Advanced LIGO Optics Status Report

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for the Core Optics Working Group

Main Efforts of the Core Optics WG

- **Sapphire test mass R&D**
  - » Focus has moved to characteristics of AdLIGO-sized substrates
  - » Beginning to understand asymptotic limits of performance ?
- **Fused silica test mass R&D**
  - » Interest has rekindled based on recent high Q results
  - » Detailed R&D plan formulated for advancing FS to AdLIGO readiness
- **Coating R&D**
  - » Probably the most serious technical risk facing AdLIGO optics
    - – Mechanical loss is high: if no improvement, sensitivity decreases by 30%
    - – Low optical loss must be preserved…
    - – Second round coating R&D program initiated

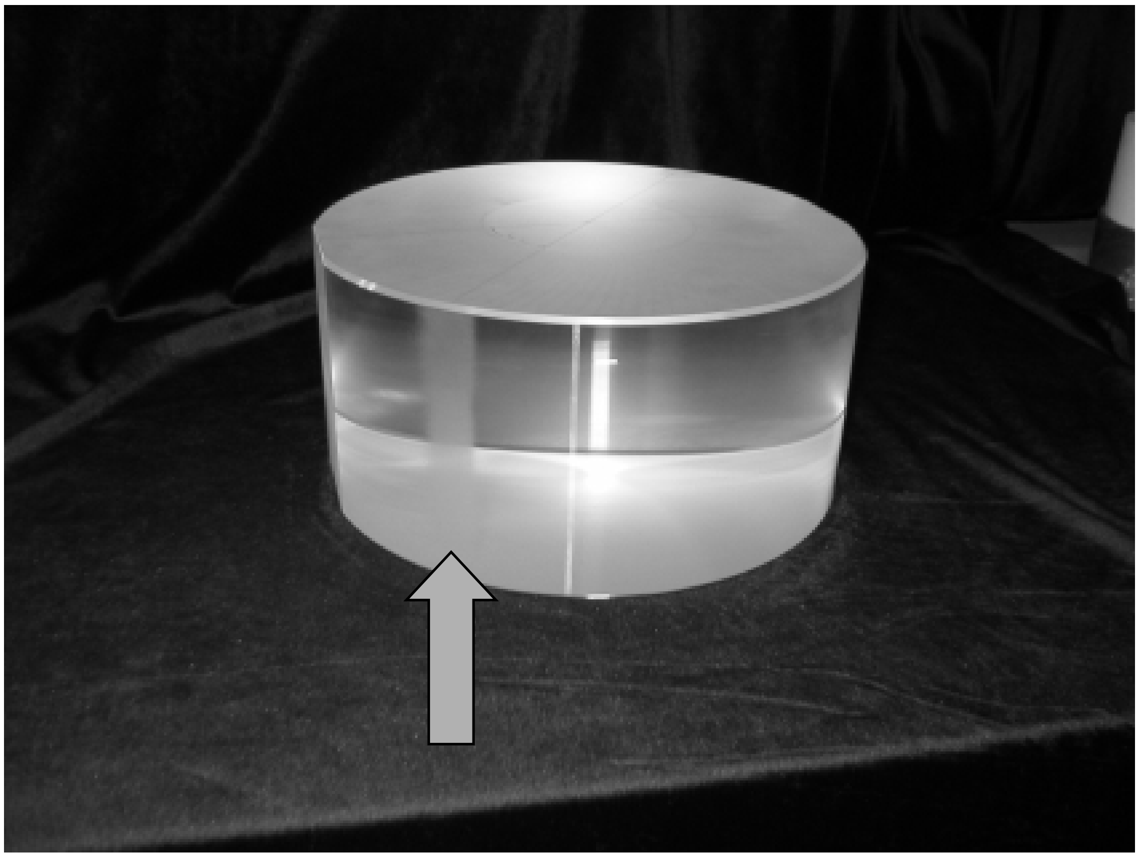
Requirements for Advanced LIGO Sapphire Test Masses

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

Mass	**40 kg**
Physical dimension	**31.4 cm x 13 cm**
Optical homogeneity	**< 10 nm rms**
Microroughness	**< 0.1 nm rms**
Internal scatter	**< 10 ppm/cm**
Absorption	**10 - 40 ppm/cm***
Thermal noise	**$Q > 2 \times 10^8$**
Birefringence	**< 0.1 rad**
Polish	**< 0.9 nm rms**

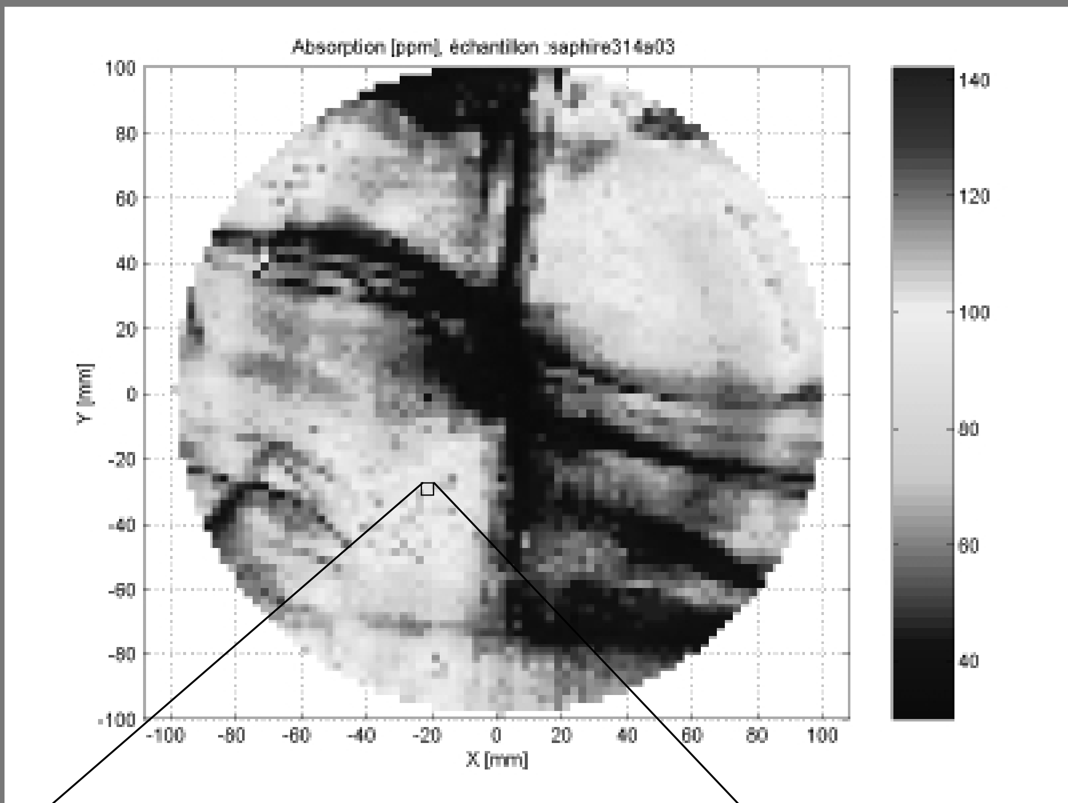
***assumes active thermal compensation at high end**

Large Sapphire Substrates

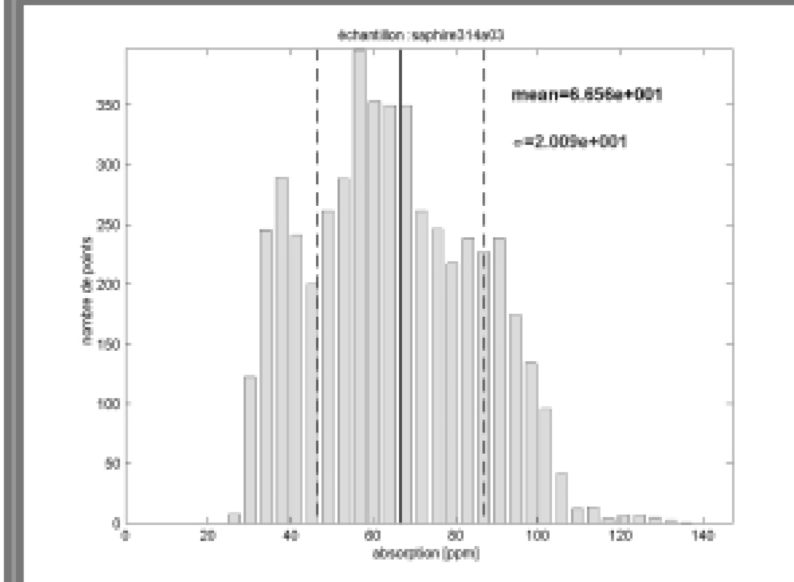


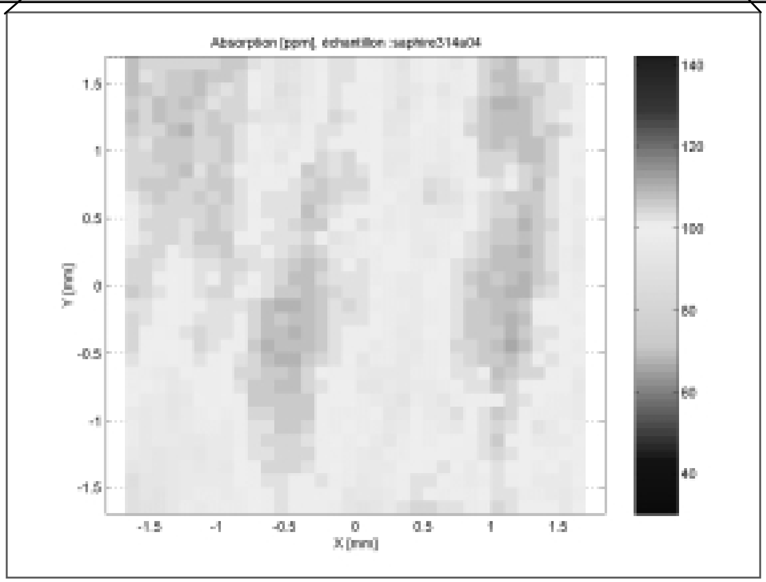
Optical Absorption in Sapphire

- **large number of small samples investigated using interferometric photothermal displacement spectroscopy at Stanford (R. Route, et al.)**
  - » **Crystal Systems: large variance in absorption: best 10 ppm/cm, worst 600 pm/cm, average 40-100 ppm/cm**
  - » **Rubicon: initial pieces show > 100 ppm/cm absorption**
- **High temperature, rapid cool annealing in oxygen reduces absorption 2X**
  - » **20-50 ppm/cm**
- **Focus moves to characterization of large sapphire pieces**
  - » **SMA sapphire inhomogeneity studies on 314 mm diameter substrates**

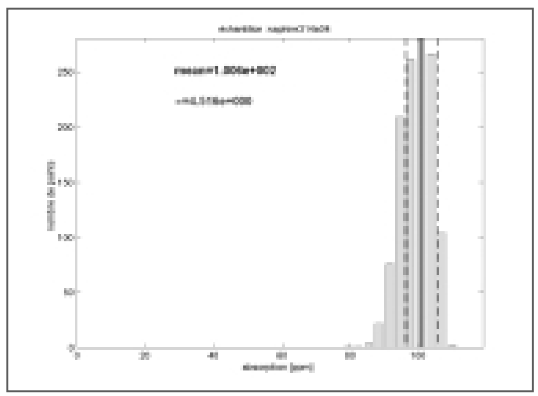


Mean absorption: **67 ppm.cm^{-1}**
ϕ 200 mm scan
2.5 mm steps





Mean absorption: **101 ppm.cm^{-1}**
3.5x3.5 mm² **zoom**
0.1 mm steps

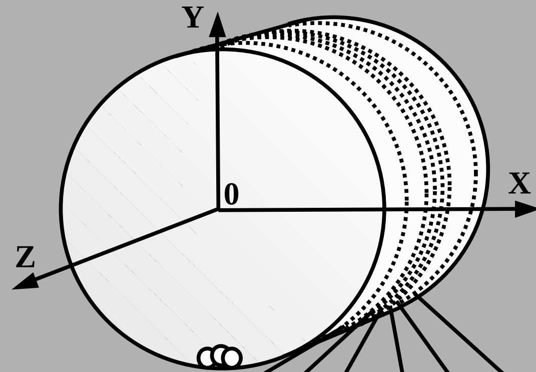


Absorption map at
Z = -63 mm

J. M. Mackowsky,
SMA-Virgo

Université Lyon I
SMA

• Absorption maps at 6 different depths



J. M. Mackowsky,
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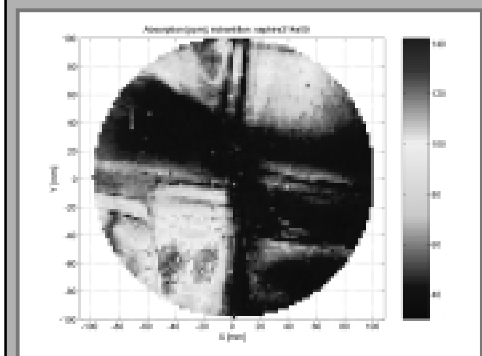
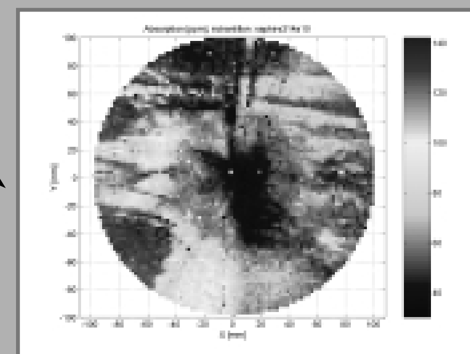
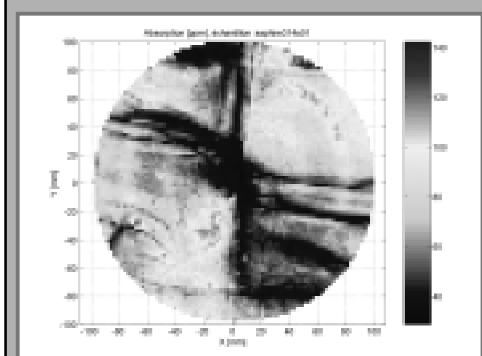


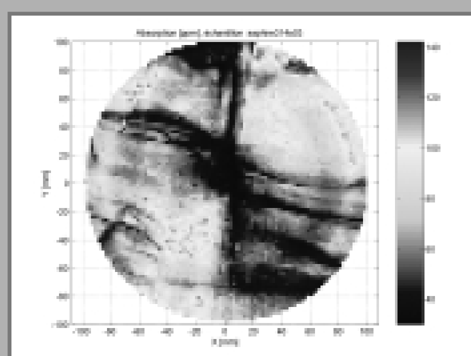
Z = -18 mm



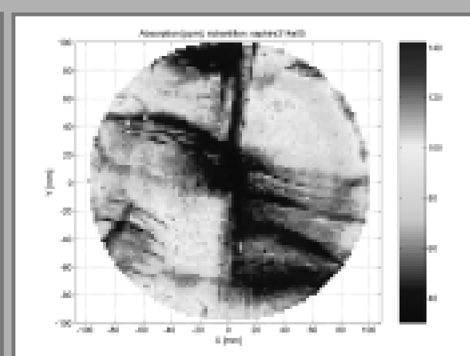
Z = -126 mm



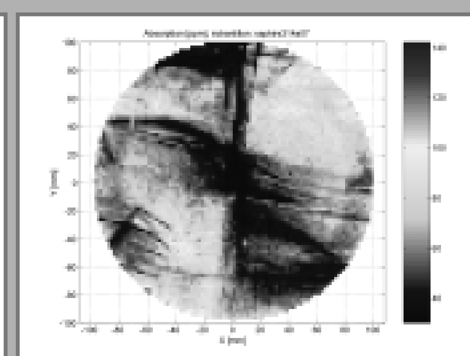
Z = -57 mm



Z = -63 mm



Z = -68 mm



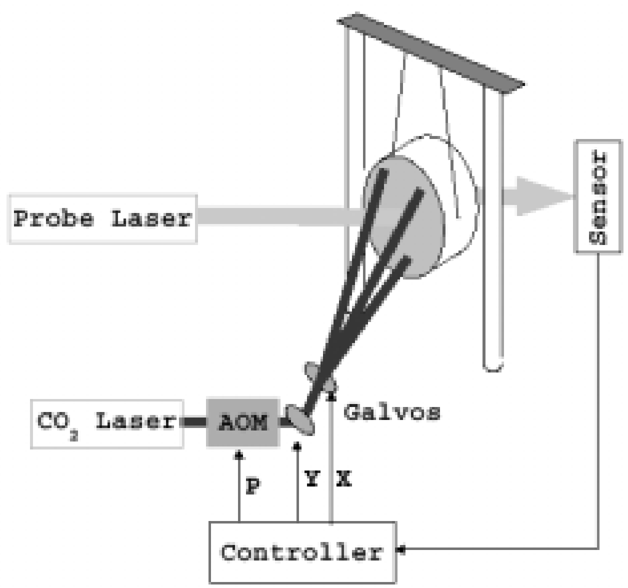
Z = -74 mm

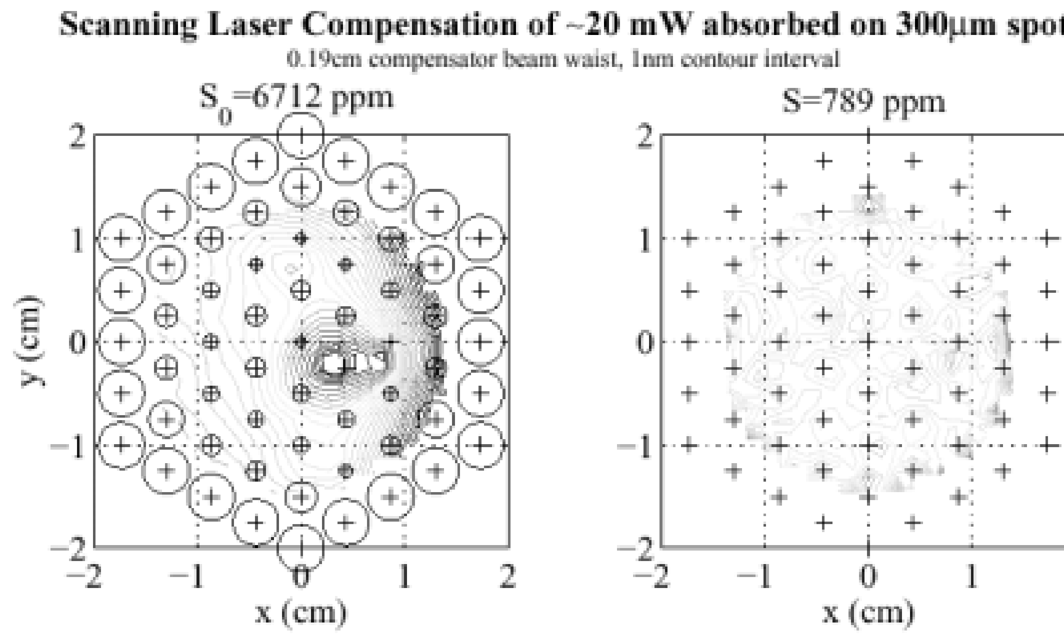
Absorption inhomogeneity in sapphire – thermal compensation

R. Lawrence, M. Zucker, MIT, see G020502-00-R.

Idea: 'Inverse spot' heating using CO_2 laser

For features < 6 mm diameter:
$P_{abs,PV}$*$Area_{feature}$ < 3000 ppm/mm^2





Identification of Trace Elements in Sapphire

S. McGuire (SUBR), G. Lamaze and E. Mackey (NIST)

- Instrumental Neutron Activation Analysis (INAA) to assess correlations between 1064 nm absorption and presence of impurity states
- No smoking gun…

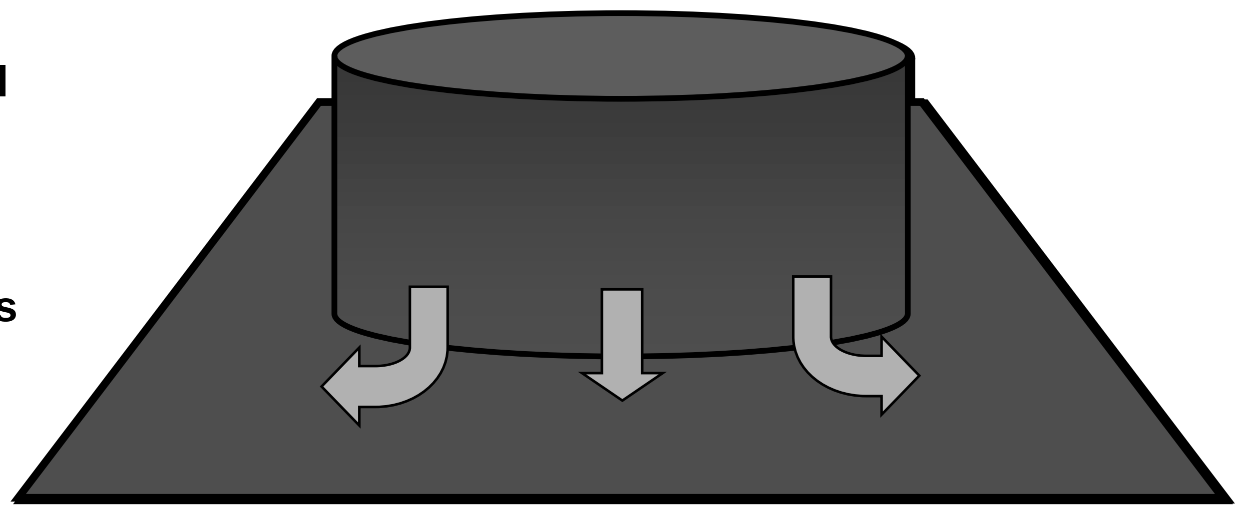
Element	Low Loss	High Loss	SRM 1575a	Certified Value
Sc	0.06 ± 0.02 ppb	0.20 ± 0.04 ppb	10.8 ± 0.8 ppb	10.1 ± 0.3 ppb
Cr	9 ± 2 ppb	8 ± 1 ppb	0.36 ±0.03 ppm	0.3 - 0.5 ppm range
Fe*	≤ 1 ppm	≤ 1 ppm	45 ± 2 ppm	46 ± 2 ppm
Co	≤ 1 ppb	1.2 ± 0.4 ppb	68 ± 3 ppb	61 ± 2 ppb
Zn	30 ± 3 ppb	40 ± 4 ppb	39 ± 2 ppm	38 ± 2 ppm
Sb	≤ 2 ppb	≤ 2 ppb	10 ± 3 ppb	not certified
La	7 ± 0.4 ppb	4 ± 0.4 ppb	53 ± 7 ppb	not certified

Reducing Absorption in Large Sapphire Substrates

R. Route, Stanford

- Best reduction seen when using rapid cooldown (> 400° C/hr)
- Difficult to achieve large gradients in large substrates
- Apply cold plate to aid cooling

1) 1400°C O_2 anneal
2) Gradually lower plate temperature
3) Large thermal gradient accelerates cool down

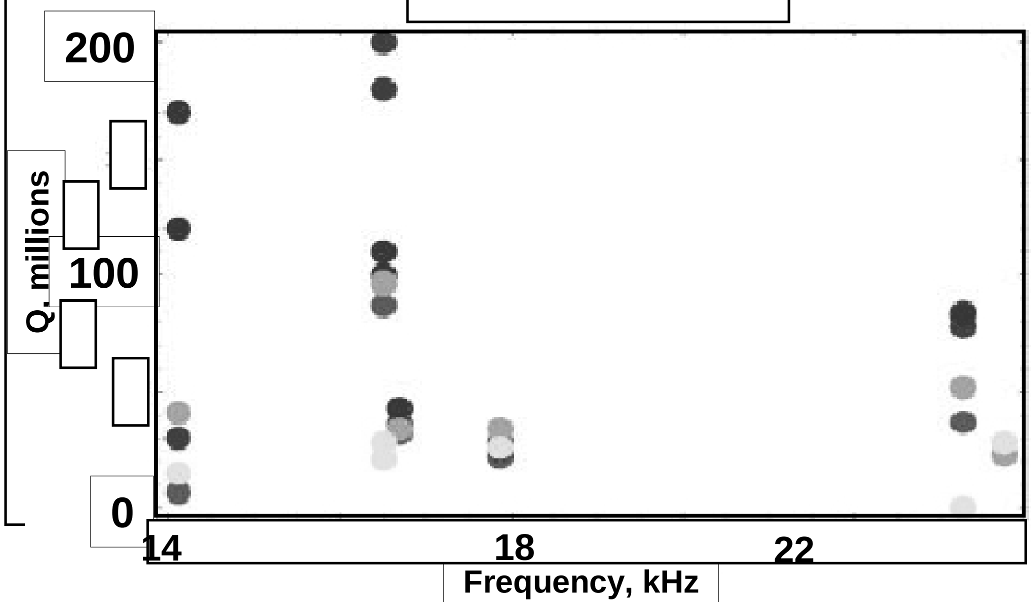


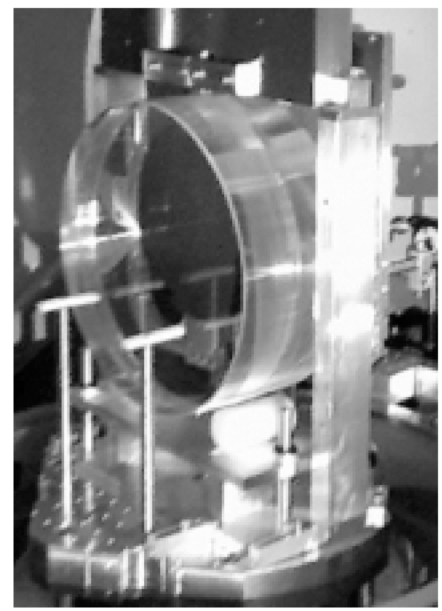
Mechanical Loss in Large Substrates - Sapphire

P. Willems and D. Busby, LIGO- T030087-00-R

- Qs in excess of $2x10^8$!!!
- frequency dependence measured; Q decreases with increasing frequency
- FE model → good agreement with measured Qs, frequency dependence

poor barrel polish contributes to loss





Fused Silica Test Mass Requirements

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

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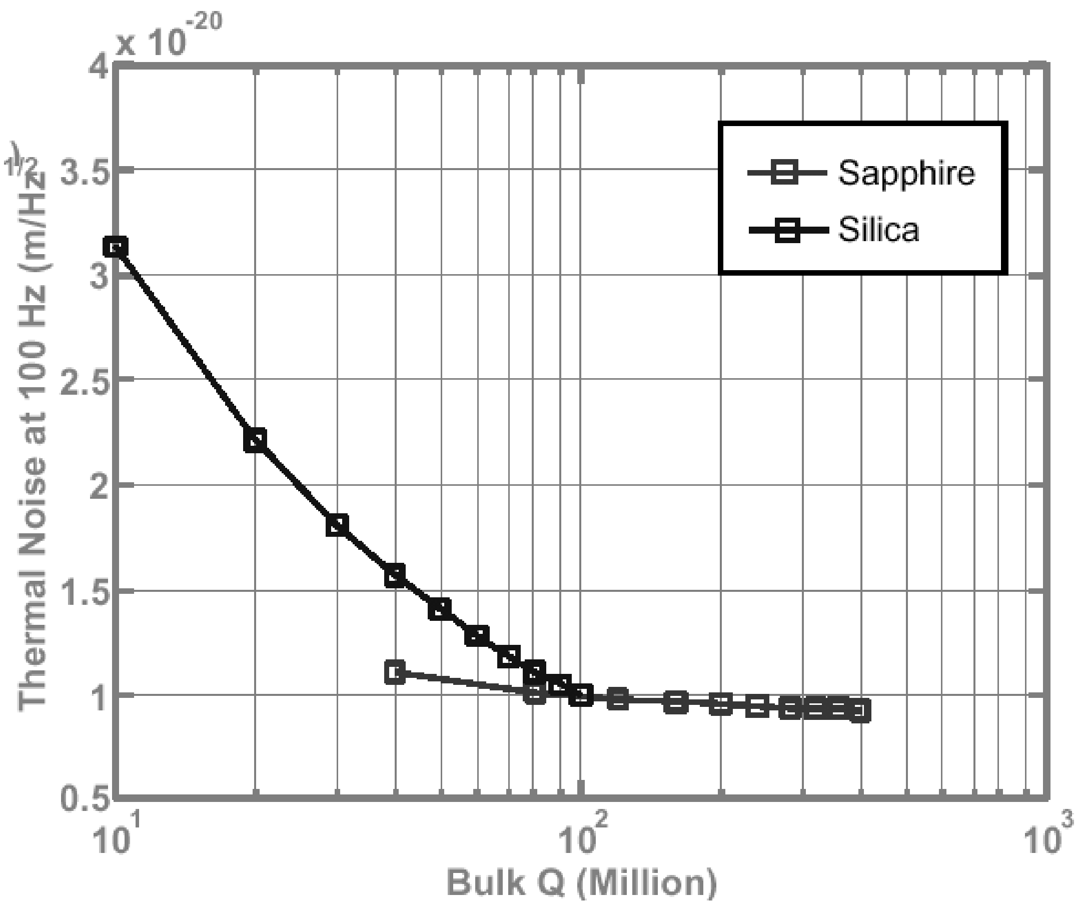
Thermal noise	**Q > 1 x 10^8**
Birefringence	**< 0.1 rad**
Polish	**< 1.2 nm rms**

***assumes active thermal compensation**

Sapphire vs. Fused Silica: Mechanical Loss

AdL Downselect Doc, LIGO-T020103-05-D, G. Billingsley, et al

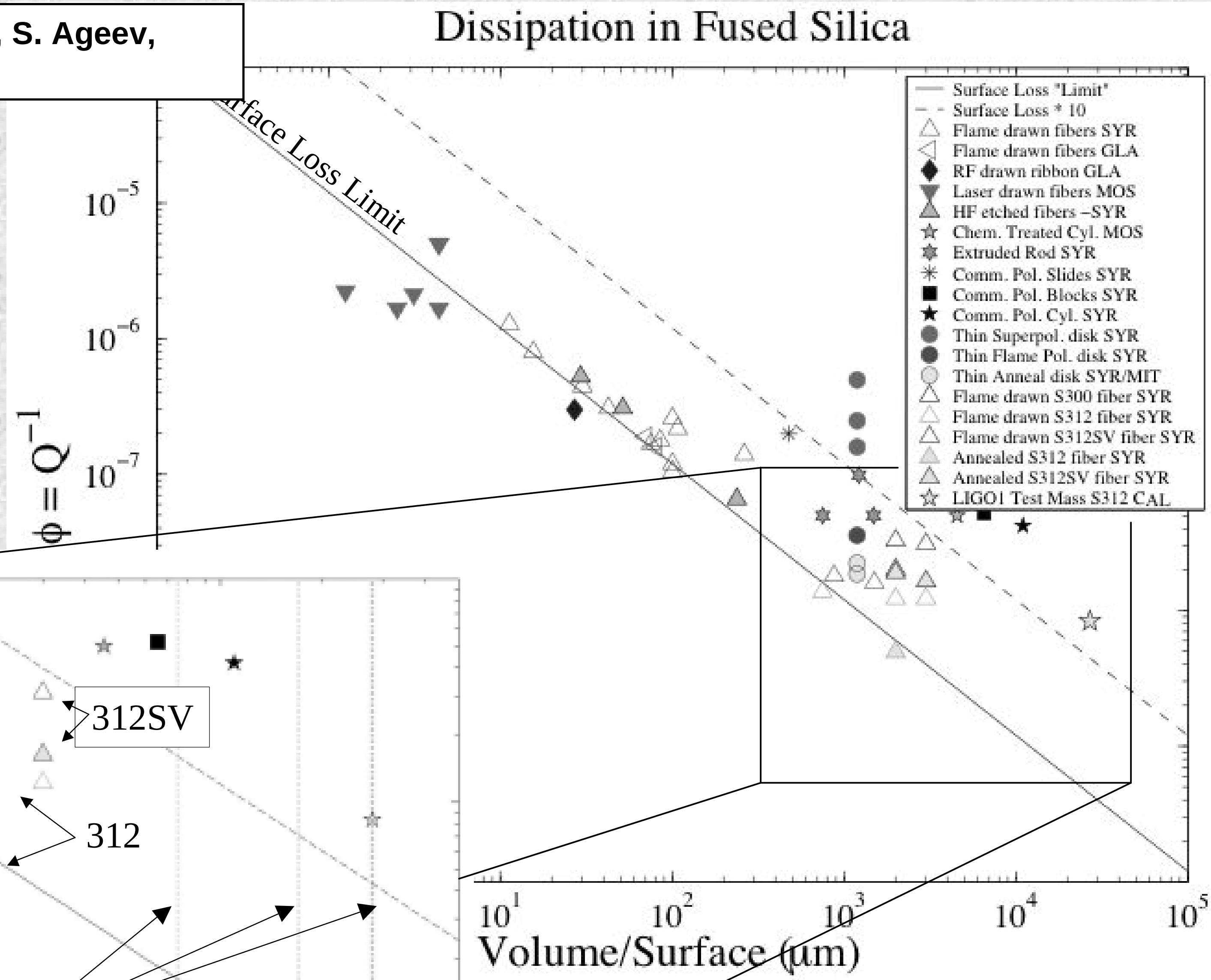
- **sapphire loss dominated by thermo-elastic noise**
- **fused silica looks much better for large Q's**
  - **not plagued by thermoelastic noise**

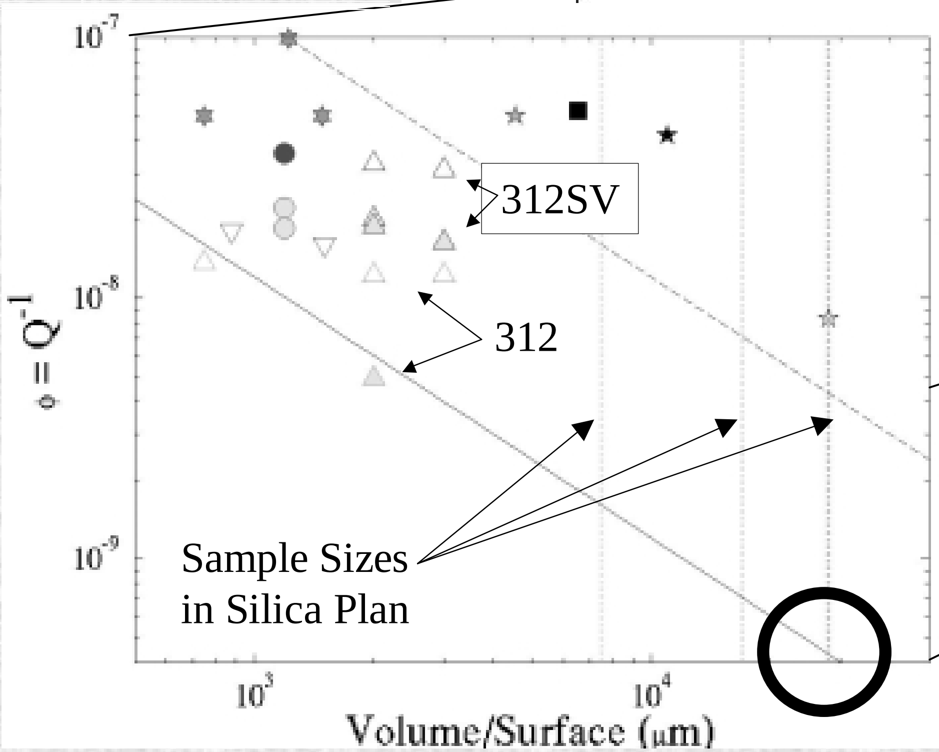


S. Penn, HWS College, S. Ageev, Syracuse

Silica Research

- Very low loss measured in annealed, flame-polished fibers (ϕ = 5e-9) and in uncoated LIGO I test masses (ϕ = 8e-9).
- Planned research to use annealing and increases in V/S to minimize loss.



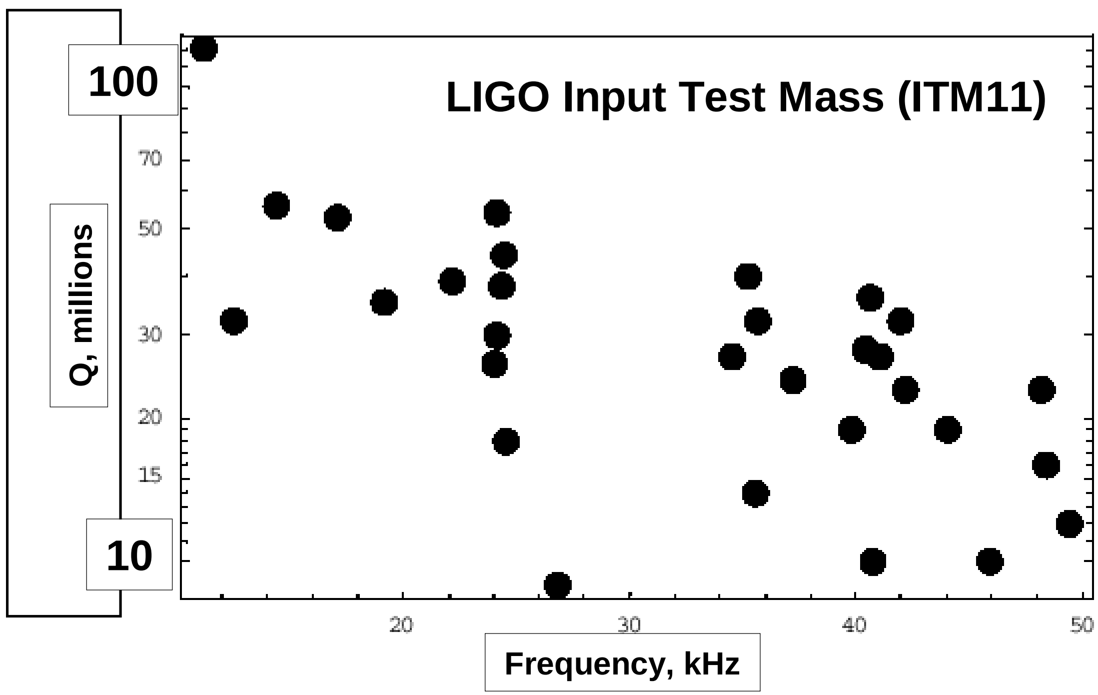


- Possible dependence of loss on silica type has been observed, being explored.
- Annealing oven has been purchased, will be installed in next few weeks.

Mechanical Loss in Large Substrates – Fused Silica

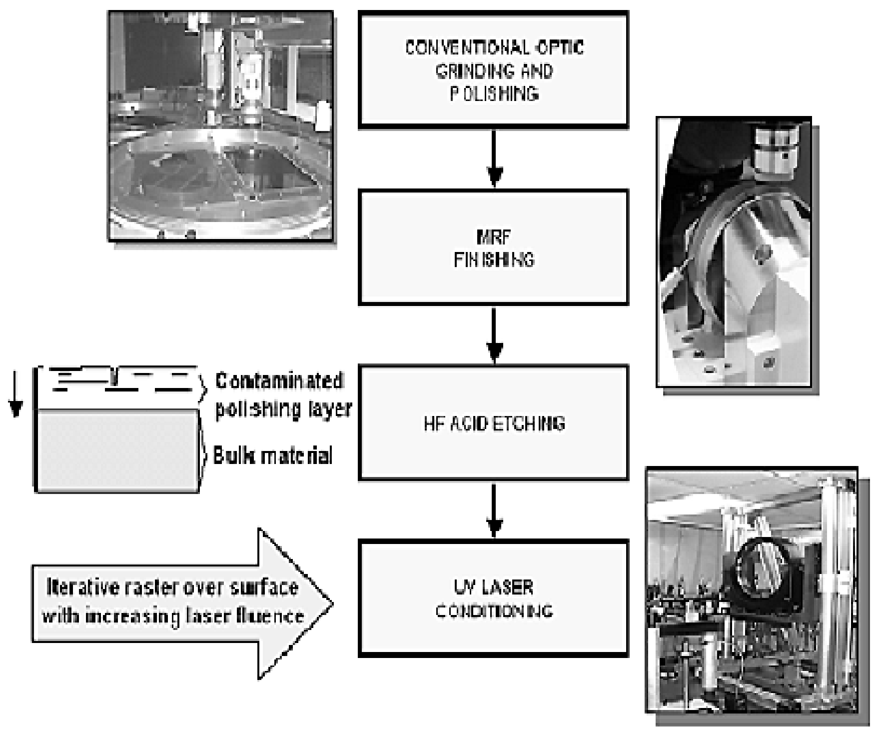
- Q ~ 1.2 x 10^8 (11.2 kHz mode) for LIGO 1 input test mass
- Puzzling result
  - » Much higher than other LIGO TMs
  - » No special treatment (annealing)

P. Willems and D. Busby, LIGO- T030087-00-R



Reducing Mechanical Loss in Fused Silica

- **bulk and surface contributions to mechanical loss; total depends on volume/surface ratio**
  - » **Lossy surface layer ('Bilby layer') dominates loss**
  - » **Bilby layer caused by polishing and subsurface damage (down to 1 μm)**
- **Magnetorheological finishing (MRF)**
  - » **Final polishing technique – does not induce subsurface damage**
  - » **Large shear stress, negligible normal stress applied to surface**



Advanced LIGO Test Mass Coatings: Requirements

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*	$< 2 \times 10^{-5}$/K* $>1 \times 10^{-6}$/K*	5×10^{-7}/K**	$< 2 \times 10^{-6}$/K** $>1 \times 10^{-7}$/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

Coating Mechanical Loss

Peter Sneddon, U. Glasgow

- **Both *thermoelastic loss*** and *loss resulting from residual dissipation* are of significance for coating thermal noise (increasing the overall thermal noise level by a few 10s of percent).**
- **Analysis of SiO_2/Ta_2O_5, SiO_2/Al_2O_3 and Al_2O_3/Ta_2O_5 coatings suggests that Ta_2O_5 has greater residual loss than SiO_2 and Al_2O_3**
  - **SiO_2 and Al_2O_3 have frequency-dependent loss**
- **For a silica substrate:**
  - **a SiO_2/Ta_2O_5 coating has the lowest thermoelastic noise and the lowest total thermal noise, though is still dominated by the loss in the Ta_2O_5.**

**** V. Braginsky, et al., Phys. Lett. A 312 244**

Coating Mechanical Loss (cont'd)

Peter Sneddon, U. Glasgow

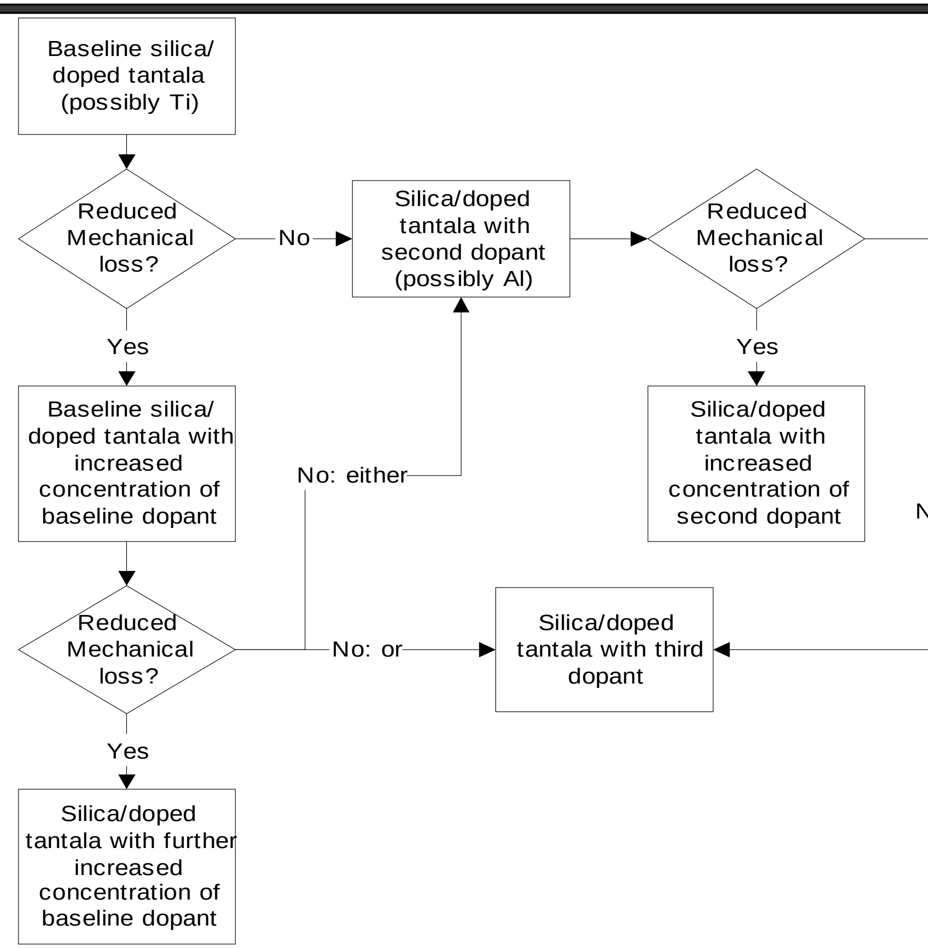
- **For a sapphire substrate:**
  - **a SiO_2/Al_2O_3 coating has the lowest overall thermal noise. However, this can only be reduced by a factor of ~ 2 before the thermoelastic floor is reached.**
  - **an Al_2O_3/Ta_2O_5 coating has a lower thermoelastic noise floor and could have a lower total thermal noise if the residual loss in the Ta_2O_5 can be reduced.**
- ***Suggests the way forward is to reduce the loss of the Ta_2O_5, or find an alternate high-index material with a lower mechanical loss and similar thermoelastic properties. This should reduce the total coating thermal noise for both silica and sapphire mirrors.***

Coating Mechanical Loss

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

Advanced LIGO Coating Development Plan

- outlines research program for participant vendors
- RFP sent to coating vendors
- 5 companies responded positively
- committee formed to evaluate proposals
- met in early August
- CSIRO, SMA-Virgo selected for coating R&D contracts



Coating Mechanical Loss: Other Areas of R&D

- **Characterization of Young's modulus**
  - » **Matching $Y_{coating}$ and $Y_{substrate}$ minimizes coating strain**
  - » **P. Khuri-Yakub (Stanford) – characterization of coating elastic properties**
    - – **Acoustic reflection technique**
    - – **For the most part, agree with known properties**
- **Coating thermal expansion-induced strain**
  - » **Absorption -> heating -> differential thermal expansion -> strain**
  - » **Initial calculations (Coyne and Srinivasan) on small optics**
    - – **Surface deformations predicted for different coatings/substrates**
  - » **Measurements underway at CIT**
- **High throughput (rapid turn-around) Q coating measurements**
  - » **Development of fiber-based readout for measuring coated thin-flexures**
  - » **Collaborative effort between R. DeSalvo (CIT), J. M. Mackowsky (SMA-Virgo), and Virgo**

Sapphire Test Mass Requirements Redux

Legend: √ = 'good' (√) = 'close' ? = 'jury still out'

Mass	**40 kg** √
Physical dimension	**31.4 cm x 13 cm** √
Optical homogeneity	**< 10 nm rms** √**
Microroughness	**< 0.1 nm rms** (√)
Internal scatter	**< 10 ppm/cm** ?
Absorption	**10 - 40 ppm/cm*** (√)
Thermal noise	**Q > 2 x 10^8** √
Birefringence	**< 0.1 rad** ?
Polish	**< 0.9 nm rms** (√)

** **engineered solution**

Fused Silica Requirements Redux

Mass	**40 kg** √
Physical dimension	**34 cm x 20 cm** √
Optical homogeneity	**< 10 nm rms** √
Microroughness	**< 0.1 nm rms** (√)
Internal scatter	**< 10 ppm/cm ?**
Absorption	**0.5 – 1.0 ppm/cm** (√)
Thermal noise	**Q > 1 x 10^8 ?**
Birefringence	**< 0.1 rad** √
Polish	**< 1.2 nm rms** √

Conclusions

- **Sapphire R&D focused on characterization of large substrates**
  - » **Pleasant surprises: large Q!!**
  - » **Unpleasant surprises: large absorption inhomogeneities**
- **Fused silica R&D moving forward**
  - » **A viable alternative to sapphire**
- **Coating R&D is a high priority**
  - » **Minimizing mechanical loss essential for AdLIGO**
  - » **Much effort, $ being spent to beating the coatings into submission**
- **Down select date: March-April 2004**
  - » **Further delay impacts AdLIGO schedule**