Advanced LIGO R & D:
Sapphire Status Report

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Rationale for Sapphire Test Masses

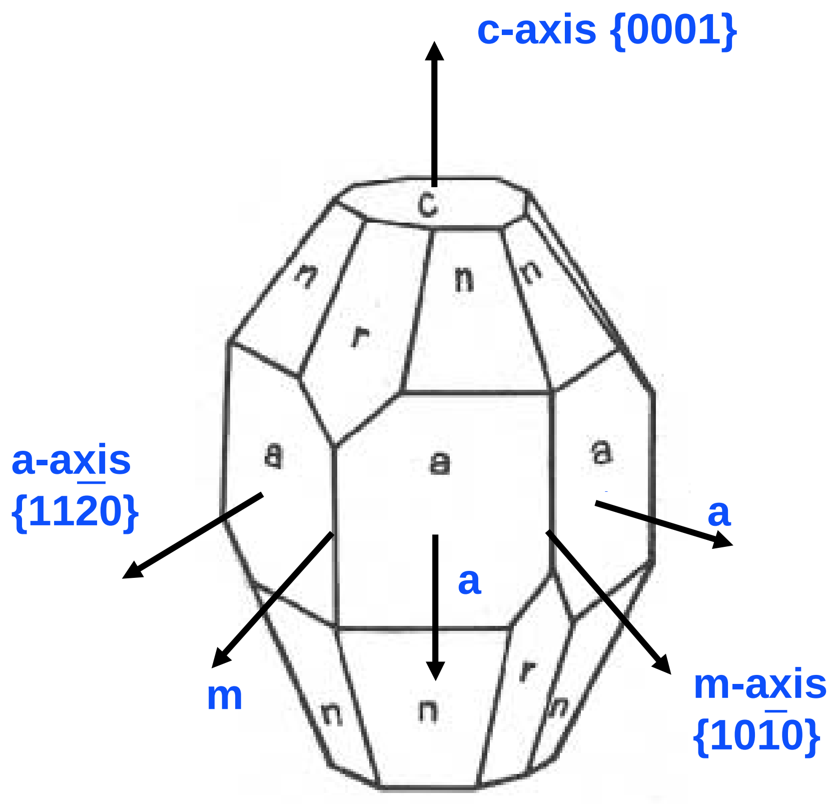
- **Mechanical and thermal properties of sapphire superior to fused silica**
  - » **at 100 Hz, thermal noise much better then fused silica:**
    - – **mechanical Q ~ 2 x 10^8 (compare fused silica Q ~ 10^7)**
  - » **dense, high thermal conductivity & sound speed**
  - » **SUPERIOR ASTROPHYSICS REACH**
- **The price to pay**
  - » **absorption greater than fused silica**
  - » **thermo-elastic noise greater than fused silica**
  - » **very hard material --> difficult to polish**
  - » **uni-axial crystalline structure --> birefringence**

Sapphire 101

- Al_2O_3 - Crystal Structure: Trigonal
- Density: 3.97 gm/cm^3
  - » compare fused silica: 2.20 gm/cm^2
- Thermal conductivity (300 K):

  κ = 40 W/m K
  - » increases to 2x10^5 W/m K at 25 K
  - » compare fused silica: 1.38 W/cm K
- Thermal expansion (300 K):

  α = 8.8 x 10^{-6} / K
  - » compare fused silica: 0.55 x 10^{-6} / K
- Figure of merit: κ/α (10^{-6} m/W)
  - » sapphire: **4.5**
  - » fused silica: **2.5**



Requirements for Advanced LIGO

P. Fritschel, et al., LIGO T010075-00

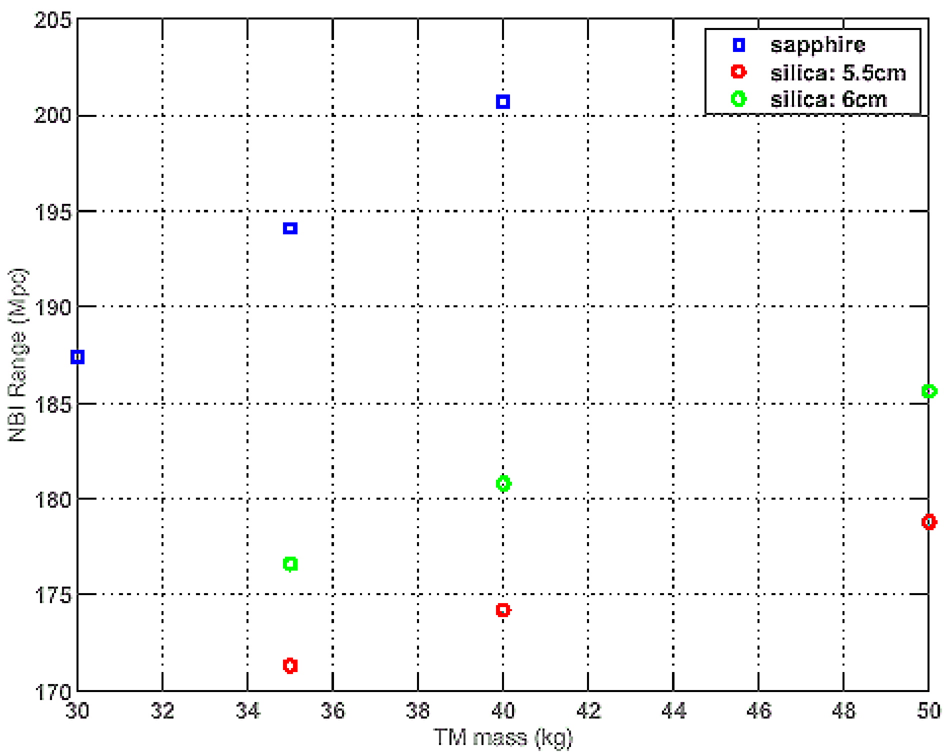
Mass	**40 kg**
Physical dimension	**31.4 cm x 13 cm**
Optical homogeneity	**< 10 nm rms**
Microroughness	**< 0.2 nm rms**
Internal scatter	**< 20 ppm/cm**
Absorption	**< 20 ppm/cm**
Thermal noise	**$Q > 2 \times 10^{8}$**
Birefringence	**< 0.1 rad**
Polish	**< 1 nm rms**

Size and Homogeneity

- **Larger mass driven by:**
  - » **radiation pressure ("Unified Quantum Limit")**
  - » **thermo-elastic noise (worse in sapphire!!):**

    $\delta x(f) \sim 1/w^{3/2}$; w=waist
- **homogeneity driven by:**
  - » **arm cavity loss**
  - » **homogeneity is axis-dependent**

NBI Range vs. Mass



Fritschel, et al., LIGO T010075-00

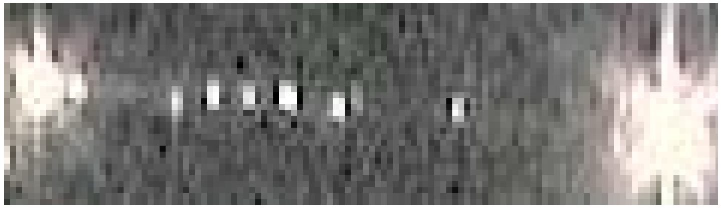
Status:

- **Size - OK**
  - **40 kg mass can be grown by CSI**
  - **314 mm x 130 mm piece to be delivered to LIGO Lab in October**
- **Homogeneity - OK (almost)**
  - **techniques include spot polishing, fluid polishing, ion-beam etching**
  - **< 14 nm rms measured on large m-axis material; reports of <10 nm by Goodrich; 55 Å microroughness**
  - **still need to clarify m- vs a-axis homogeneity**
  - **microroughness < 1 Å on small ion-beam etched pieces by CSIRO (nice technique, but $$)**

Scatter and Absorption

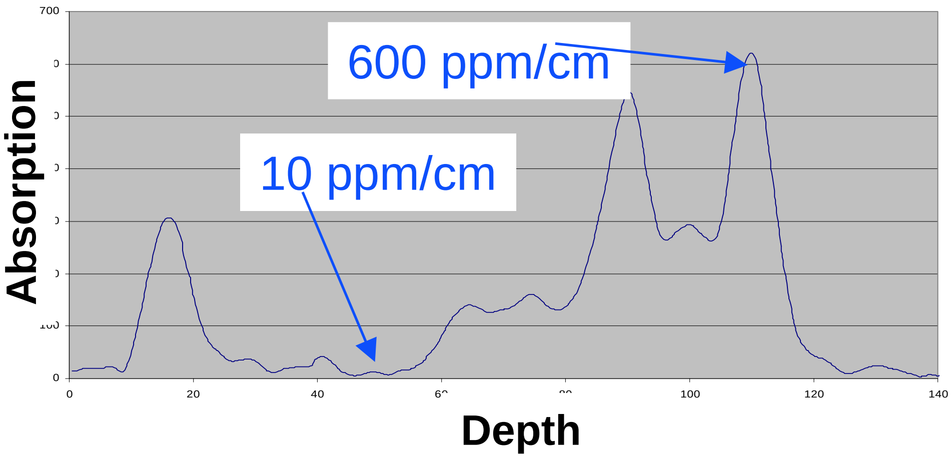
- **Internal Scatter driven by:**
  - » **ITM + BS scatter --> power recycling cavity loss**
  - » **potential light scatter into asymmetric port PD (mitigated by output mode cleaner)**
- **Absorption driven by:**
  - » **thermal lensing in ITM substrate ---> loss of sideband power in power recycling cavity**

"Bad" sapphire



J. Li, D. Blair, UWA

"Rosetta" Sapphire



R. Route, M. Fejer, Stanford

Status:

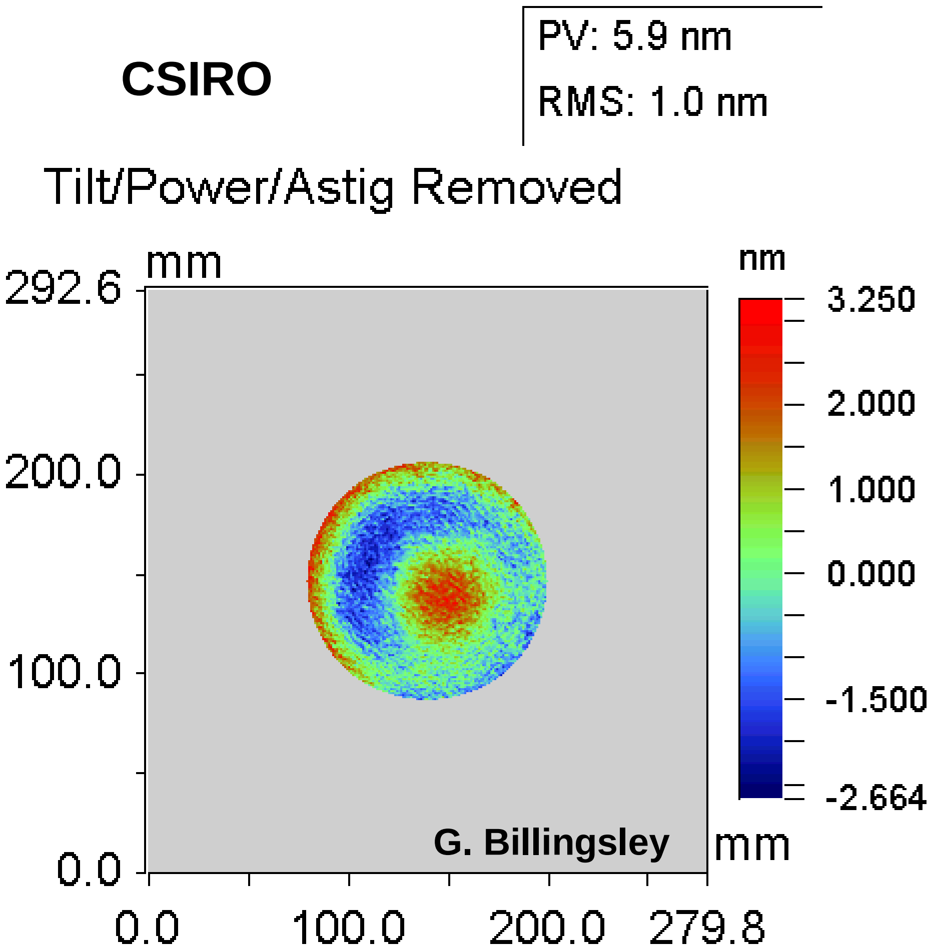
- Scatter - **GUARDED**
  - qualitative data “looks good”
  - no easy knobs to turn elsewhere to correct (some trade-off with absorption possible, but…)
  - quantitative data and statistics pending

- Absorption - **GUARDED**
  - 10 ppm/cm (requirement) seen in isolated small substrates from CSI
  - 30-40 ppm/cm is the norm
  - process and materials characterization on going:
    - annealing methods under investigation
    - impurity species, concentrations under investigation
  - <u>adaptive thermal compensation may mitigate requirement</u>

Polishing

- **Surface figure driven by:**
  - » **deviations lead to loss and higher modal contamination**
    - – **contrast defect**
    - – **loss of power at dark port**
  - » **modeled using FFT codes and MELODY**
- **sapphire is a hard material; difficult to polish**

CSIRO



Polishing

<u>Status:</u>

- **Polishing - OK**
  - **1 nm rms demonstrated by CSIRO on 120 mm substrates**
  - **1.5 Å < microroughness after polishing**
    - **note: no homogeneity compensation**

Birefringence

- **Stress Birefringence driven by:**
  - » **polarization rotation in the ITM leads to loss on the BS and possible arm cavity power imbalance**
  - » **stress birefringence intrinsic to crystals**
- **Thermal birefringence due to heating**
  - » **photo-elastic effect**

LIGO

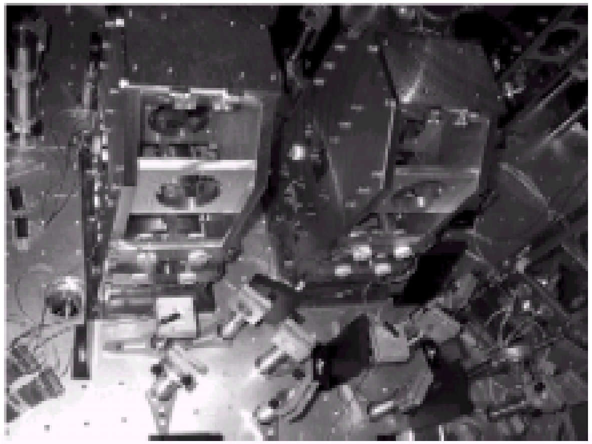
Birefringence

Status:

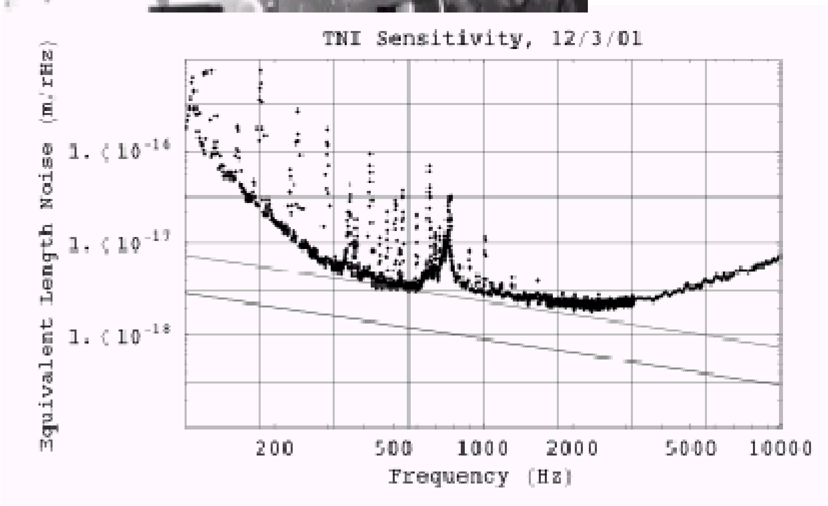
- Stress Birefringence - OK (almost)
  - LIGO Lab metrology show low birefringence, but measurements limited by homogeneity
  - effect of suspension points unknown
- Thermal Birefringence - UNKNOWN
  - needs testing at laser powers comparable to Advanced LIGO power recycling
    - Gingin High Power Test Facility

Thermal Noise

- **Thermal noise driven by:**
  - » **ASTROPHYSICS REACH at 100 Hz**
  - » **internal friction, thermo-elastic damping play a role**
- **Thermal noise compromised by addition of optical coating**
  - » **affects fused silica, too**
- **LIGO Lab Thermal Noise Interferometer program to determine sapphire noise**



**E. Black,
S. Rao, and
K. Libbrecht**



Thermal Noise

Status:

- **Thermal Noise - GUARDED**
  - **requisite Q's measured on small substrates**
    - **need measurements on large substrates**
  - **coating compromise under intense investigation**
  - **TNI should confirm thermal displacement noise**

Meeting the Requirements for Advanced LIGO

Mass	**OK**
Physical dimension	**OK**
Optical homogeneity	**(OK)**
Microroughness	**(OK)**
Internal scatter	**GUARDED**
Absorption	**GUARDED**
Thermal noise	**GUARDED**
Birefringence	**(OK)**
Polish	**OK**

Summary and Future

- **Guardedly optimistic about pursuing sapphire**
  - » **'improvement gradient' positive on most problematic issues**
    - – **absorption?**
  - » **not too many more possibilities for unpleasant surprises**
  - » **coating problem is troublesome, but becoming more understood every day**
- **Advanced LIGO test mass material down select slated for December 2002**
  - » **still on schedule**
    - – **'down select' committee selection underway**
  - » **would be nice to know more, but can make an informed decision**