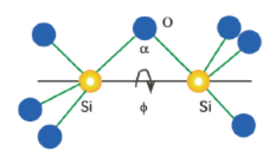


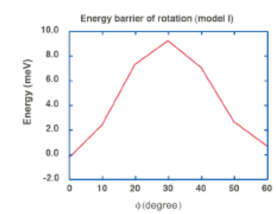
- Have a working semi-empirical model of loss in fused silica
  - » Frequency dependence from two level systems
  - » Surface loss as observed phenomenon



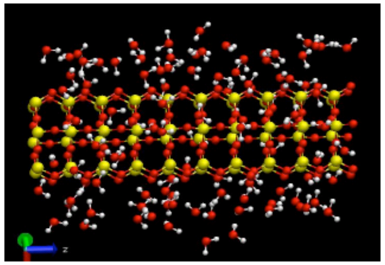
Quantum calculations of silica

- Develop full molecular description of silica loss
  - » Surface loss caused by two-member rings?

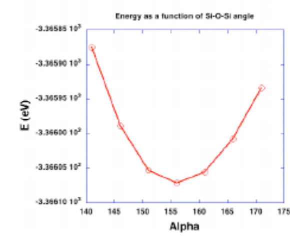




- Generalize to other amorphous oxides - analogous two level systems



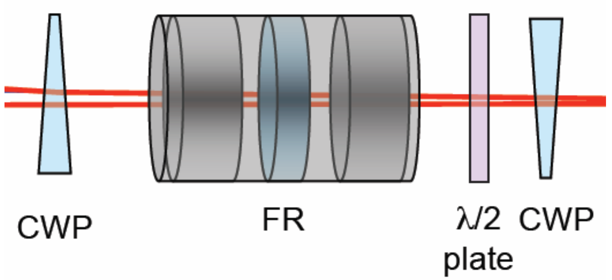
A snapshot of SiO_2rod-water interaction

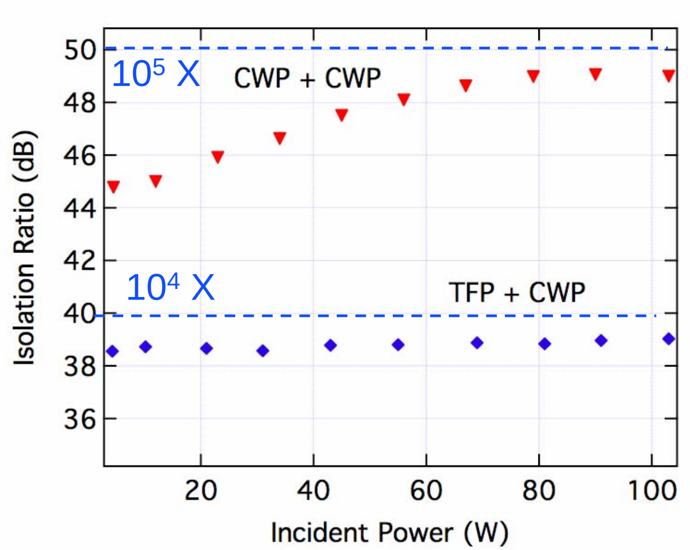


Alpha=angle(Si-O-Si)

Ancillary optical components for next generation detectors

- Modulators and Faraday isolators also impacted by absorption of laser radiation
  - » Modulators:
    - – thermal lensing
    - – Nonlinear frequency conversion
    - – Degradation due to long term exposure
  - » Faraday isolators
    - – Thermal lensing
    - – Thermally-induced depolarization
      - dV/dt
      - Photo-elastic effect
    - – In-vacuum performance
- For Advanced LIGO
  - » Modulators use new EO materials – RTP
    - – See V. Quetschke poster
  - » Faraday isolator
    - – Two TGG crystal design for birefringence compenation
    - – Negative dn/dT material for passive thermal lensing compensation



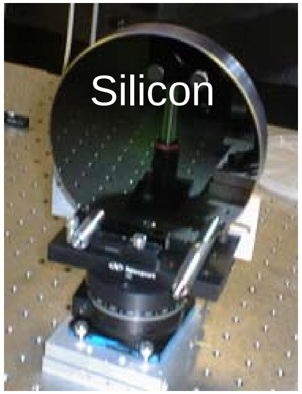


3rd generation detectors: materials and masses

- For third generation detectors, we want
  - » Test masses with more mass (100 kg or more)
    - – Standard quantum limit:

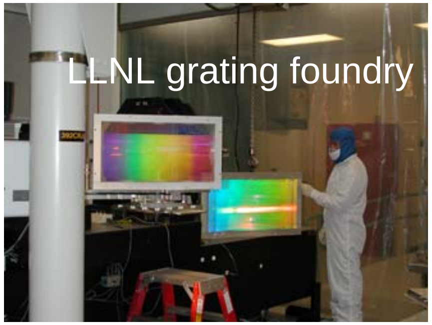
$$h_{SQL}(f) = \sqrt{\frac{8\hbar}{4\pi^2 f^2 L^2 M}} \longrightarrow \frac{1}{h^3} \sim M^{3/2}$$

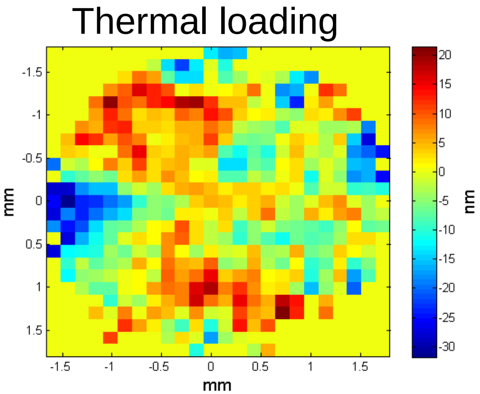
  - » Better material properties
    - – Improved Brownian and thermo-elastic noise performance
    - – High thermal conductivity κ; low thermal expansion
    - – Able to produce large masses (with high homogeneity)
  - » Candidate materials
    - – Sapphire
      - Low Brownian noise
        - » Higher thermo-elastic noise
      - Good κ
      - We know a lot about it
        - » Studied extensively for Advanced LIGO before fused silica was selected
    - – Silicon
      - High κ
      - Large masses
      - thermal noise comparable to sapphire at room temperature



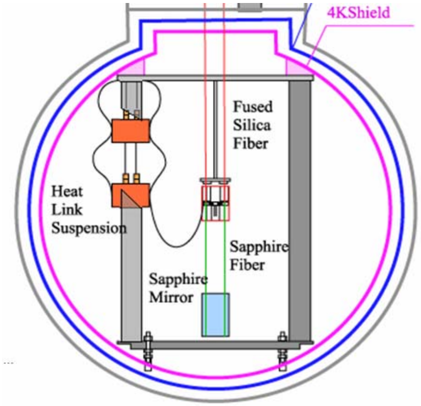
3rd generation detectors: reflective optics and cryogenics

- All reflective optical configurations
  - » Diffraction gratings   Byer Group, Stanford; Schnabel Group, Hannover
    - – Minimize thermal loading due to substrate absorption
    - – R&D in the following areas
      - Efficiency
      - Aperture size
      - Thermal effects
      - Scatter loss
      - Contamination





  - » Total internal reflection   Braginsky Group, Moscow State
    - – Eliminate coatings → eliminate coating thermal noise
      - Substrate absorption
  - » Cryogenic test masses   LCGT, Japan
    - – Reduce thermal noise directly at the source
      - Heat extraction, vibration coupling



LCGT prototype suspension

Conclusions

- First generation gravitational wave detectors
  - » LIGO, GEO, Virgo
  - » Optics worked well for the most part!
    - – Need for some mitigation after installation
    - – Develop understanding of importance of mirror variability, surface contamination
- Second generation detectors
  - » Advanced LIGO, Advanced Virgo, GEO-HF
  - » Lots of R&D already done
    - – Fused silica mirrors
    - – Optical coatings limit performance
- Third generation detectors
  - » Einstein GW telescope
    - – Still lots of work needed to select optimum
      - Materials
      - Gratings?
      - Cryogenics?