Sapphire Development Program

Jordan Camp

LSC meeting
LIGO Livingston Observatory
Mar. 15, 2001

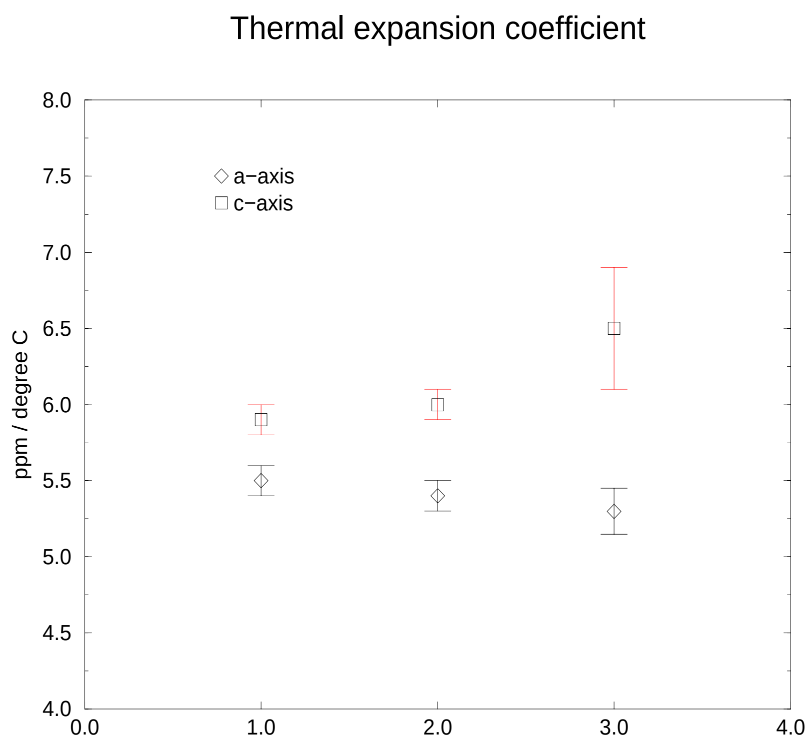
Why Sapphire ?

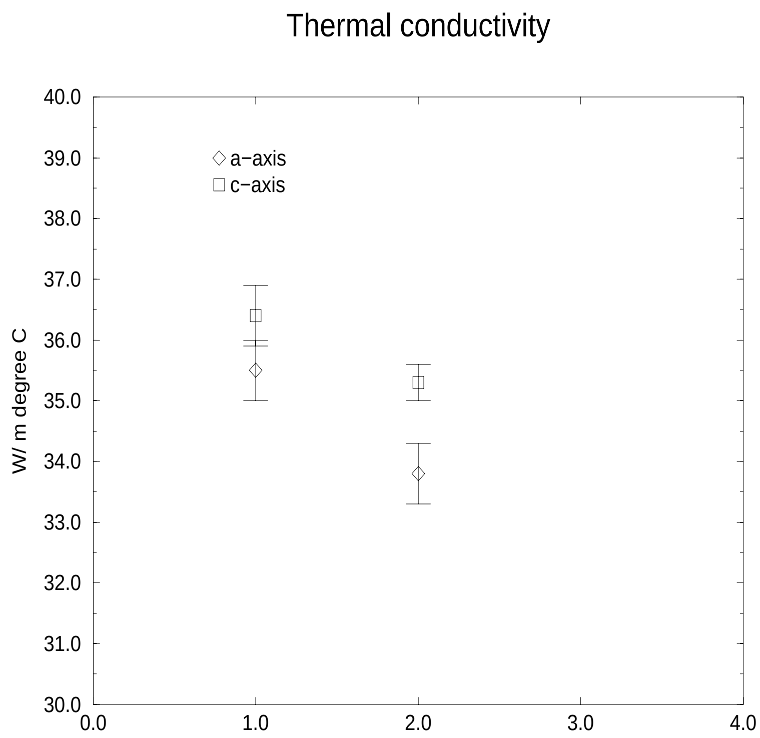
- Sapphire performance comparable to fused silica
  - ~ 200 Mpc range for NS inspiral from sapphire (165 Mpc for fused silica)
  - sapphire narrow-band sensitivity ~ 2 x higher than fs from 500-1000 Hz
  - Thermoelastic damping noise is limit to sapphire performance
- Sapphire much better material for high power
  - Thermal conductivity 30 x higher than fused silica
  - Rayleigh scattering ~ 30 x lower than fused silica
- R&D effort for both sapphire, fused silica continues
  - effect of coating, bonding on thermal noise of materials
  - other surface effects, absorption, etc.

LSC Sapphire Test Program

- Measure thermophysical constants
  - establish thermoelastic damping noise for sapphire
- Measure optical and mechanical characteristics
  - absorption (Stanford, Southern University)
  - polishibility (Caltech)
  - optical homogeneity (Caltech)
  - mechanical Q (Stanford, U. Glasgow)
  - birefringence (Caltech)
  - low frequency losses (Syracuse)

Sapphire Thermophysical Constants





- thermoelastic damping noise ~ $\alpha^2 \sigma / w_0^{3/2}$

Sapphire vs. Fused Silica Thermal Noise

- Fused Silica
  - Q of 3 x 10^7
  - thermal noise tail from mechanical resonances
- Sapphire
  - Q of 2 x 10^8
  - thermal noise from low-frequency temperature fluctuations coupling to material expansion
- Ultimate NS inspiral sensitivity achievable with these optical materials is very close (within 20%)

Thermal Distortion in Advanced LIGO

Source of Absorption	Test Mass Optical Distortion (nm)	
	Sapphire	Fused Silica
Substrate (Sapphire: 20 ppm/cm) (Fused Silica: 1 ppm/cm)	40 nm	40 nm
Coating (0.5 ppm)	25 nm	400 nm

- Design optic sag of 60 nm
- Arm cavity stored power ~ 800 kW
- Thermal distortion could also be lowered by reducing coating absorption, or implementing thermal compensation

Sapphire Absorption

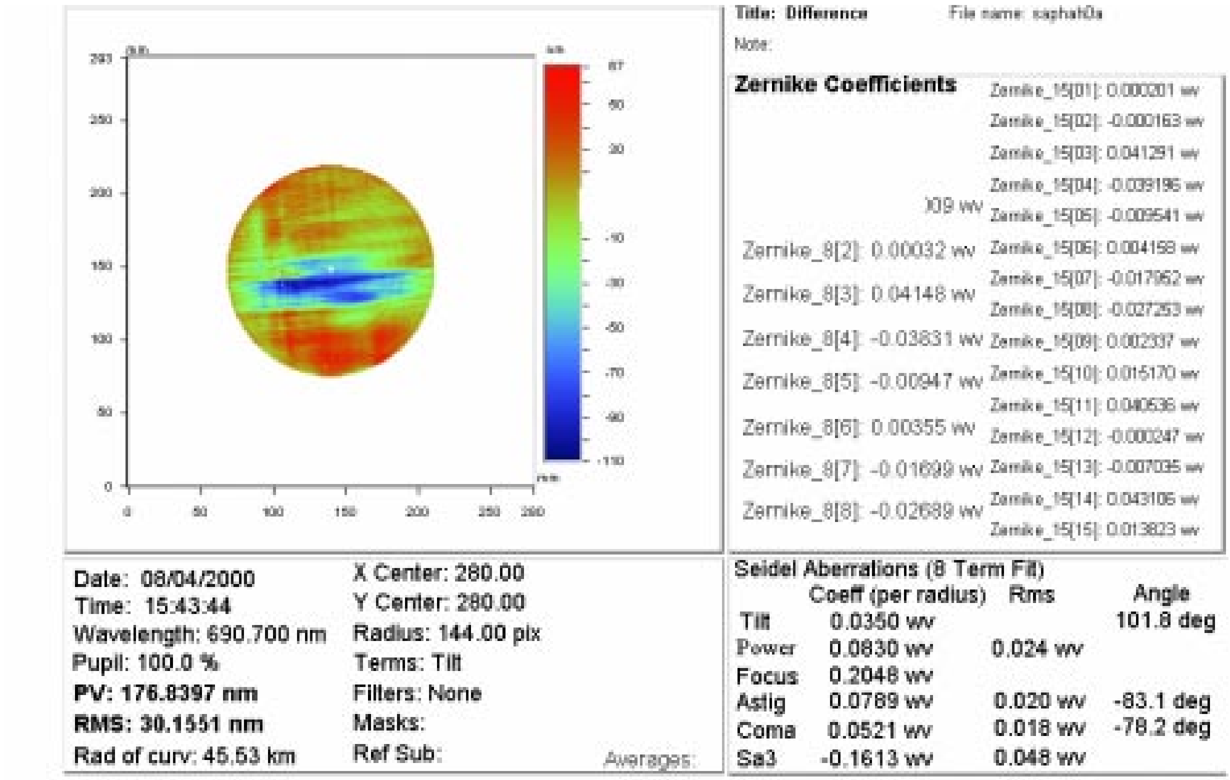
- Nominal CS sapphire absorption 80 ppm / cm
- Attempt to identify impurities
  - ›› 15 ppm / cm seen in one high purity starting material at one boule location
  - ›› most starting materials show no correlation with absorption
- Annealing study undertaken to reduce absorption
  - ›› 1600 C air bake gives 20 ppm / cm absorption uniform through sample
  - ›› tests to continue at higher bake temperatures

Polishing Tests

- CSIRO surface polish of 15 cm x 8 cm test piece: preliminary results meets advanced LIGO requirements
  - < 1 nm rms surface figure
  - 0.2 nm rms microroughness
  - ROC target of 50 km +/- 10 km

- Additional effort underway at General Optics

Polishing Tests: Optical Homogeneity



- need factor 5 - 10 reduction of inhomogeneity
  - ›› spot polish by Raytheon-Danbury

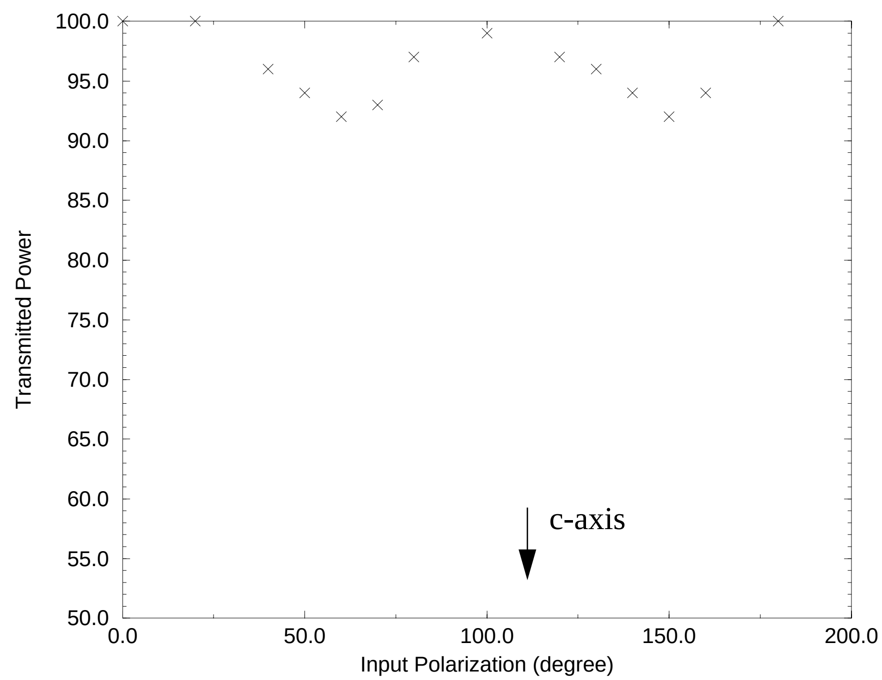
Mechanical Q

- Mechanical Q's of > 2 x 10^8 confirmed for variety of sapphire substrate shapes
- Tests underway for effect of (lossy) coating on thermal noise
  - preliminary result: coating has effect on Q (both fs and sapphire)
    - effect of order tens of %
  - thermal noise of coating itself ?
- Other effects: surface loss, bonding effects, etc.
  - TNI
  - Syracuse low-frequency anelastic loss measurements

Birefringence

- Surface of m-axis crystal has anisotropic properties
  - light not precisely aligned with optical axis will suffer polarization rotation
  - result is power loss at beamsplitter
  - birefringence in both coating and substrate
- Test measurement of birefringence of 3” x 1.5” sapphire
  - monitor transmission of high finesse Fabry-Perot cavity as function of input polarization of light
  - compare coating optical axes with substrate optical axes

Birefringence



- Alignment of input polarization within 10 degree of c-axis of crystal gives recycling gain loss of < 5% in advanced LIGO

Sapphire Summary

- Absorption at 20 ppm / cm, almost OK
  - annealing direction established, will try to push absorption lower
- Polish OK
  - need to demonstrate spot polish, but expect to work
- Birefringence OK
  - need to measure full size optic, expect to work
- Mechanical Q: coating, bonding effects under study

- Sapphire performance comparable to fused silica, but significantly less thermal distortion
  - this is present picture, but R&D continues

What's Next

- Futher sapphire tests
  - ›› quantify effect of coating on thermal noise
  - ›› drive substrate absorption lower
  - ›› measure birefringence of full size part
  - ›› lab test of spot polish
  - ›› grow 35 cm dia. substrate
  - ›› attempt large crystal growth at SIOM (alternate sapphire vendor)
  - ›› direct thermal noise measurements at TNI, Syracuse
- Fused silica tests
  - ›› verify low absorption for large substrates
  - ›› effect of coating on Q

What’s Next (cont.)

- Test Mass material selection 6/02: sapphire or fused silica
  - performance, cost of both materials
  - R&D to lower coating absorption
  - thermal compensation system performance