Test Mass Substrate Material Selection for Advanced LIGO:

An Update from the Optics Working Group

David Reitze
UF
for the OWG

Test Mass Material Selection

- At the LSC meeting, Livingston, LA, March 2004:

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

RECORD OF DECISION/AGREEMENT (RODA)

Document	LIGO-M040020-00-Y
Date:	27 Jan 2004
Title:	RODA: Sapphire/fused silica downselect date
To the Attention of:	COC: GariLynn Billingsley, Bill Kells, Helena Armandula, Gregg Harry SUS: Ken Strain, Norna Robertson, Janeen Romie, Mark Barton, Justin Greenhalgh, Caroline Cantley, Calum Torrie, Jim Hough TNI: Eric Black, Ken Libbrecht AOS: Phil Willems, Dave Ottaway, Mike Smith Systems: Peter Fritschel, Dennis Coyne, David Shoemaker
cc:	aligo_systems, aligo_sus

- Date for selection: June 30, 2004

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June 30th has passed; where are we?

- Deadline driven by intimate link between optics and suspensions
  - » Physical dimensions of test mass material different for sapphire and fused silica
  - » Test mass size difference affects quad suspension design
    - – Must fix size to move design forward (and keep UK funding synchronized…)
- Do we have enough information to make a *good* decision? We always want more…
  - » Very active R&D programs in sapphire and silica still producing important results
  - » Link between substrate and coating performance made clear over last two years; leads to a more complex decision
- Agreement between SUS and OWG to push back decision
  - » Not a problem given current AdL funding and construction schedule

Down Selection Participants

- LSC Participants
  - » Helena Armandula, Gari Billingsley, Eric Black, Jordan Camp*, Dennis Coyne, Marty Fejer*, Sam Finn*, Peter Fritschel*, Gregg Harry, Jim Hough*, Steve Penn, Dave Reitze, Roger Route, Norna Robertson, Shiela Rowan, Peter Saulson*, David Shoemaker**, Phil Willems*

  * DS committee member, **DS chair
- Industrial Partners/Contributors
  - » Chandra Khattak (Crystal Systems, sapphire), Jean-Marie Mackowsky (SMA Virgo, coatings), Roger Netterfield (CSIRO, coatings)

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Sapphire Test Mass Requirements

P. Fritschel, et al., LIGO T010075-00; G. Billingsley, et al., LIGO-T020103-08

	Value	*Driver*
Mass	**40 kg**	**SQL**
Physical dimension	**31.4 cm x 13 cm**	**density of sapphire**
Optical homogeneity	**< 10 nm rms***	**sideband loss in RC**
Microroughness	**< 0.1 nm rms**	**75 ppm arm cavity loss**
Internal scatter	**< 50 ppm (2X)***	**Overall carrier loss**
Bulk Absorption	**< 100 ppm/cm****	**Overall carrier loss; optical path distortion**
Coating Absorption	**< 1 ppm**	**75 ppm arm cavity loss**
Thermal noise	**$Q > 2 \times 10^8$**	**Sensitivity in 50-300 Hz band**
Birefringence	**< 0.1 rad***	**Overall carrier loss**
Polish	**< 0.9 nm rms**	**75 ppm arm cavity loss**

***ITM only** ****assumes active thermal compensation above ~40 ppm/cm**

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Fused Silica Test Mass Requirements

P. Fritschel, et al., LIGO T010075-00; G. Billingsley, et al., LIGO-T020103-05

	Value	*Driver*
Mass	**40 kg**	**SQL**
Physical dimension	**3.4 cm x 20 cm**	**density of silica**
Optical homogeneity	**< 10 nm rms***	**sideband loss in RC**
Microroughness	**< 0.1 nm rms**	**75 ppm arm cavity loss**
Internal scatter	**< 50 ppm (2X)***	**Overall carrier loss**
Bulk Absorption	**< 3 ppm/cm****	**Overall carrier loss; optical path distortion**
Coating Absorption	**< 0.5 ppm**	**75 ppm arm cavity loss**
Thermal noise	**$Q > 1 \times 10^8$**	**Sensitivity in 50-300 Hz band**
Birefringence	**< 0.1 rad***	**Overall carrier loss**
Polish	**< 1.2 nm rms**	**75 ppm arm cavity loss**

*ITM only **assumes active thermal compensation

The Importance of Coatings

G. Harry, et al., LIGO-C030187-00-R

Parameter	Sapphire goal	Sapphire requirement	Fused Silica goal	Fused Silica requirement
Mechanical loss[1]	2×10^{-5} *	6×10^{-5} *	1×10^{-5} **	3×10^{-5} **
OpticalAbsorption[2]	0.5 ppm	1 ppm	0.2 ppm	0.5 ppm
Thermal expansion[3]	5×10^{-6}/K*	< 2×10^{-5}/K* >1×10^{-6}/K*	5×10^{-7}/K**	< 2×10^{-6}/K** >1×10^{-7}/K**
Birefringence[4]	1×10^{-4} rad	2×10^{-4} rad	-	-
Scatter[5]	1 ppm	2 ppm	1 ppm	2 ppm
Thickness uniformity[5]	10^{-3} (over 21.5 cm diameter) 10^{-2} (over 33.0 cm diameter)	10^{-3} (over 21.5 cm diameter) 10^{-2} (over 30.0 cm diameter)	10^{-3} (over 21.5 cm diameter) 10^{-2} (over 33.0 cm diameter)	10^{-3} (over 21.5 cm diameter) 10^{-2} (over 30.0 cm diameter)
ITM HR transmission	-	5×10^{-3} $\pm 2.5 \times 10^{-4}$	-	5×10^{-3} $\pm 2.5 \times 10^{-4}$
ETM HR transmission	5 ppm	10 ppm	5 ppm	10 ppm
Test Mass HR matching $2 (T_1-T_2)/(T_1+T_2)$[6]	5×10^{-3}	1×10^{-2}	5×10^{-3}	1×10^{-2}
AR reflectivity	-	200 ±20 ppm	-	200 ±20 ppm

Currently
Mechanical loss: 2-3 x 10^{-4} (tantala)
Absorption: ~ 0.5-1 ppm

Decision Criteria: Beyond the physical, optical, and mechanical characteristics…

- Primacy of the astrophysics mission of Advanced LIGO
  - » Which substrate is better suited to optimizing the number, type, and parameter estimation of detectable events?
- IFO performance - “Will it work if we choose _______?”
  - » Hard failure mode – interferometer will not operate (or operate with significant reduction in sensitivity)
  - » Soft failure mode – some reduced sensitivity, reach
- IFO Schedule – “Will there be delays?”
  - » Fabrication delays
  - » Commissioning delays
- IFO Implementation Issues → thermal compensation
- Cost – turns out to be about the same for both materials
- Fallback
  - » “If we choose substrate X and discover a nasty hard failure mode, how easily can we fall back to substrate Y?”

DS 'Methodology'

- Exchange and coordination of research through meetings and telecons
  - » Scheduled monthly OWG meetings
  - » Frequent (at least monthly, sometimes more) meetings to discuss coating R&D
- Formal 'Down-selection' telecons
  - » Define and refine selection criteria
  - » Identify gaps in knowledge
  - » Quantify risk
- Score sheet for sapphire and silica
  - » All scores have 'error bars'
  - » Some error bars are larger than others…
  - » Some things are still unknown…
- Work Product → recommendation to the LIGO Lab management (who will make the final decision)

Astrophysics Selection Criteria

G. Harry, D. Shoemaker, MIT

- Different sources → different performance metrics for sapphire and fused silica→
  - » NS-NS inspiral
  - » 10 $M_\odot$ BH-BH merger
  - » Accreting low mass X-ray binary source near 700 Hz
  - » Stochastic background

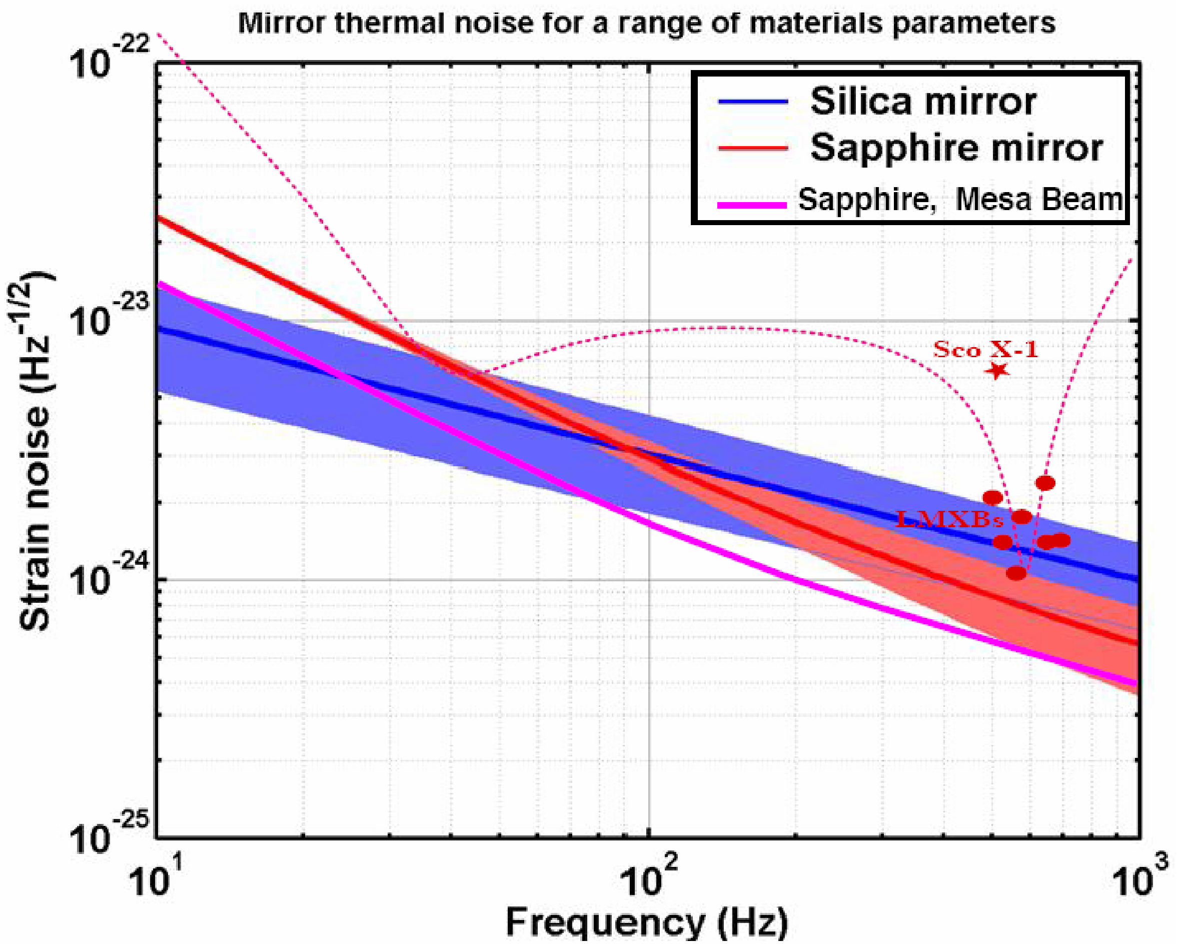
(Bildstein, arXiv:astro-ph/0212004)

- Evaluate on Bench 2.1
  - » Consider optimistic, pessimistic, and baseline TM parameters
  - » Normalized performance dependent on event type
    - – Inspirals, mergers, XRB → $(2*\mathrm{Range}_{subX}/\Sigma \mathrm{Range})^3$
    - – Stochastic → $\mathrm{Log}(\Omega_{subX}/\Omega_{subY})$
  - » Equal weighting for events

Thermal Noise Performance: LMXBs

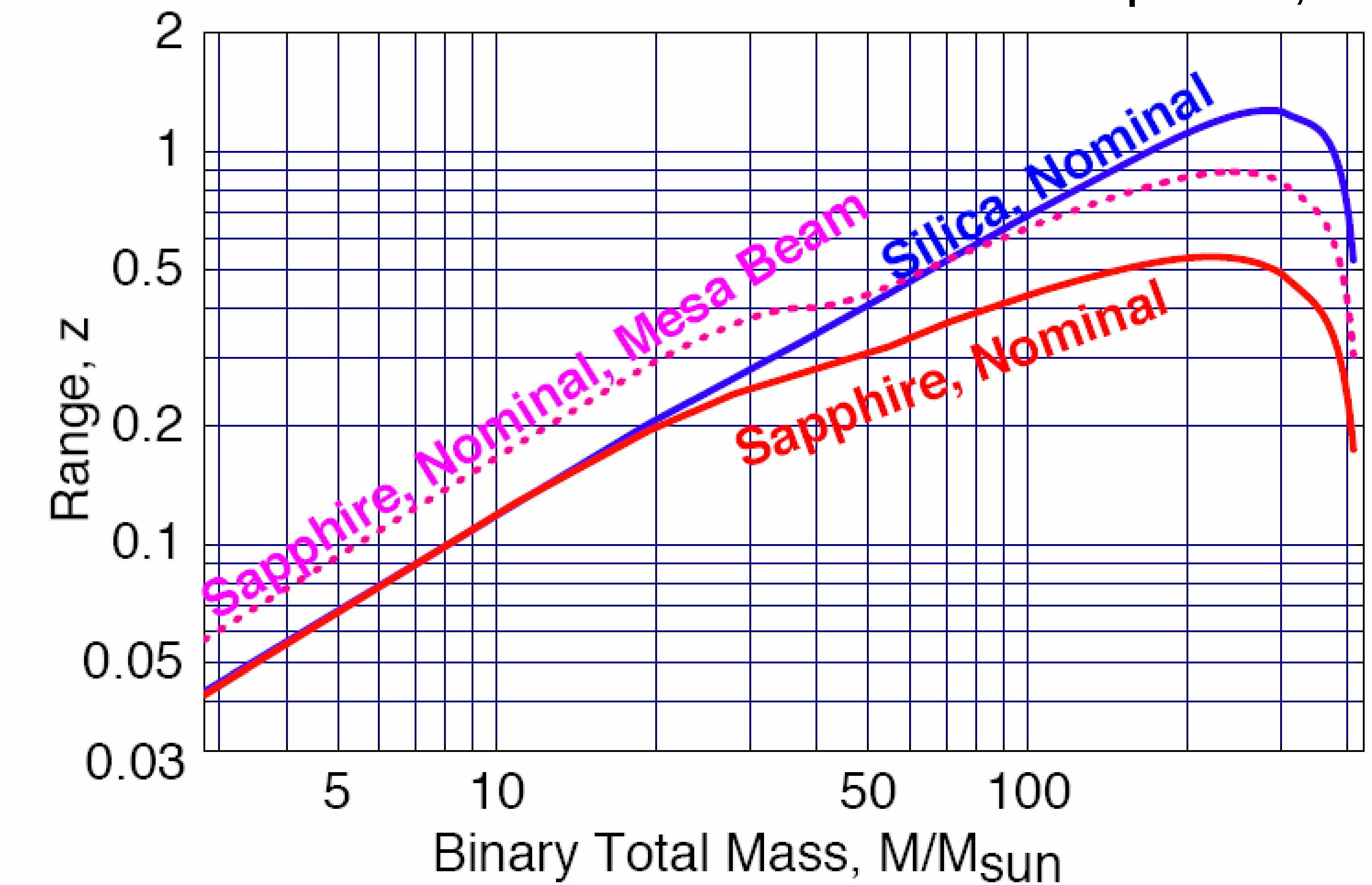
P. Fritschel, G. Harry, MIT
Kip Thorne, CIT

- FS has better low frequency performance
  - » But more uncertainty
  - » Sapphire TE noise helped by mesa beam
- Sapphire has better high frequency performance
  - » Sapphire sees almost all LMXBs



Impact on BHBH binary searches

Kip Thorne, CIT



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Astrophysics Score Sheet

		SAPPHIRE		SILICA		Weight
		value	normalized	value	normalized	
NSNS distance (MPC)						
	baseline	191	1.00	191	1.00	1.00
	optimistic	208	0.73	254	1.33	1.00
	pessimistic	165	1.12	153	0.89	1.00
10Ms BHBH distance (MPC)						
	baseline	923	0.82	1052	1.21	1.00
	optimistic	1016	0.52	1510	1.71	1.00
	pessimistic	762	0.97	775	1.03	1.00
LMXB at 730 Hz, $x10^{-25}$						
	baseline	6.8	2.64	12	0.48	1.00
	optimistic	4.5	2.20	7	0.54	1.00
	pessimistic	9.6	2.37	16	0.51	1.00
Stochastic background Ω, $x10^{-9}$						
	baseline	1.7	0.98	1.2	1.02	1.00
	optimistic	1.6	0.98	1.1	1.02	1.00
	pessimistic	1.7	1.01	1.9	0.99	1.00
Weighted astrophysical performance		1.28		0.98		

Performance Selection Criteria

- Which substrate has the best opportunity for reaching the AdLIGO SRD sensitivity?
- Risks for sapphire
  - » Growth of 15-18 large blanks with average absorption < 100 ppm/cm and absorption fluctuations < 0.25 mean absorption
  - » Not as much known about coatings on sapphire
    - – Adhesion, absorption
  - » Thermal noise from differential thermal expansion between silica bonding ears and sapphire flats
- Risks for Silica
  - » Mechanical loss not yet completely understood for large substrates
  - » Coating absorption inhomogeneities → thermal compensation challenge
- Risks for both
  - » Parametric excitation of mirror Stokes modes by laser

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Performance Score Sheet

- Fused silica 1.5x more likely to ‘perform’
- Stokes instability – how important? V.B. Braginsky, et al., Phys. Lett. (2001).

	Sapphire	Silica
fabrication of satisfactory substrates	0.85	0.98
polishing, also sides	0.77	0.93
coating, also adhesion	0.8	0.85
bonding suspension 'ears'	0.85	0.92
managing Stokes instability	TBD	TBD
electrostatic charging	0.85	0.9
PRODUCT of success measures	0.52	0.77

Schedule Perspective

- Evaluation of ‘schedule slippage’ risk
- Vendor delays
  - » Sapphire crystal growth
  - » More difficult to polish sapphire to required tolerances; more steps involved (compensating polish)
  - » Sapphire may require high temperature annealing
  - » Coating adhesion on sapphire
- Assembly delays
  - » Bonding ears for suspension fibers
- Commissioning delays
  - » electrostatic charging

Schedule Score Sheet

- Fused silica 1.9x more likely to meet schedule
  - » Parametric instabilitiy, charging not well investigated

	Sapphire	Silica
fabrication of satisfactory substrates	0.8	0.98
polishing, also sides	0.57	0.87
coating, also adhesion	0.98	0.98
bonding suspension 'ears'	0.95	0.95
managing Stokes instability	TBD	TBD
electrostatic charging	TBD	TBD
PRODUCT of success measures	0.42	0.79

Implementation Perspective

- How does the choice of substrate impact implementing AdLIGO IFOs?
  - » Can we fit a second interferometer at one of the sites?
  - » Suspension issues related to TM size differences?
  - » Thermal compensation
  - » Fallback

Implementation Score Sheet

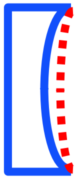
- Sapphire 4.5x better than silica
- Thermal compensation implementation critical

	Sapphire	Silica
second interferometer at a site	0.9	0.9
suspension design	0.85	0.9
thermal compensation	0.86	0.17
angular instability	0.85	0.9
fallback to the alternative substrate	TBD	TBD
PRODUCT of success measures	0.56	0.12

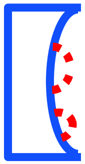
Thermal Compensation

Phil Willems, CIT, Ryan Lawrence, MIT

- Implemented in LIGO I
  - » Stabilization of power recycling cavity for RF sidebands
- For AdLIGO, require homogeneous and inhomogeneous compensation
- Homogeneous heating: beam profile imprints $\Delta T(r)$ on mirror due to average absorption
  - » $\Delta OPD = \Delta T(r)\,(dn/dT)\,L \rightarrow$ bulk index optical path distortion
  - » $\Delta L = \alpha\,\Delta T(r)\,L \rightarrow$ surface physical distortion
  - » Compensate using a ring heater or laser (CO_2 the current choice)



- Inhomogeneous heating: beam profile imprints $\Delta T(x,y,z)$ on mirror due to fluctuations in absorption
  - » Compensate using a laser (CO_2 the current choice)



- Both substrate and coating absorption problematic
  - » Coating more so!

Thermal Compensation (cont'd)

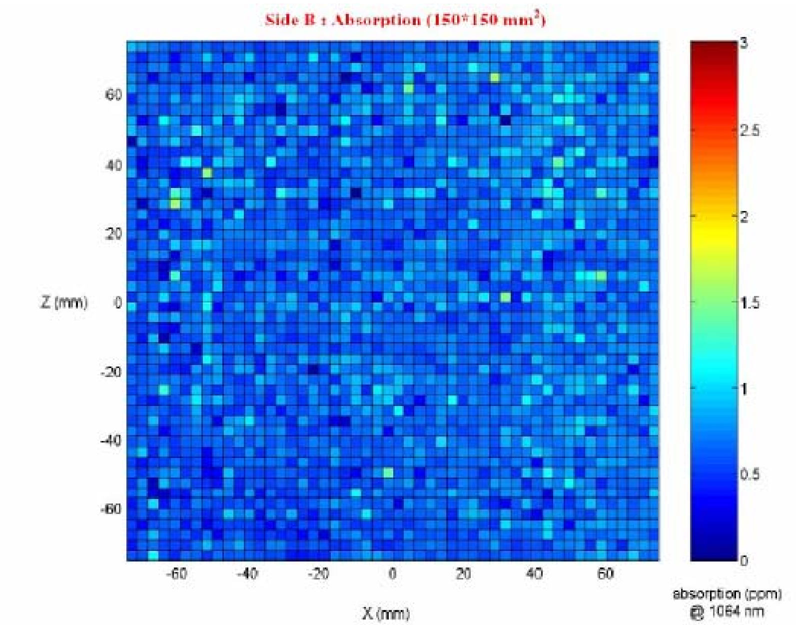
Phil Willems, CIT

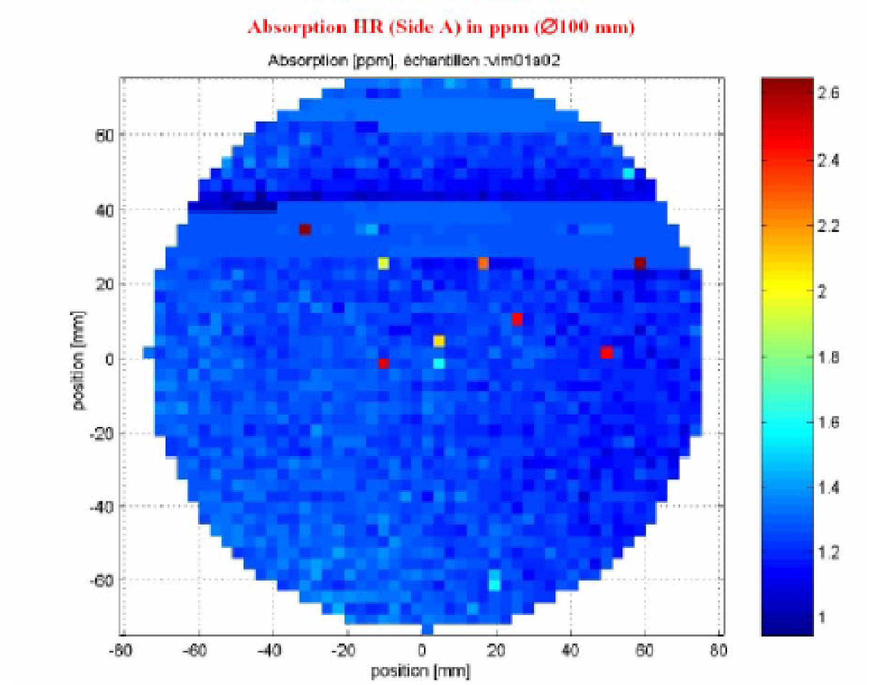
- Affects AdLIGO in 3 ways

1) Arm cavity mode and scattered power
   a. Homogeneous → waist, spots on end mirrors are power dependent
      i. Mode changes → **sapphire = 0.9, silica = 0.8**
      ii. For laser actuation, worry about injecting noise → **sapphire = 0.5, silica = 0.9**
   b. Inhomogeneous → coating absorption inhomogeneties
      i. Not much known, but can tolerate 30 mW (I) hot spots → **sapphire = 0.8, silica = 0.2**

Coating Absorption Maps - Fused Silica

- SMA Virgo





Thermal Compensation (cont'd)

Phil Willems, CIT

2) RF sideband power in the recycling cavities

- RF sidebands resonate in PR, SR cavities

Thermal distortions clamp sideband power

i. Silica compensable for coating absorption < 0.5 ppm

ii. Sapphire compensable for coating absorption < 0.5 ppm

  i. Inhomogeneites cause significant problems for sapphire

sapphire = 0.8, silica = 0.6

3) Efficiency of GW coupling to dark port

- GWs resonate in SR thermally distorted SR cavity
  - depends on operational mode (tuned vs detuned)
  - depends on frequency range (source)

sapphire = 0.6, silica = 0.4

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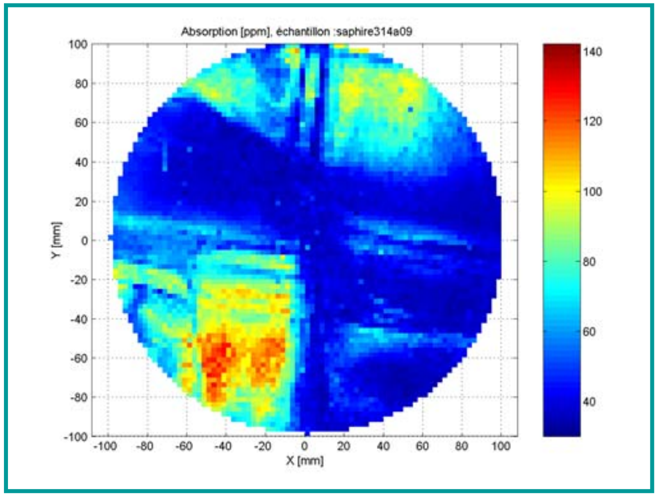
Sapphire Outstanding Issues

- Absorption in large substrates:
  - » 3 pieces measured by SMA-Virgo
    - – **#1 (314 mm x 130 mm): 60 ppm/cm average, 30 –130 ppm/cm range**
    - – **#2 (314 mm x 130 mm): 31 ppm/cm average, 10 – 53 ppm/cm range**
    - – **#3 (250 mm x 100 mm): 49-55 ppm/cm average, 29 –110 ppm/cm range**
- Post-growth annealing studies (Stanford)
  - » Annealing time scaling with substrate size?
  - » Does annealing smoothout inhomogeneous absorption?

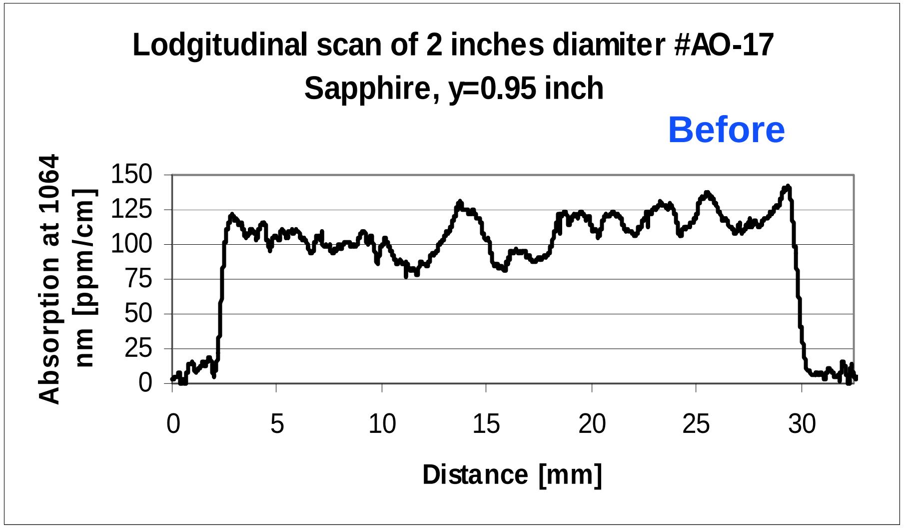


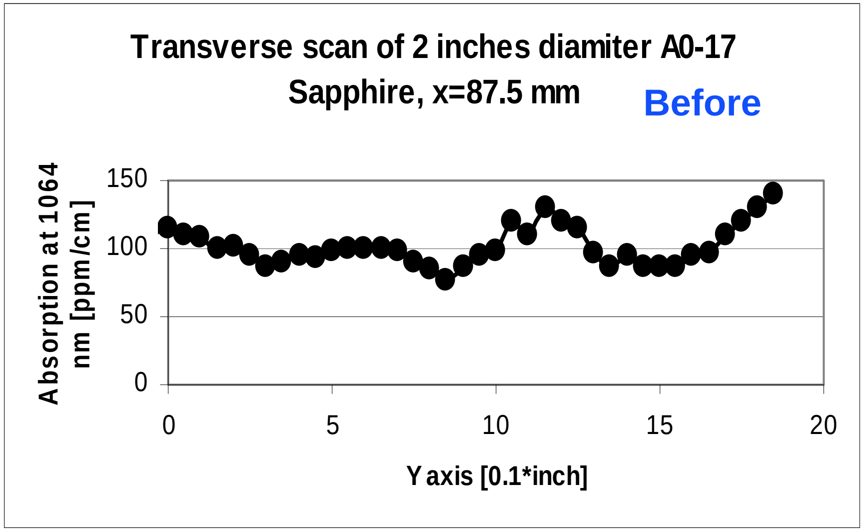
Absorption in Sapphire

R. Route, M. Fejer, Stanford

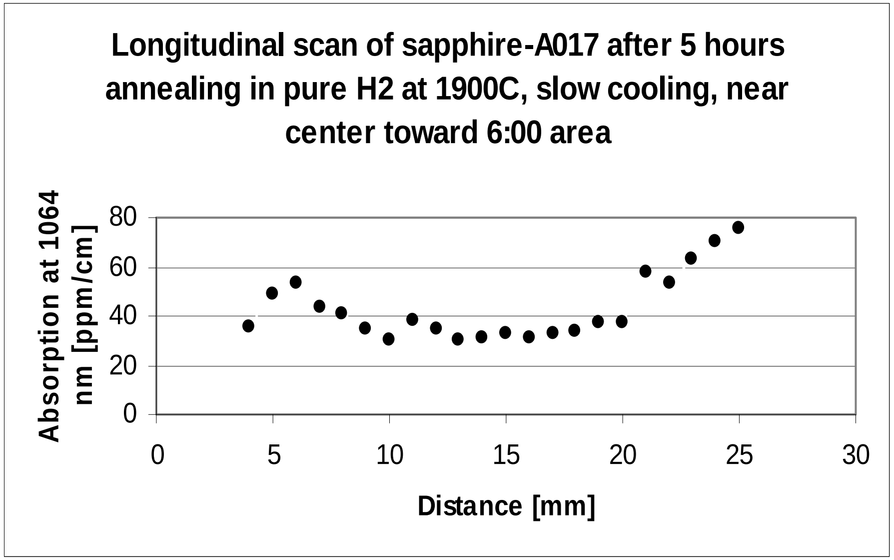
- Investigates methods for reducing homogeneous and inhomogeneous absorption using high temperature anneal and cooling
  - » Vary T, cool down period, annealing gas
- In small samples (2” x 2”), see reductions to 10-20 ppm/ range
  - » Need to look at larger samples
- Possible evidence for ‘smoothing’ of inhomogeneities due to diffusion
  - » Need more statistics

CSI-A017 sapphire cylinder – results of hydrogen-annealing at 1900°C

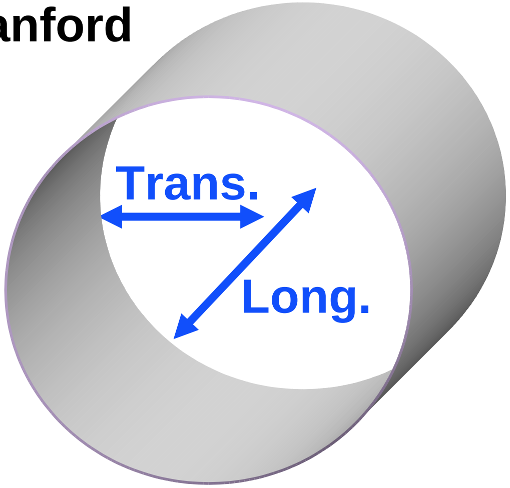




After



R. Route, M. Fejer, Stanford



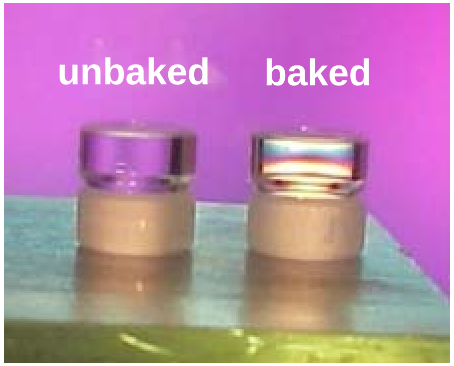
Hi-Temp. Vacuum Annealing Results

(Promising but need more data on high spatial frequency inhomogeneities and kinetics)

ID	Start Date	Actual Temp.	Time	Heat/Cool	Ambient	Before HT	After HT	Comments	Ambient Spec.
Half CSI windows, 25.4 mm dia by 12.5 mm thick									
103-A	11/10/1999	1198 C	12 hrs	310 C/hr	0.2 CFH	30	20-25		H2/N2
103-A	1/22/2000	1800 C	80 hrs	800 C/hr	Hi-Vac.	20-25	18		< E-5 Torr
103-B	11/11/1999	1198 C	16 hrs	310 C/hr	0.2 CFH	27-30	20		Wet H2/N2
103-B	12/9/1999	1800 C	24 hrs	800 C/hr	Hi-Vac.	20	12-15		< E-5 Torr
103-B	1/12/2000	1800 C	42 hrs	20 C/hr	Hi-Vac.	12-15	12	Repolish req'd	< E-5 Torr
106-A	11/11/1999	1800 C	15 hrs	800 C/hr	Hi-Vac.	80-100	30-35		< E-5 Torr
107	3/11/2000	1800 C	100 hrs	20 C/hr	Hi-Vac.	80	40-80		< E-5 Torr
107	3/16/2000	1800 C	96 hrs	20 C/hr	Hi-Vac.	40-80	30-45		< E-5 Torr
107	4/14/2000	1800 C	100 hrs	20 C/hr	Hi-Vac.	30-45	TBD		< E-5 Torr
105-T-A	3/29/2000	1198C	10 hrs	200C/hr	0.2 CFH	40-55	27-37		H2/N2
105-T-A	3/31/2000	1800 C	96 hrs	20 C/hr	Hi-Vac.	27-37	12-18		< E-5 Torr
105-T-A	4/14/2000	1800 C	100 hrs	20 C/hr	Hi-Vac.	12-18	TBD		< E-5 Torr
105-T-B	3/31/2000	1800 C	96 hrs	20 C/hr	Hi-Vac.	45-65	15-17		< E-5 Torr
105-T-B	4/16/2000	1125 C	12 hrs	100 C/hr	0.2 CFH	15-17	15-17		H2/N2
105-T-B	4/20/2000	1125 C	100 hrs	25 C/hr	0.2 CFH	15-17	TBD		H2/N2
CSI a-axis cylinders, 50 mm dia by 50 mm long, Hemlite grade									
A227	6/3/2000	1800 C	100 hrs	20 C/hr	Hi-Vac.	50-100	7 - 50	Fractured	< E-5 Torr
AO-17	8/2/2000	1900 C	5 hrs	20 C/hr	~ 0.2 CFH	80 -140	30 - 80		Pure H2
	8/5/2000	1800 C	100 hrs	20 C/hr	Hi-Vac.	30 - 80	5 - 60		< E-5 Torr

Sapphire Outstanding Issues II

- Sapphire mirror coatings
  - » Coating process not as mature as fused silica
    - – Adhesion
      - Microroughness
      - Cleaning surface after polishing
      - R&D effort required by vendor
- Excess noise from silica-sapphire bonding interface
  - » Differential thermal expansion
  - → Stress → creaking
  - » Inhomogeneous bonds suffer more…
  - » Not much known…



Fused Silica Outstanding Issues

- Coating absorption
  - » Identified as a potentially serious problem for thermal compensation in AdLIGO
    - – Homogeneous absorption: > 1 ppm ‘breaks’ interferometer
    - – Inhomogeneous absorption: carrier arm cavity loss; sideband PRM, SRM loss
- Thermal noise in fused silica
  - » Understanding of mechanical loss
    - – Large substrates
    - – Frequency dependence

Mechanical Loss in Fused Silica

Steve Penn, HWS

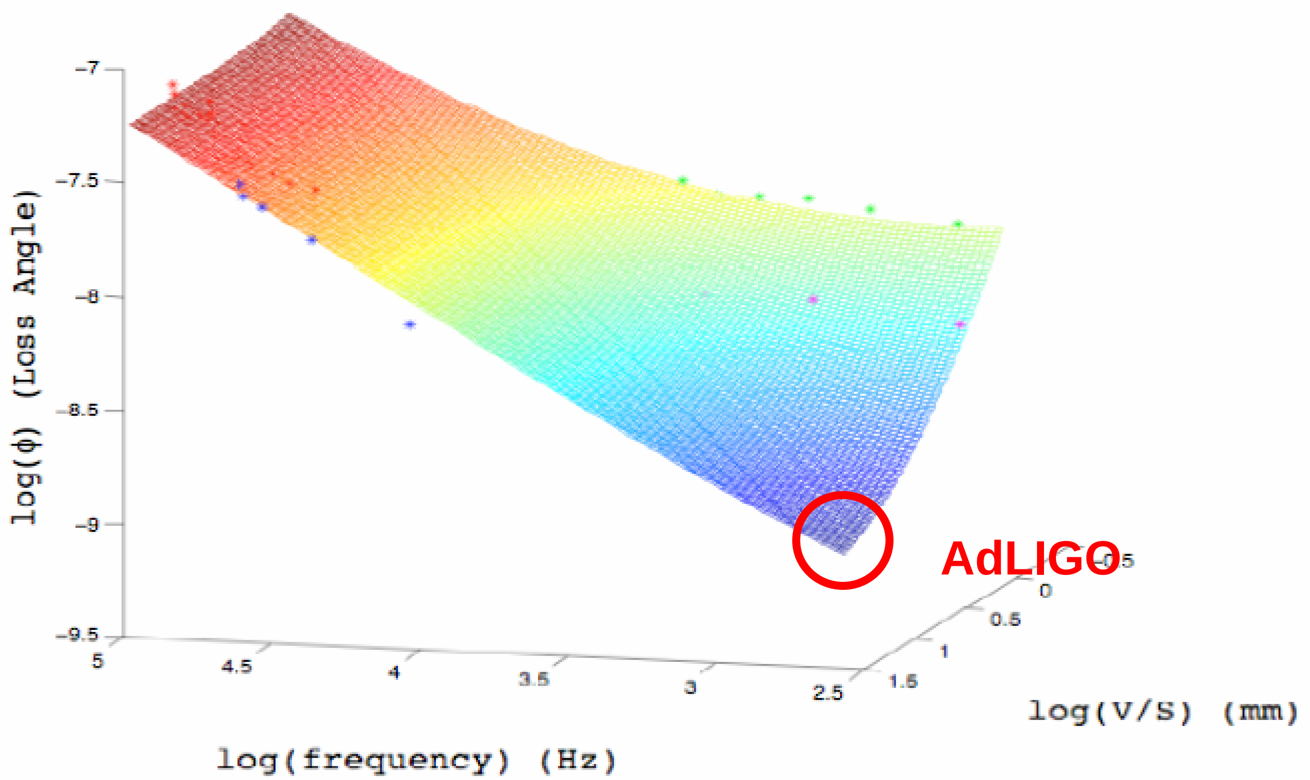
- Need fused silica $Q < 10^8$ for AdLIGO
- Salient data
  - » Syracuse group: low frequency $\phi \sim (V/S)^{-1}$
  - » Measurements on large substrates done at high frequencies (above GW band)
- Empirical model for frequency dependence of fused silica

$$\phi(f, \tfrac{V}{S}) = \left(C_1 / \tfrac{V}{S}\right) + C_2 f^{C_3} + C_4 \phi_{th}$$

Mechanical Loss in Fused Silica

Steve Penn, HWS

Summary: $\phi = 6.18e{-}09\ (S/V) + 7.88e{-}12\ f^{0.77} + 0.827\ \phi_{th}$



Advanced LIGO Coating Research

- Major efforts focused on:
  - » Reducing mechanical loss (thermal, thermo-elastic noise)…
  - » Reducing optical loss (coating absorption and scattering)…
  - » … without forgetting about homogeneity, birefringence, uniformity
- Advanced LIGO R&D groups: Caltech, Glasgow Hobart William Smith College, MIT, Stanford
- Joint R&D efforts with:
  - » CSIRO – stoichiometry, optical loss, Young's modulus of tantala
  - » SMA Virgo – doping and different coatings to reducing mechanical loss

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“Coating thermal noise engineering”

Greg Harry, MIT

- Doping with Ta_2O_5 with Ti relaxes stress
- SMA-Virgo/Glasgow/MIT effort

λ/4 SiO_2 – λ/4 Ta_2O_5 Coatings with TiO_2 dopant

Dopant Conc.	Loss Angle
None	$2.7\ 10^{-4}$
Low	$1.8\ 10^{-4}$
Medium	$1.6\ 10^{-4}$
High	?

Conclusions

- Selection of test mass substrate entering final phase
  - » Late by 'official schedule', nonetheless the delay has been worthwhile
- Sapphire better based on astrophysics considerations
  - » Assumes all sources are equally interesting
- Fused silica better on confidence in performance, schedule
- On cost and implementation, roughly equal except for thermal compensation
  - » Caveat is thermal compensation; favors sapphire, but scary for both…
- Active R&D efforts continuing in sapphire absorption, silica 'Q', coatings
- DS meeting tomorrow 8 am
  - » Decision likely in the very near future
  - » Input solicited

Interpretation of Score

1 = perfectly confident

0.98 = as high as we could hope

0.95 = very good rating for an individual element

0.9 = pretty confident

0.8 = marginally acceptable confidence

0.5 = a 50-50 chance that the thing will work (2x worse sensitivity, <2years delay to SRD)

0 = certain failure

LSC OWG Program Additions

- Today, SWG/OWG joint meeting, 3:30-6:30
  - » Add Erika D'Ambrosia – "Equivalence relation between non spherical optical cavities and application to advanced G.W. interferometers."
- Tomorrow 9:00 – noon
  - » Add Hiro Yamamoto - "Effects of as-built Mirrors"
  - » Add Erika D'Ambrosia – "Flat-Top Beam Profile Cavity Prototype"
  - » Add David Jackrel – "Update on High Power Photodiode Development"