Core Optics Components

Design Requirements Review

Armandula, Billingsley, Harry, Kells

5 Jan 2004

Documents

- System Documents
  - » T010075-00 Advanced LIGO System Design Document
  - » T010076 -01 Optical Layout for Advanced LIGO
- Documents being reviewed today
  - » T000127 COC Design Requirements Document
  - » T000128 COC Development Plan
  - » T000098 Conceptual Design Document
  - » T020103 Test Mass Material Downselect Document
- Pertinent documents not being reviewed today
  - » C030187 Coating Development Plan
  - » T030233 Coating Test Plan

Presentations

- Kells
  - » Optical loss/requirements
- Billingsley
  - » Interfaces
  - » Optical design/development
- Harry
  - » Mechanical loss/requirements
  - » Coating design/development
- Armandula
  - » Handling
  - » Cleaning

System Requirements

(Kells)

- COC Optical Properties
- COC Test Mass Losses
- Absorption

COC Optical properties

- *A* axis Sapphire assumed as benchmark:
  - » Chosen for lowest rms bulk striae inhomogeneity (cold state).
  - » Residual striae to be reduced to < 10nm rms by AR surface comp. Polish.
- Depart from LIGO I “point” recycling cavity concept.
  - » Crucial dependence on AOS to servo RC to match.
  - » Stringent absorption specs. To best allow reasonable compensation.
  - » Still may need ~ “point” comp. Of TM surface 1 ROC for hot match
    - – Will this be certainly stable when cold ?
- Require polish quality to ~match best achieved in LIGO I
  - » Extended to ~2x transverse size (may be more of a challenge for coating)
- New coating development with emphasis on Mech. Q
  - » But preserve low absorption, HR transmission, *reduced* point defects.
  - » Coating uniformity and low HR transmission related to minimal layer N?

COC TM Losses

- Critical Total single arm effective loss budget = 75 ppm:
  - » Holds G_{RC}= 17 with T_{ITM}=.005
  - » Cold state: no indir

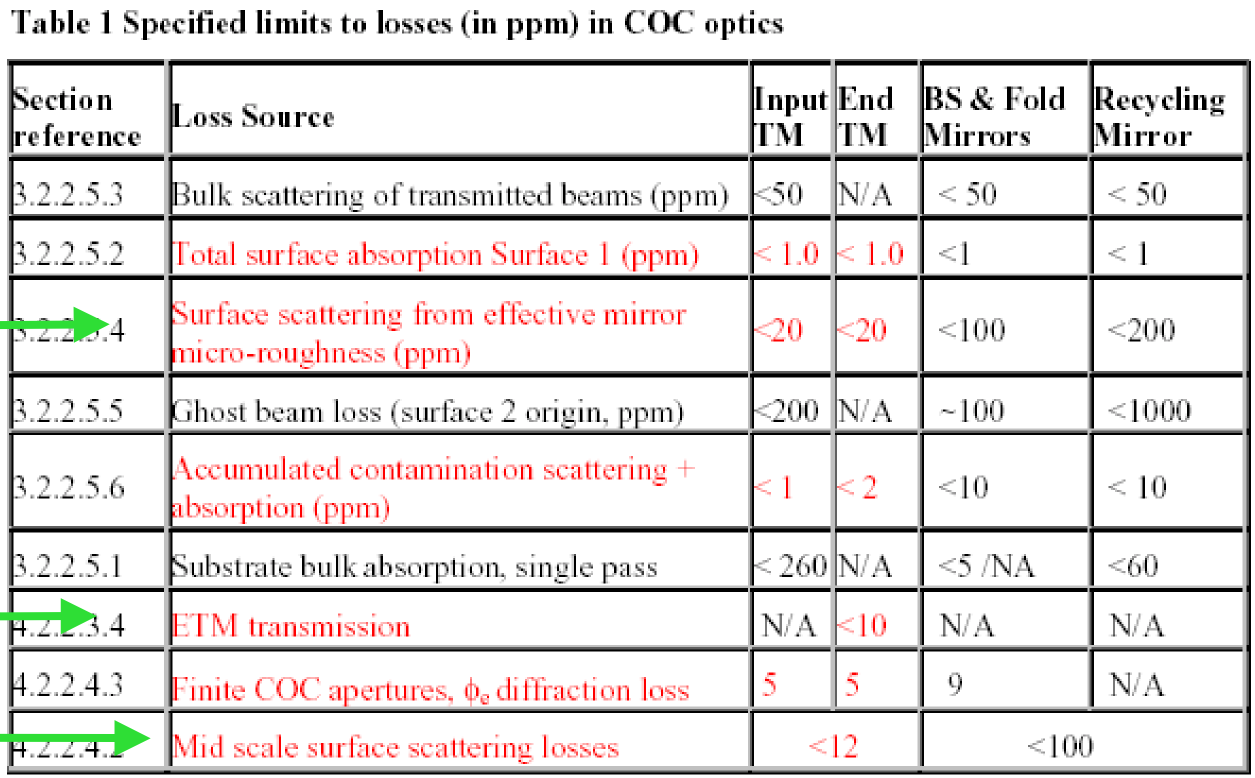


Table 1 Specified limits to losses (in ppm) in COC optics

Section reference	Loss Source	Input TM	End TM	BS & Fold Mirrors	Recycling Mirror
3.2.2.5.3	Bulk scattering of transmitted beams (ppm)	<50	N/A	< 50	< 50
3.2.2.5.2	Total surface absorption Surface 1 (ppm)	< 1.0	< 1.0	<1	< 1
3.2.2.5.4	Surface scattering from effective mirror micro-roughness (ppm)	<20	<20	<100	<200
3.2.2.5.5	Ghost beam loss (surface 2 origin, ppm)	<200	N/A	~100	<1000
3.2.2.5.6	Accumulated contamination scattering + absorption (ppm)	< 1	< 2	<10	< 10
3.2.2.5.1	Substrate bulk absorption, single pass	< 260	N/A	<5 /NA	<60
4.2.2.3.4	ETM transmission	N/A	<10	N/A	N/A
4.2.2.4.3	Finite COC apertures, ϕ_e diffraction loss	5	5	9	N/A
4.2.2.4.2	Mid scale surface scattering losses	<12		<100	

Achieved in polish but not in as built LIGO I TMs Compatible with highest Q coating ?

Compatible with highest Q coating ?

Crude extrapolation from as built LIGO I FFT model

Absorption (thermal)

- Challenge of thermal distortion addressed by:
  - » Require lowest reasonable absorptions:
    - – Bulk ~20 ppm/cm (to be achieved) dominates lensing.
    - – HR surface ~1ppm (presumed easy) contributes 28% of lensing
  - » AOS adaptive compensation will be crucial
    - – Compensate S recycling cavity thermal distortion to "cold" optical specs.
    - – D compensation to maintain CD_{CR} and individual arm match.

~equal contribution to surface deformation

- HR surface deformation (wrt LIGO I) now substantial
  - » Pushed by g = .93
  - » Not adaptive compensated: "point design" of HR ROC ?
  - » If compensated cold state nearly unstable.

Interfaces, Design/Development

(Billingsley)

- Interfaces
  - » Suspensions
  - » Thermal
  - » Alignment/control
- Optical Design/Development
  - » Hot Issues
    - – Downselect
    - – Charge buildup
    - – Scatter
    - – Coating mechanical loss
  - » ITM design as an example (all others are easier)
  - » Development status of sapphire

Interfaces - Suspensions

- Size (depends on test mass material) → SUS
- Mass tolerance → COC
- Mounting flats → COC
  - » Some negotiation needed due to optical loss
- Clocking of sapphire ITM →SUS and →IOO
  - » C-axis must be parallel to beam polarization ~<1° TBD
- Location of reference marks →COC
- Charge on optics → new issue

Interfaces - Thermal

- Absorption of ITM bulk COC & AOS
  - » Sapphire absorption structure is not controllable
  - » Pros and cons to various fused silica material – may negotiate
- Size and absorption of CP (compensation plates) →COC
  - » Current understanding is ~Beamsplitter size, lowest absorption (~1ppm/cm)
- Coating Absorption Uniformity →COC (new issue)
  - » Dependent on substrate choice (PRELIMINARY)
    - – For fused silica TM ~ 30 ppb variation on .5ppm requirement
    - – For sapphire TM ~ 1 ppm variation on on 1ppm requirement

Interfaces – Alignment/Control

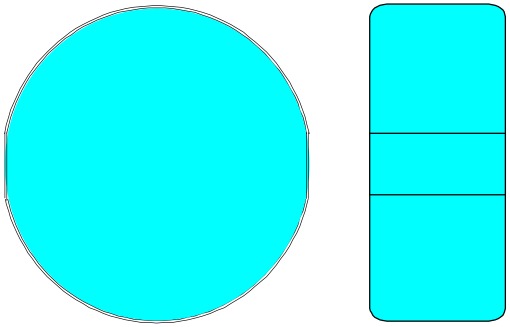
- Wedge angles/tolerance → COC
- AR surface reflectivity/tolerance →COC
- Assuming no negative impact to critical COC performance

Design/Development Hot Issues

- Downselect – LIGO-T020103
  - » Uniformity/magnitude of absorption in sapphire bulk
  - » Uniformity of coating absorption (impact on cleaning?)
  - » Frequency dependence of mechanical loss in sapphire (below 10KHz)
  - » Anisotropy of mechanical loss in sapphire
  - » Reduction of mechanical loss in fused silica (Penn, HWS)
  - » OD polish on sapphire (ok, lukewarm issue)
- Charge buildup on optics
  - » Needs a subsystem home and a dedicated effort
- Scatter as seen in initial LIGO
  - » Defined as total of: polish defects, microroughness, coating defects, coating scatter, particulate contamination
- Coating mechanical loss (covered by Harry/Armandula)

Optical Design & Development

- Basic Design
  - » Sapphire or fused silica test masses (downselect this year)
  - » All others are fused silica of different sizes (low absorption fs for BS & CP)
  - » Symmetric wedge for transmissive optics
  - » Polished flats on OD for suspension attachment (except RMs)
  - » High quality polish
  - » Ion beam coating



Design for Sapphire: ITM is most difficult

Mass	**40 kg, demonstrated**
Physical dimension	**314 mm x 130 mm, with chips at bevel**
Optical homogeneity	**< 10 nm rms, compensated**
Microroughness	**< 0.1 nm rms, demonstrated**
Internal scatter	**< 50 ppm, needs measurement!**
Absorption	**20 ppm/cm, needs compensation**
Birefringence	**demonstrated < 50 ppm**
Polish/2*w*	**< 0.9 nm rms, demonstrated/15cm**
Coating Absorption Unif.	**< 1ppm variation**

What changes for fused silica TMs

- Size – 340mm x 200mm
- Polish - <0.95 nm rms over 2*w*
- Absorption - <1ppm/cm
- Coating absorption uniformity 30ppb variation? TBD

Sapphire - Material Status

- Five experimental growth runs Crystal Systems
  - » Two of five 15” boules are considered good optical quality
  - » Two of five are not
  - » LIGO has bought one “good” and one “not” to test for use as transmissive and non-transmissive test masses
  - » Measure and compare
    - – Absorption – in process
    - – Scatter – not yet in process
    - – Homogeneity – not yet in process
    - – Q – completed by Willems, results: similar

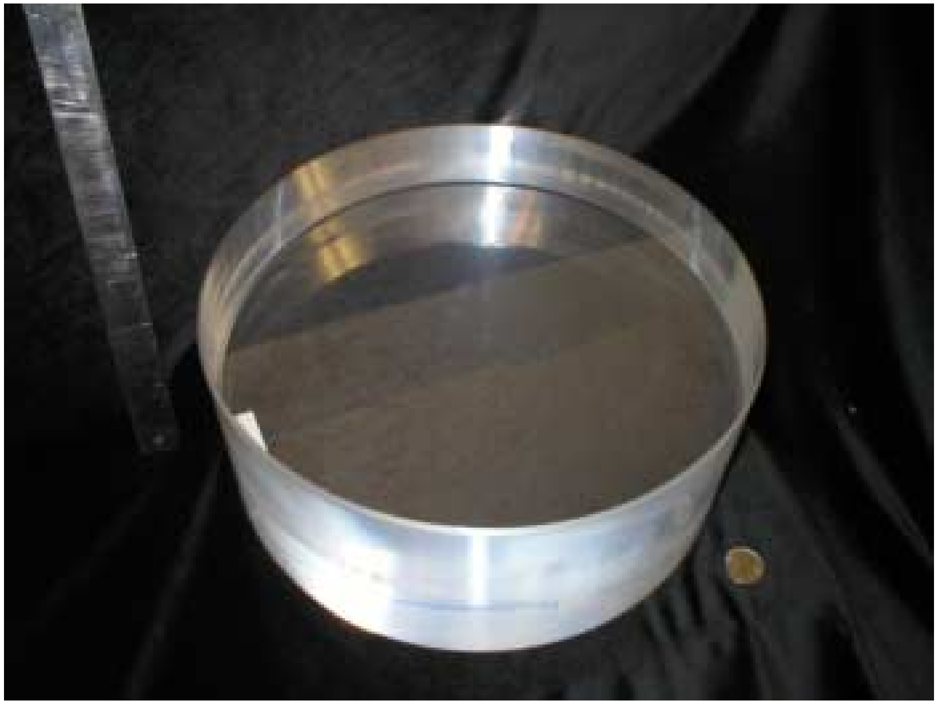
Sapphire - Material Status cont’d

- Shanghai Institute of Optics and Fine Mechanics
    - Furnace is in place
    - No large pieces yet
    - Does not yet appear to be a viable second source
- Rubicon
    - Optical quality is good
    - Absorption is high (~several hundred ppm/cm)
    - Would need development if used as a second source

Full size Sapphire substrates

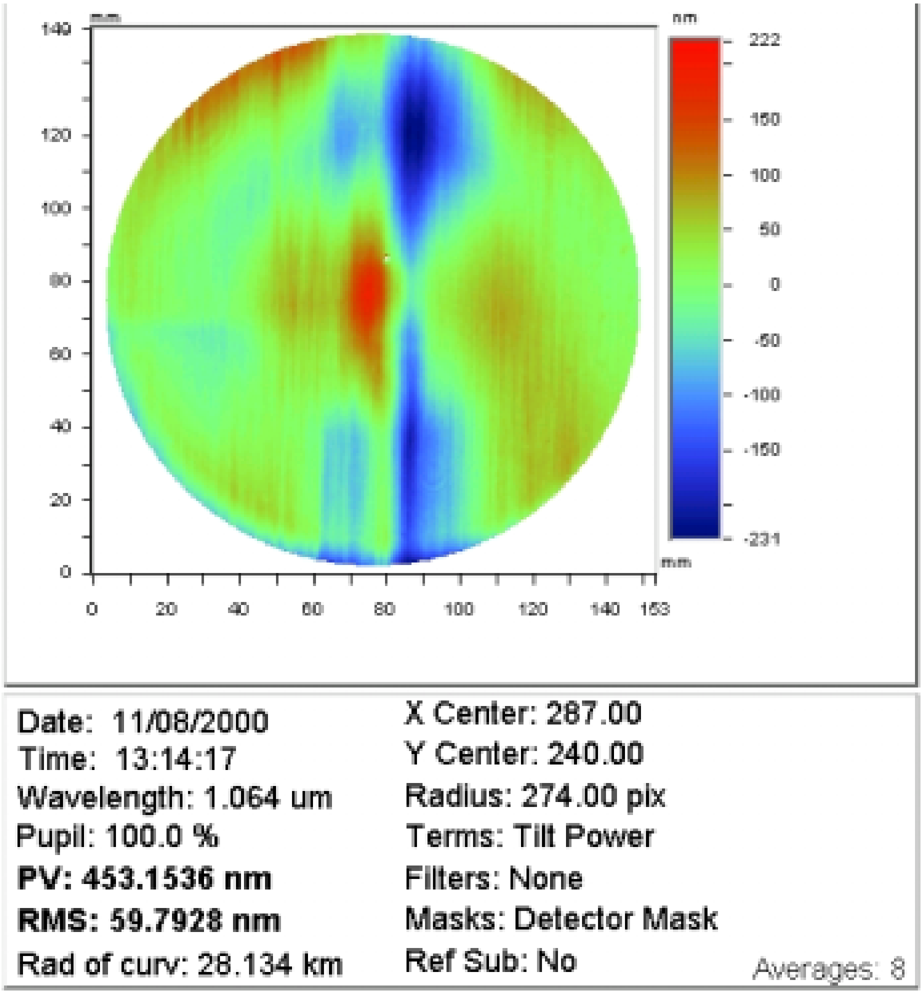
Crystal Systems delivery of 2 Pathfinder pieces Jan ‘03

314 mm x 130 mm



Sapphire optical properties
Homogeneity

- Compensation studies
  - » CSIRO
    - – Fluid jet polishing
    - – Compensating coating deposition
    - – Ion beam etch
  - » Goodrich
    - – Computer controlled polishing



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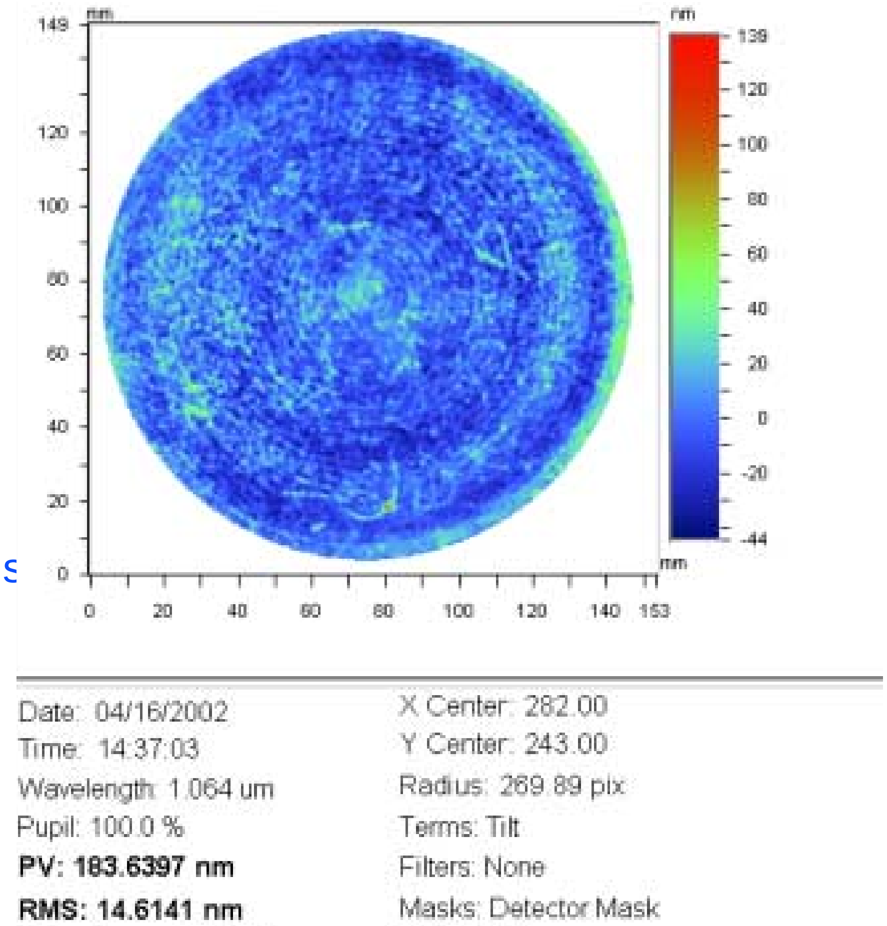
Time: 13:14:17
Wavelength: 1.064 um
Pupil: 100.0 %
PV: 453.1536 nm
RMS: 59.7928 nm
Rad of curv: 28.134 km

X Center: 287.00
Y Center: 240.00
Radius: 274.00 pix
Terms: Tilt Power
Filters: None
Masks: Detector Mask
Ref Sub: No
Averages: 8

Homogeneity Compensation

- Compensation studies
  - » CSIRO
    - – Fluid jet polishing
    - – Compensating coating deposition
    - – Ion beam etch
  - » Goodrich (formerly Perkin Elmer, HDOS, Raytheon)
    - – Computer controlled polishing
    - – Goodrich compensation ~10nm rms



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Wavelength: 1.064 um
Pupil: 100.0 %
PV: 183.6397 nm
RMS: 14.6141 nm

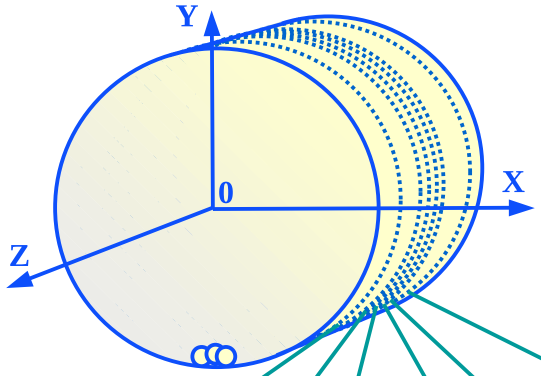
X Center: 282.00
Y Center: 243.00
Radius: 269.89 pix
Terms: Tilt
Filters: None
Masks: Detector Mask

Sapphire optical properties
Polishing

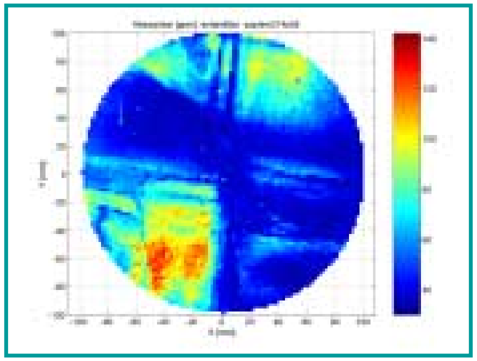
- CSIRO
  - » 0.11 nm rms microroughness
  - » 1.0 nm rms surface figure error over 120 mm diameter
- Wave Precision
  - » <0.1 nm rms microroughness
  - » Figure is metrology driven

Sapphire optical properties: Absorption

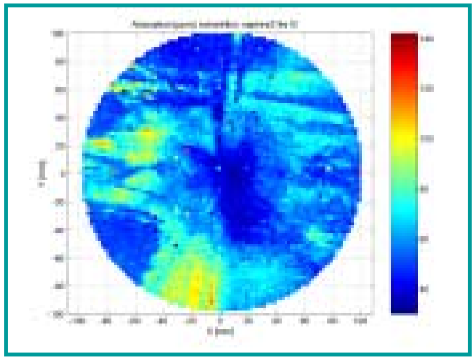
- Absorption reduction: Stanford (Route, Fejer, et. al.)
  - ~10 ppm/cm required in order to obviate thermal compensation
  - Typically 50 ppm/cm in large samples as received
  - Isolated observations at 10 ppm/cm, existence proof
  - Annealing Studies on small samples have produced results of 20 – 30 ppm/cm absorption using rapid cooling
  - Annealing on 3” optic produced same results
  - Need annealing study with CSI using large boules/furnace
- Higher absorption material useable with active thermal compensation
  - Lower absorption is easier; especially if there is spatial variation
- Spatial variation -Measured full size boule at Lyon 3-03
- Two more large boules at Lyon for measurement now



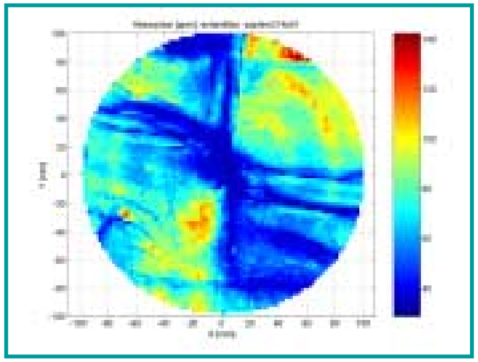
- Sapphire absorption maps
- 6 different depths
- Color scale 40 to 140 ppm/cm
- X and Y scale –100 to 100 mm



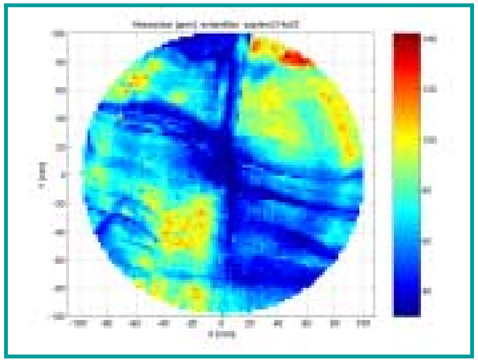
Z = -18 mm



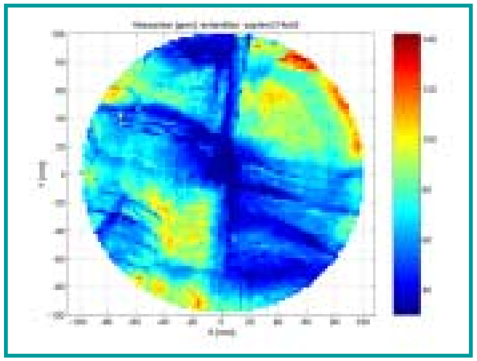
Z = -126 mm



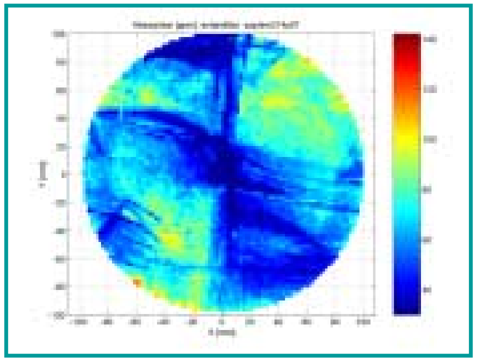
Z = -57 mm



Z = -63 mm



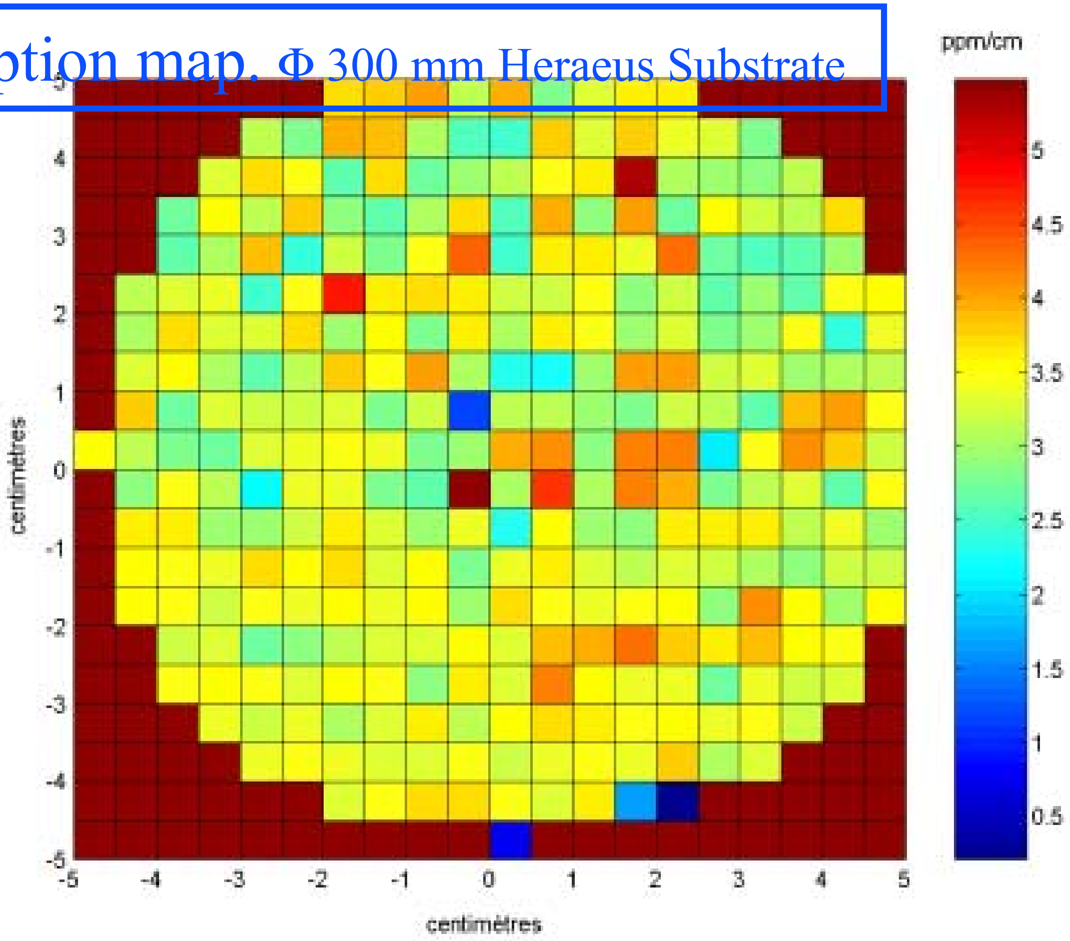
Z = -68 mm



Z = -74 mm

Absorption Measurement of fused silica

Bulk absorption map. Φ 300 mm Heraeus Substrate



IPN Lyon
SMA

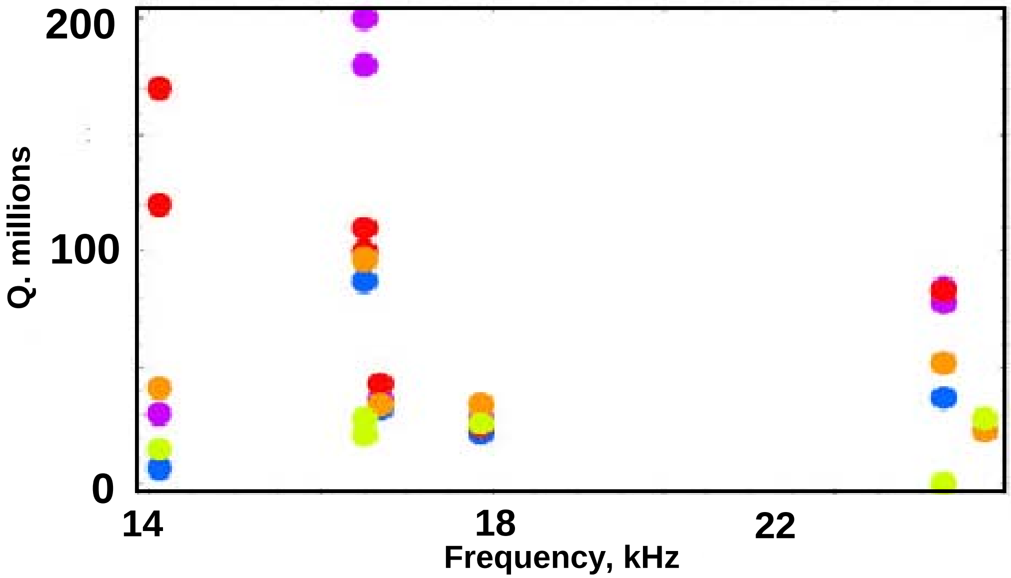
Mechanical Loss in Large Substrates – Sapphire

Slide stolen from Reitze

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

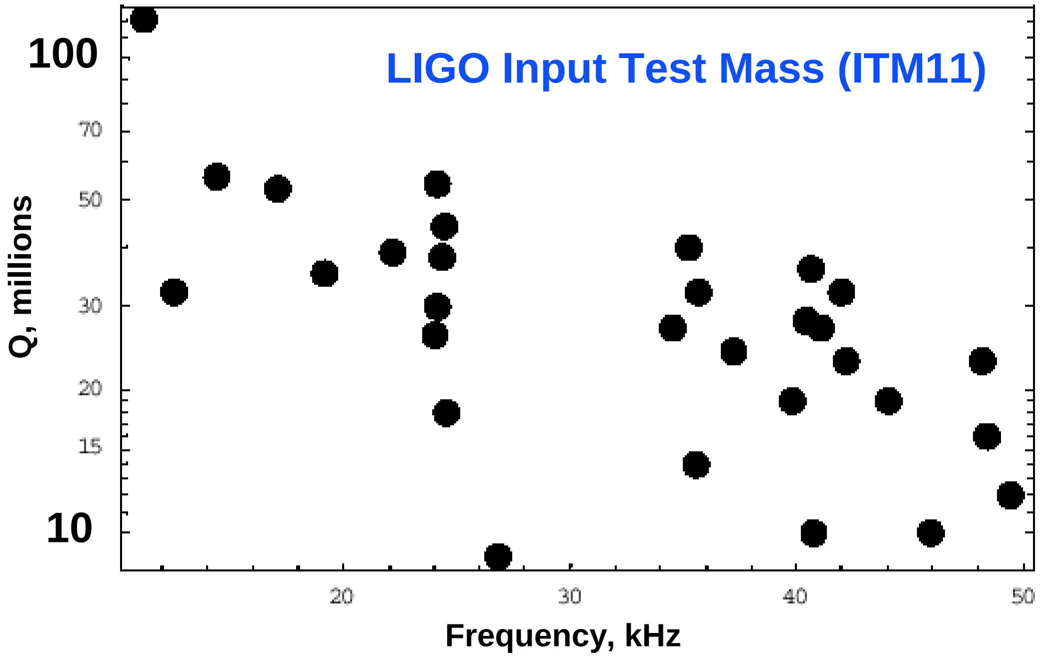


Mechanical Loss in Large Substrates – Fused Silica

Slide stolen from Reitze

- 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)

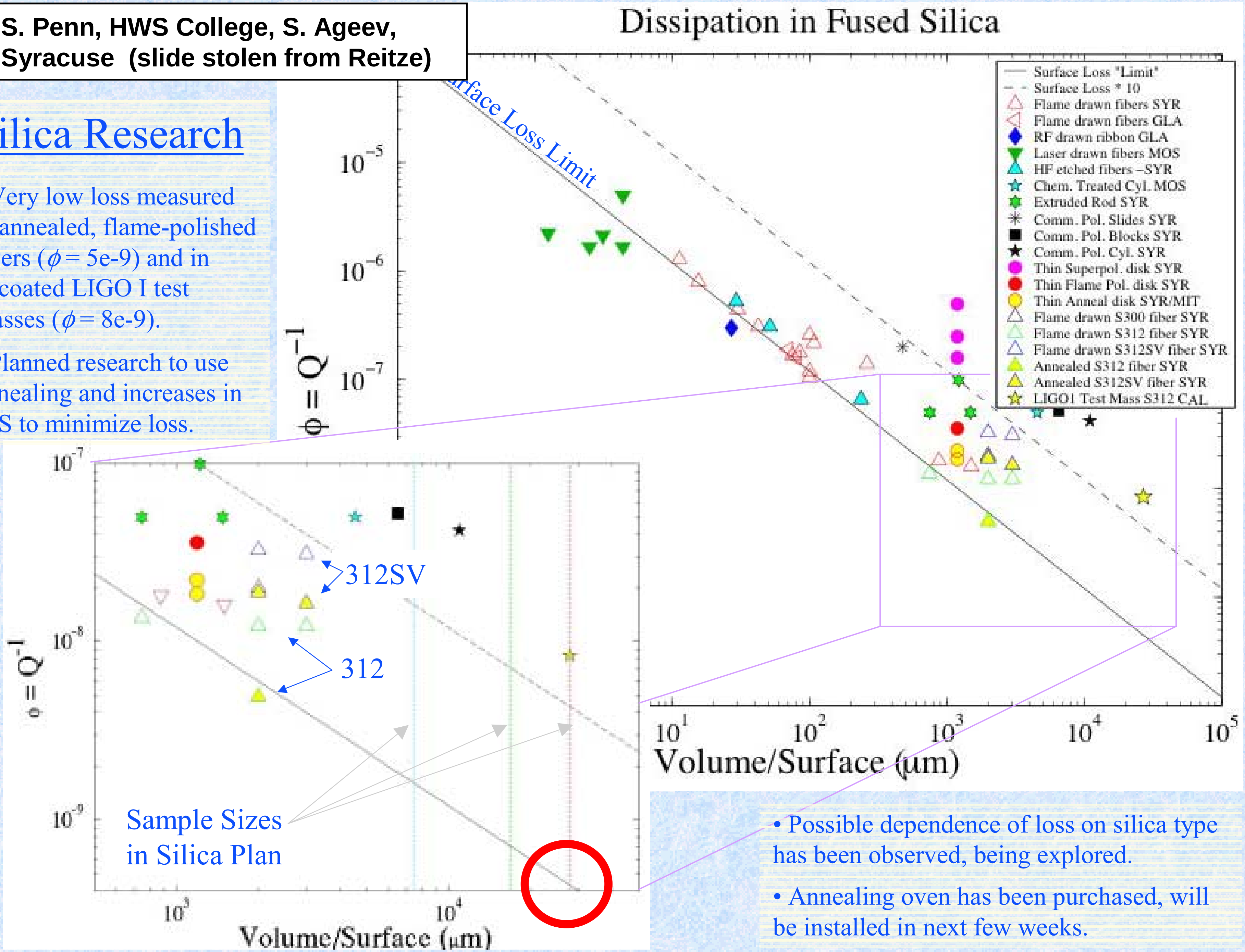
P. Willems and D. Busby, LIGO- T030087-00-R



S. Penn, HWS College, S. Ageev, Syracuse (slide stolen from Reitze)

Silica Research

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



Sample Sizes in Silica Plan

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

Advanced LIGO Coating Research

Gregg Harry (MIT) Cognizant Scientist
Helena Armandula (Caltech)

January 6th, 2004

Coating Development Specifications for Test Masses

Parameter	Sapphire goal	Sapphire requirement	Fused Silica goal	Fused Silica requirement
Mechanical loss	2×10^{-5}	6×10^{-5}	1×10^{-5}	3×10^{-5}
Optical Absorption	0.5 ppm	1 ppm	0.2 ppm	0.5 ppm
Thermal expansion	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	1×10^{-4} rad	2×10^{-4} rad	-	-
Scatter	1 ppm	2 ppm	1 ppm	2 ppm
Thickness uniformity	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	5×10^{-3}	1×10^{-2}	5×10^{-3}	1×10^{-2}
AR reflectivity	-	200 ±20 ppm	-	200 ±20 ppm

Adv LIGO Coating Requirements

Mechanical loss

Fused silica : $\phi < 3 \times 10^{-5}$ (goal 1×10^{-5})
Sapphire: $\phi < 6 \times 10^{-5}$ (goal 2×10^{-5})

These numbers are guides, thermal noise will depend on many other parameters with ϕ.

Source of requirements on all parameters influencing thermal noise
Brownian thermal noise equation (Nakagawa/Gretarsson)
Thermoelastic noise (Braginsky/Fejer)
advLIGO sensitivity modeling with BENCH

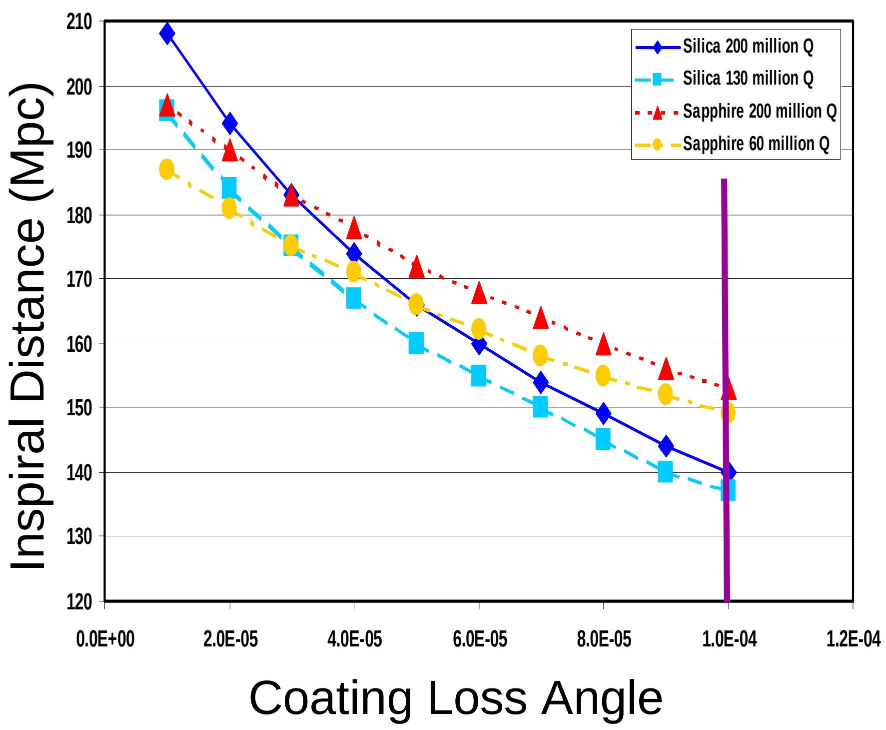
Optical absorption

Fused silica: 0.5 ppm (goal 0.2 ppm)
Sapphire: 1 ppm (goal 0.5 ppm)

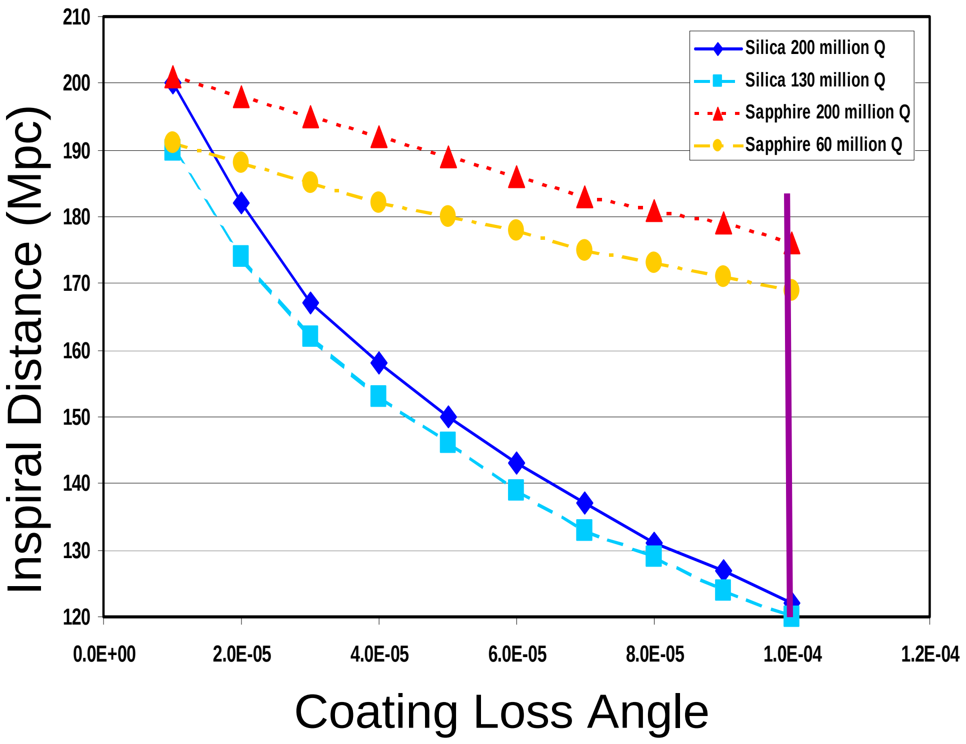
Optical requirements come from best available technology in coating industry

Advanced LIGO Sensitivity vs Coating Loss Angle

BNS Range vs ϕ for Y_{coat} = 70 GPa



BNS Range vs ϕ for Y_{coat} = 200 GPa

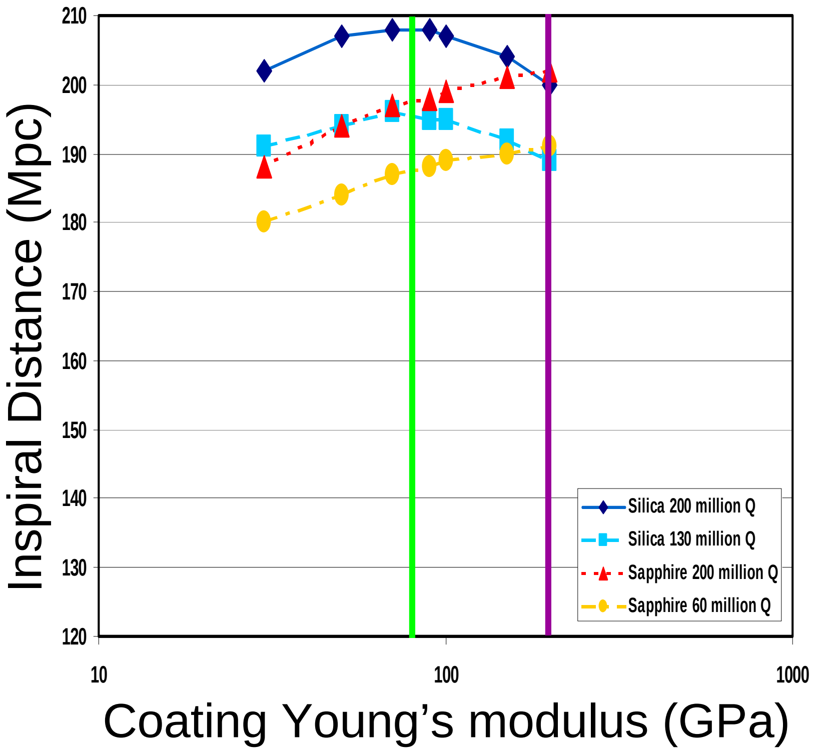


Current Status

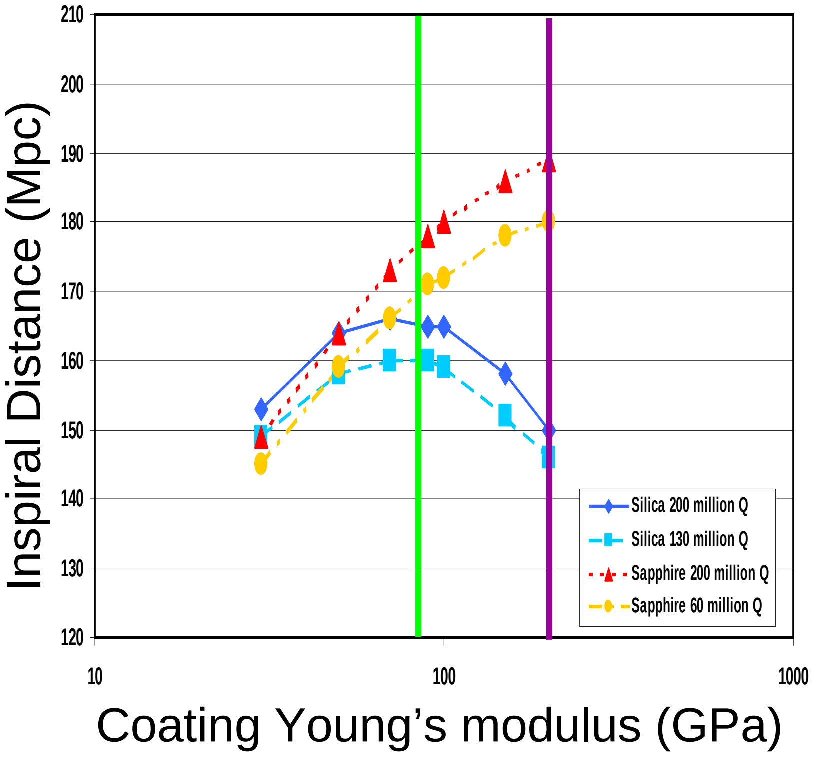
| - Doped tantala-based coatings

Advanced LIGO Sensitivity vs Coating Young’s modulus

BNS Range vs Y for ϕ_{coat} = 1 10^{-5}



BNS Range vs Y for ϕ_{coat} = 5 10^{-5}



Current Status

| - Alumina based coating

| - Silica based coating

Collaboration

Experiments to understand coating mechanical loss are being carried out by LSC collaboration

- MIT
- Glasgow
- Syracuse
- Hobart and William Smith

Measuring Techniques / Results for Initial LIGO Silica/Tantala Coating

Three inch diameter silica substrates were coated by SMA/Virgo with layers of alternating silica and tantala, similar to the initial LIGO coating

Q factors were measured by exciting resonances in the samples and recording the subsequent decay

Two different diameters of fused silica substrates

Thick samples (3” dia. x 1” thick) - 4 modes measured

$\phi_c = (2.8 \pm 0.7) \times 10^{-4}$

Thin samples (3” dia. x 0.100” thick) - 3 modes measured

$\phi_{\text{butterfly}} = 2.7 \times 10^{-4}$

$\phi_{\text{drumhead}} = 3.1 \times 10^{-4}$

Work performed / Results

Performed measurements on several coatings with different amounts of layers (2 to 60) and with various layer thickness in different combinations ($\lambda/4$ - $\lambda/4$; $\lambda/8$ - $3\lambda/8$; $\lambda 8$ - $\lambda/8$)

Concluded that:

- Substrate / coating interface is not a significant source of loss.
- Coating layer interfaces are not a dominant source of loss
- Found that Ta_2O_5 has a higher loss than SiO_2 or Al_2O_3

Experiments and Status

Material combinations tested:

Nb_2O_5 / SiO_2

Ta_2O_5 / Al_2O_3

Al_2O_3 / SiO_2

Ti-Doped Ta_2O_5 / SiO_2

Improved coating loss over non-doped Ta_2O_5:

$\phi_c = 1.8 \times 10^{-4}$

Program Overview

- Plan to concentrate on developing low mechanical loss coating first
- Optical and thermal properties will be watched during development, but will not drive it until mechanical loss is better understood and/or a low mechanical loss coating is developed
- Selected 2 coating vendors for next round of experiments

    SMA/Virgo in Lyon France

    CSIRO in Sydney Australia

- Next phase of coating development has begun

Coating Development
Coating Plan

- **Dopant experiment**
  Continue with dopant evaluation. SiO_2/TiO_2 doped with Ti showed a reduction in mechanical loss without sacrificing n, Y, or optical loss.

- **New materials experiment**
  HfO_2 is being investigated.
  Triple alloy of Si/O/N will be looked at next

- **Annealing experiment**
  The annealing experiment consists of several runs without depositing new coatings but with varying annealing parameters of already coated samples

- **Ion bombardment of substrate during coating**
- **Vary deposition parameters and inert gas**
- **Nanolayers (thin alternating sublayers)**
  - Layers of Nb2O5 / Al2O3
  - Layers of Ta2O5 / SiO2
- **Interfacial layers**
  - Metal or organic flexible layers between layers
  - Requires extensive modelling

R & D Milestones

➢ Start Coating Development	January 2004
➢ Material Downselect	June 2004
➢ Develop Cleaning Process	December 2004
➢ Coating Material Downselect	December 2004
➢ LASTI’s ETM Finished	April 2005

Thermal Noise Modeling

Analytical and FEA models we need

Analytical

- *Finite sized, coated mirrors*
  N. Nakagawa is thinking about this problem
- *Anisotropic substrate*
  Used for sapphire, may be unnecessary
- *Inhomogeneous loss distribution*
  Probably better done by finite element analysis (FEA)

Finite Element Models

- Effect of suspension wires on modal Q's
  I-DEAS model of thermal noise (Coyne et al)
- Effect of finite mirrors and inhomogeneous loss
  TAMA model (Numata et al), need a portable version

Sensitivity Studies

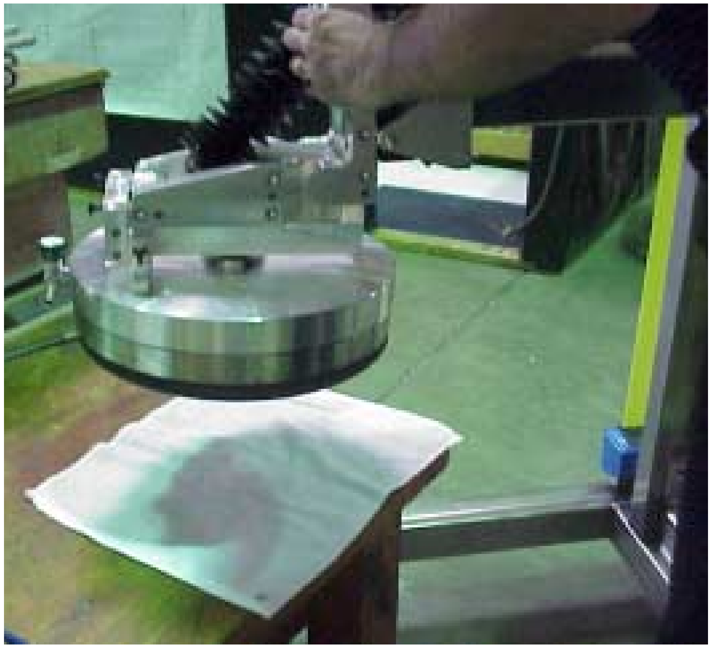
- Trade offs for various coating and substrate parameters
  BENCH used now

Handling Equipment

- Ergo-Arm

Handling Equipment

- Current design can lift and move Advanced LIGO mirrors



Mirror Cleaning

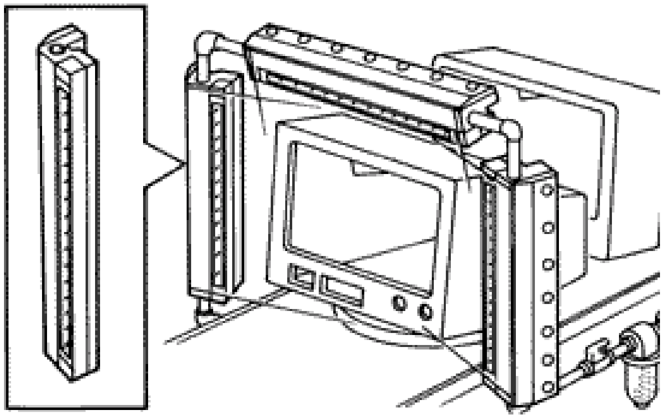
- **If mirrors get contaminated, they will require cleaning**

  ➢ Suggested cleaning process:

  1. Wash mirror with a mild detergent and warm DI water.
  2. Rinse thoroughly with particle free DI water in a cleaning tank.
  3. Slowly withdraw the mirror, allow it to rest on its side and and let it dry under a clean hood fitted with ionizing bars.

To preserve cleanliness…

- Perform all assembly procedures in Class 100 environments aided by ionizing curtains



Ionizing air curtains arranged in a halo configuration quickly neutralizes static, then remove lint and dust from the objects being assembled. They work with compressed air.