Coating Thermal Noise Research for Gravitational Wave Detectors

K. Craig[1], I.W. Martin[1], M. Abernathy[1], R. Bassiri[1,2],
K. Borisenko[3], A. Cumming[1], K. Evans[1], K. Haughian[1], M. M. Fejer[2],
A. Gretarsson[4], G. M. Harry[5], J. Hennig[1], E. Hirose[9], G. Hofmann[6],
J. Hough[1], J. Komma[6], A. Lin[2], I. MacLaren[1], R. Nawrodt[6], S. Penn[8],
S. Reid[7] R. Route[2], S. Rowan[1], J. Scott[1], C. Schwarz[6],
K. Waseda[10], K. Yamamoto[9]

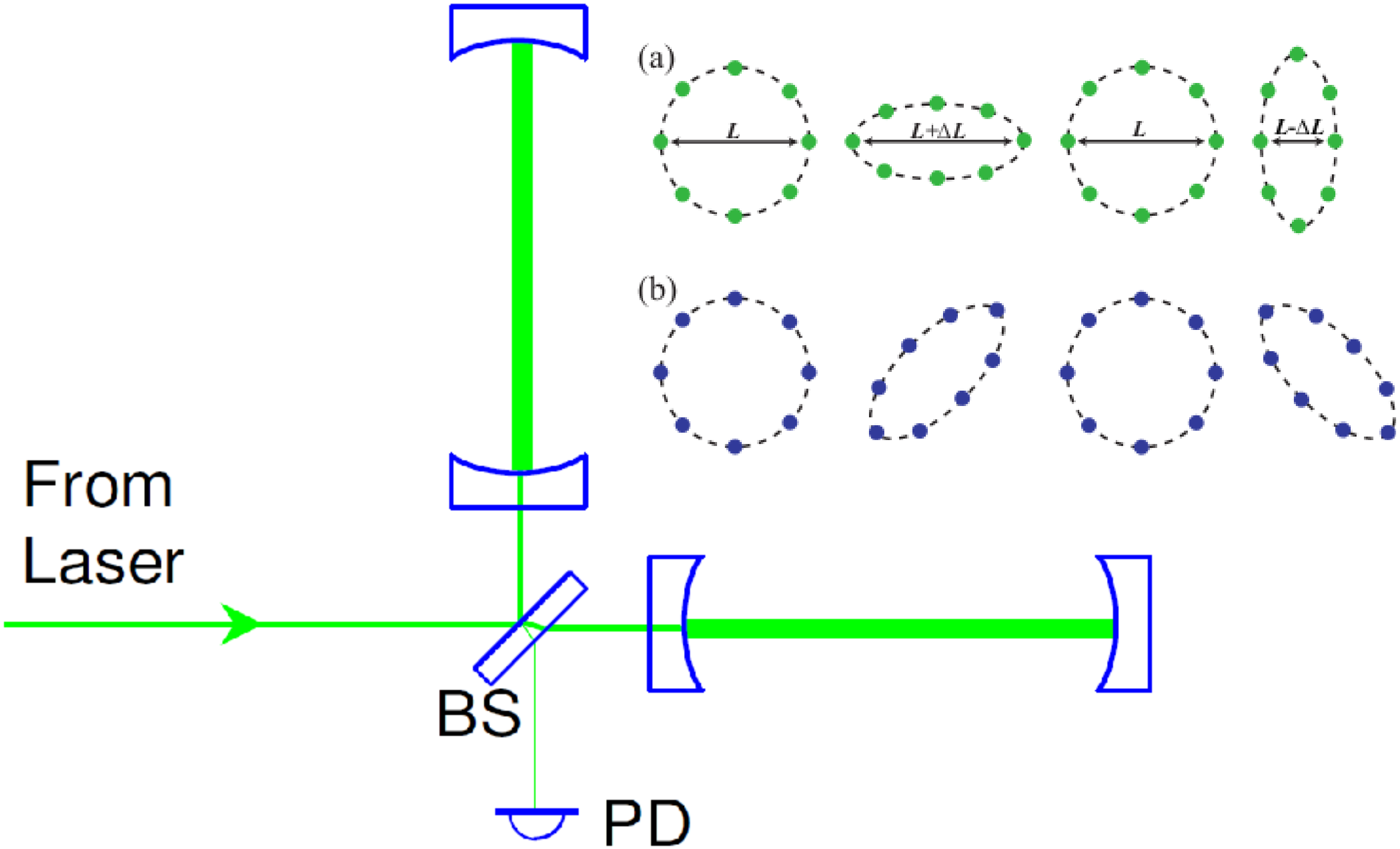
[1] SUPA, University of Glasgow
[2]Stanford University
[3]Oxford University
[4]Embry-Riddle Aeronautical University
[5]American University
[6]University of Jena
[7]SUPA, University of the West of Scotland
[8]Hobart and William Smith College
[9]ICRR, University of Tokyo
[10]NAOJ

ICRR, University of Tokyo, Kashiwanoha, April 2013

Overview

- An introduction to coating thermal noise and its importance to gravitational wave detectors
- Description of cantilevers and ion-beam sputtering
- A description of the Glasgow cryostats
- A selection of results from these measurements
- Structural modelling
- Disk work – crystalline coatings
- Work here at the ICRR

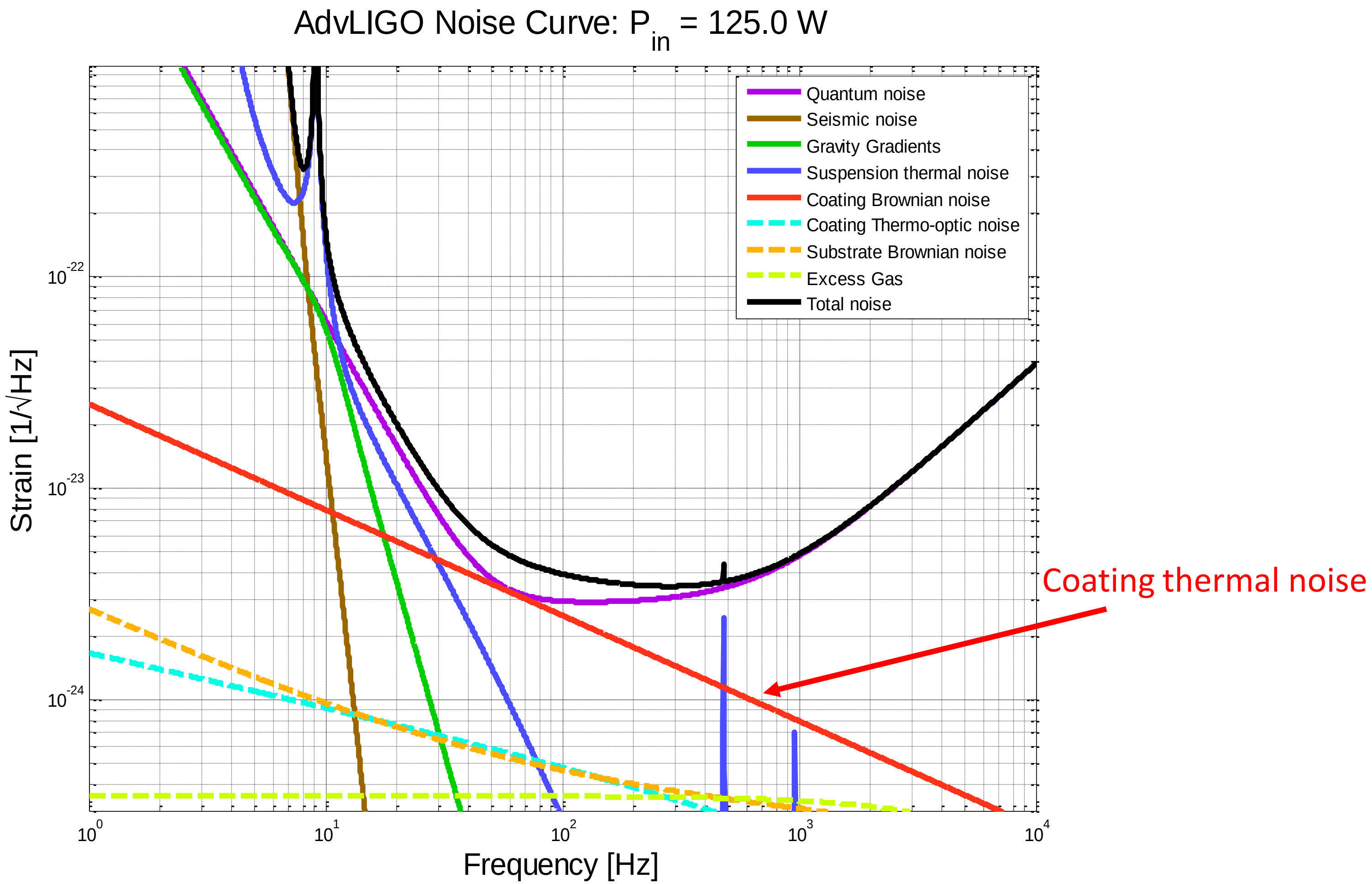
Michelson Interferometers



The effect of gravitational waves on a ring of test particles

- Anything which couples into the optical path length of the interferometer is a noise source

Estimated noise – Advanced LIGO



- Research aimed at reducing coating Brownian noise
- How can we reduce this noise?

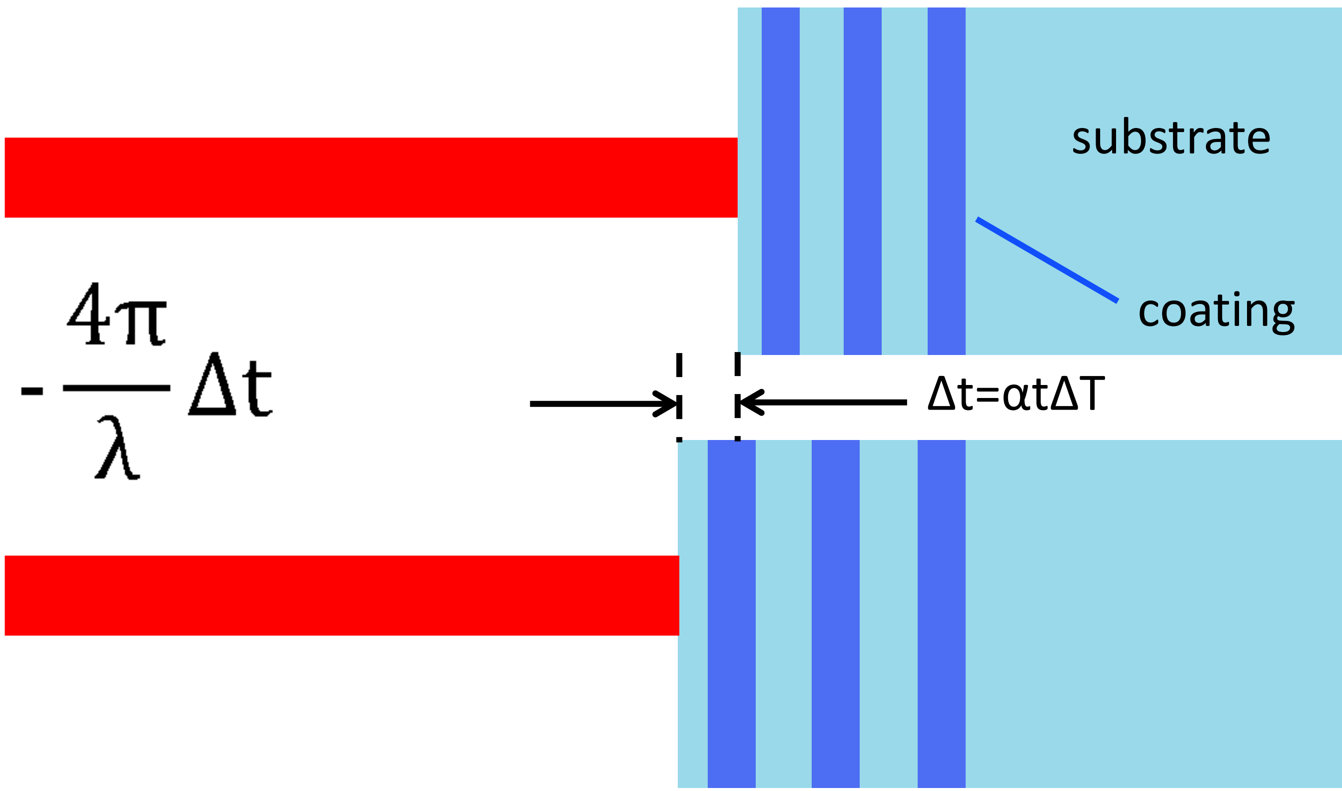
Coating Thermal Noise

- What is meant by "coating thermal noise?"
- Coating thermal noise may be split into two types:
- Brownian thermal noise
- Thermo-optic noise
- Thermo-optic noise may be further decomposed into thermoelastic and thermorefractive noise
- What causes each of these, and how do they affect a gravitational wave detector?

Thermoelastic noise

- Thermoelastic noise is the apparent expansion of the mirror coating into the probe beam causing change in phase

$$\Delta\varphi_{TE} = -\frac{4\pi}{\lambda}\Delta t$$



Thermo-refractive noise

- Thermo-refractive noise comes from both the physical change in size of coating layers AND the change in refractive index with temperature in the coating
- This may be combined with thermo-elastic noise to produce thermo-optic noise (detailed by M.Evans et al. 2008)

$$S_{TO}(\omega,T) \approx \frac{2\sqrt{2}}{\pi}\frac{k_B T^2}{w^2\sqrt{\kappa C\omega}} \times \left(\alpha_c d - \frac{\partial n}{\partial T}\lambda - \alpha_s d\frac{C_C}{C_S}\right)^2$$

Coating Brownian Noise

- Caused by Brownian motion of mirror surface
- Coating Brownian noise is responsible for the largest contribution to the overall detector noise by the optics

Temperature

Coating thickness

$$S_x(f,T) \approx \frac{2k_B T}{\pi^2 f} \frac{d}{w^2\, Y} \phi \left(\frac{Y'}{Y} + \frac{Y}{Y'} \right)$$

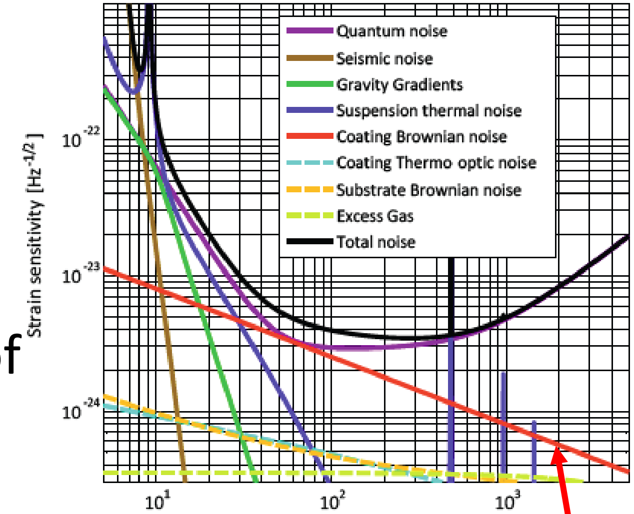
Laser beam radius

Coating mechanical loss

- This is estimated to be the limiting factor for Advanced LIGO at its most sensitive frequencies

Coating thermal noise

- Coating mechanical loss important for GW detector noise budget
- Important to characterise coatings for a dependable estimate of noise
- Glasgow also involved in the development of coatings with reduced thermal noise for:
  - Enhancements to Advanced LIGO (LIGO3)
    - May operate at cryogenic temperature (120 K?) or room temperature (or both – cryo-xylophone)
    - May operate around 1550 nm
  - 3rd generation detectors e.g. ET (LF)
    - Cryogenics (10 or 20 K)
    - Change of wavelength to 1550 nm



GWINC aLIGO noise budget

Coating thermal noise

Temperature

Coating thickness

$$S_x(f,T) \approx \frac{2k_B T}{\pi^2 f} \frac{d}{w^2 Y} \phi \left(\frac{Y'}{Y} + \frac{Y}{Y'} \right)$$

Laser beam radius

Coating mechanical loss

Paths to improved coating TN performance

- Better amorphous coatings - we know they work! Just starting to understand what causes their dissipation
  - (alternate materials - amorphous silicon for 1550nm?)

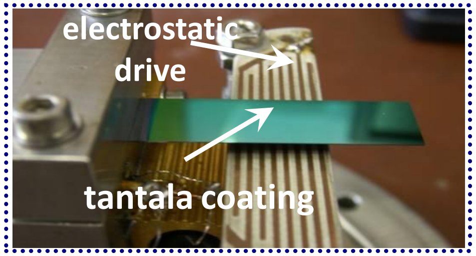
- Crystalline coatings:
  - Intrinsic Brownian loss of AlGAs shown to be low (few x 10-6 at 10K - G. Cole, GWADW Hawaii 2011)
    - Low Brownian noise after being transferred to new substrate?
    - Can they be used successfully on silicon at low temperature?

  - GaP/AlGaP alternative - lattice matched to silicon - what is loss?

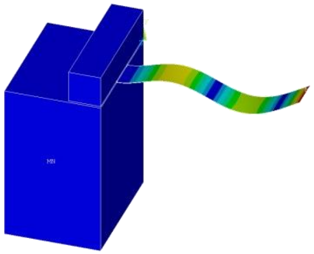
- Remove coatings entirely?
  - Diffractive / waveguide optics
  - lots of increased (lossy?) surface area - what really is the thermal noise?
    - Benefits not clear at room T – very promising on silicon at low T?
    - See D. Heinert et al. LIGO-P1300034-v1

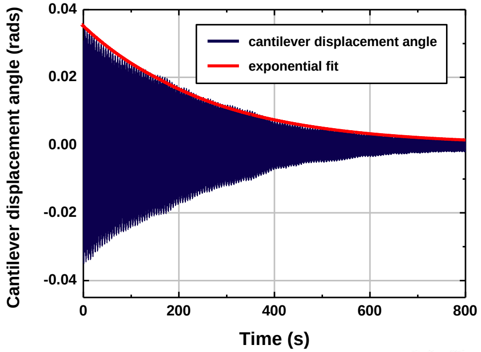
- Way ahead not yet clear – studies ongoing in each of these areas

Cryogenic coating loss measurements



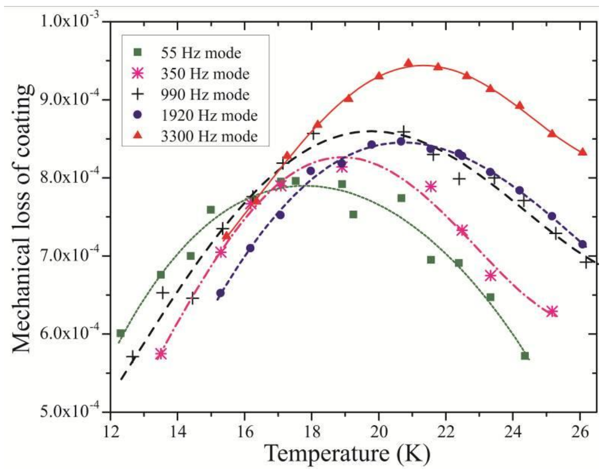
$$\phi(f_0) = \frac{\Delta f}{f_0} = \frac{E_{\mathrm{lost\,per\,cycle}}}{2\pi E_{\mathrm{stored}}}$$





$$A(t) = A_0 e^{-\phi(\omega_0)\frac{\omega_0 t}{2}}$$

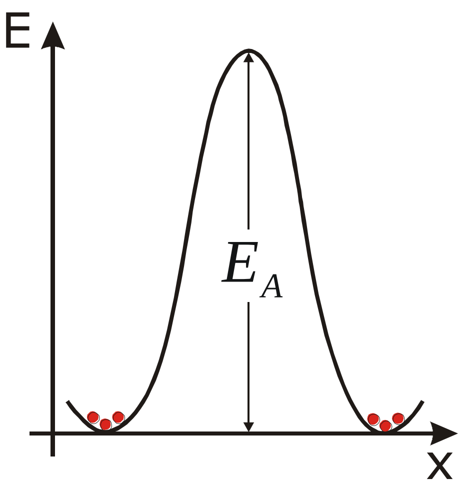
- Loss measured from ring down experiments using coated cantilever samples
- Analysis of cryogenic loss peaks can reveal characteristics of microscopic energy loss mechanisms



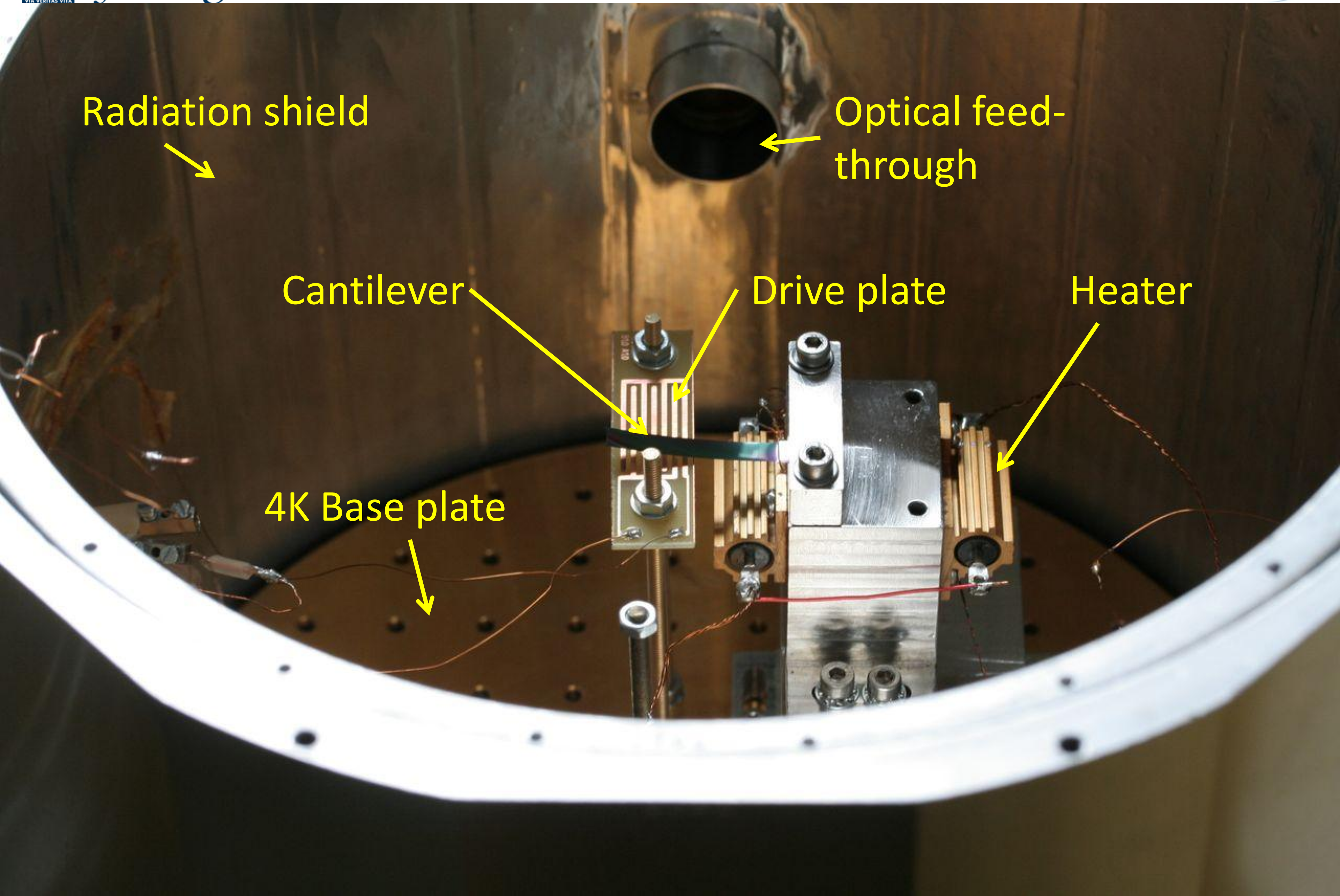
$$\tau = \tau_0 e^{\frac{E_a}{K_B T}}$$

τ_0 = relaxation constant

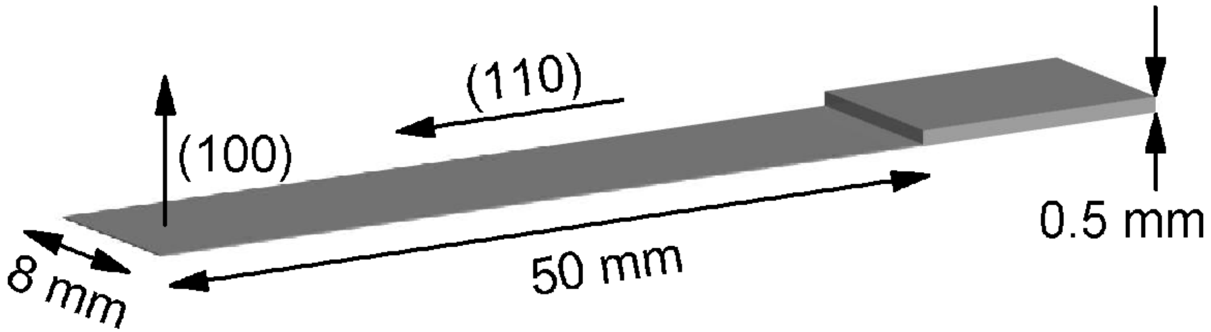
E_a = activation energy



Cryostat interior

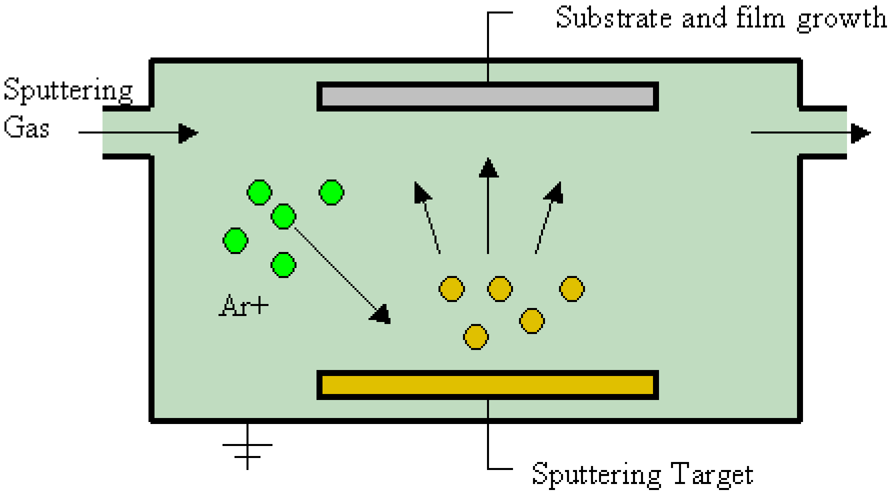


Cantilevers



- Silicon cantilevers made by Kelvin Nanotechnology by etching silicon wafers
- Cantilever only 50 microns thick!
- Silicon thermo-elastic loss dominates at high temperatures (>150K)
- Fused silica cantilevers used for room temperature coating loss measurements
- Silica cantilevers made by laser welding thin silica cantilever blades onto a thicker clamping block

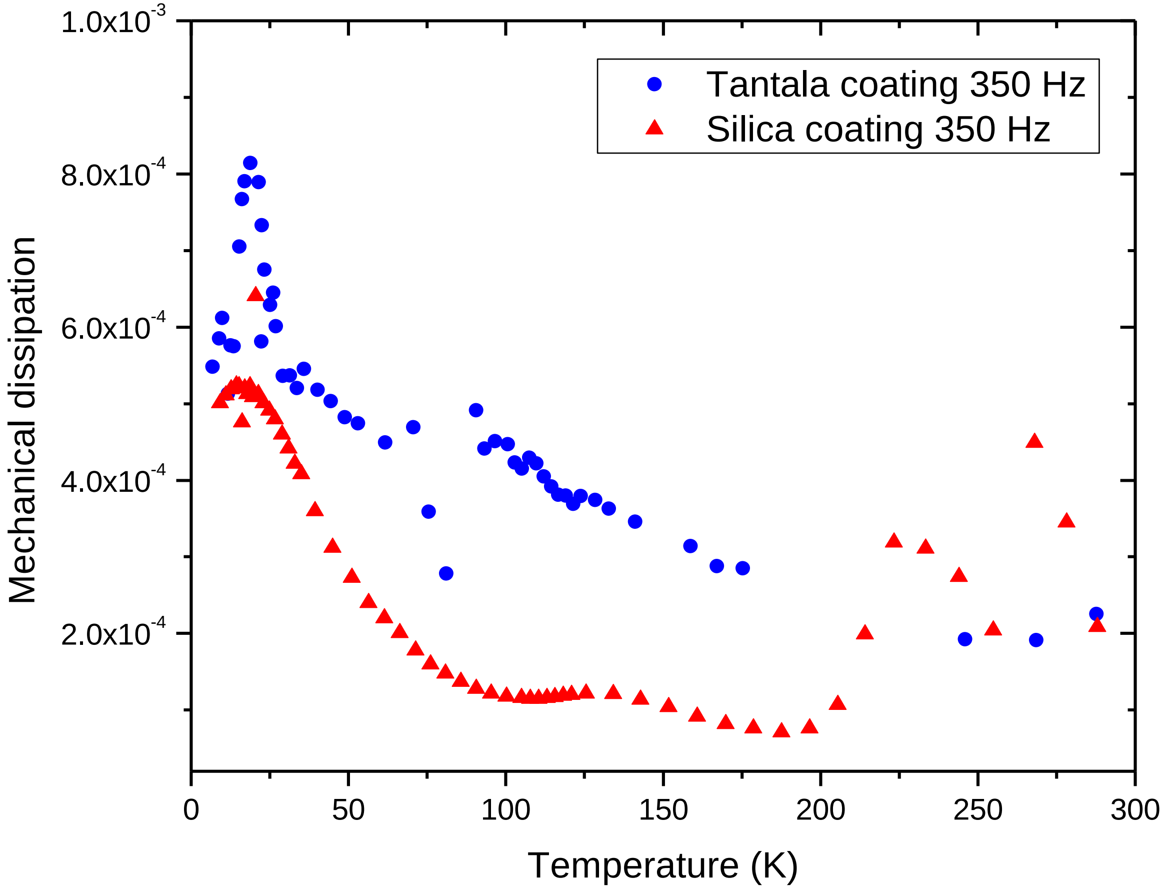
Ion Beam Sputtering (IBS)



- Ion beam sputtering commonly used for film deposition
- Argon ions collide with sputtering material, knocking them free
- Material then condenses on the substrate

- Advances in technology – dual ion beam sputtering
- Apparatus very large, expensive and difficult to operate – hence pay for a company to produce coatings
- Currently used for mirror coatings in gravitational wave detectors

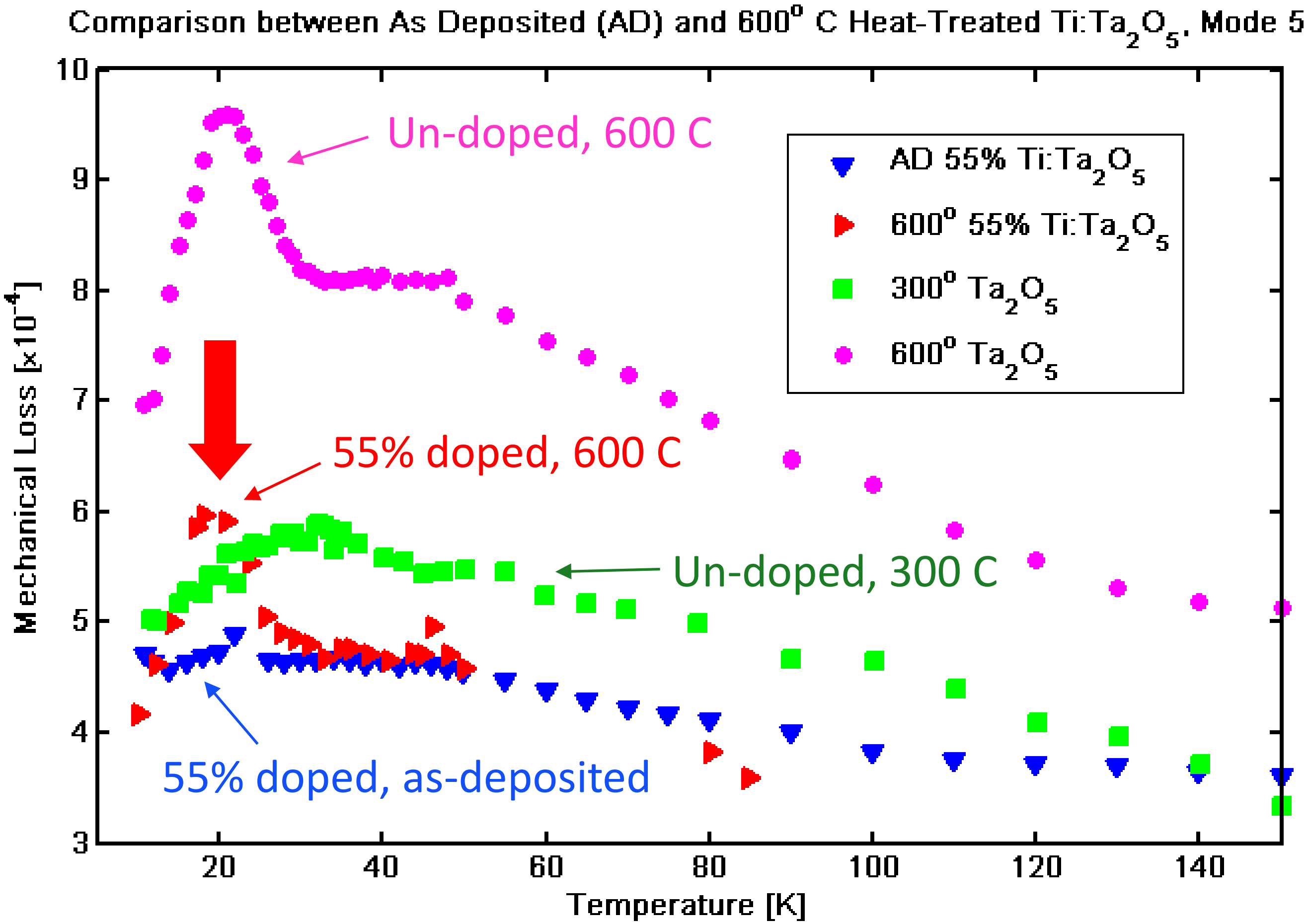
Current coatings – silica/tantala



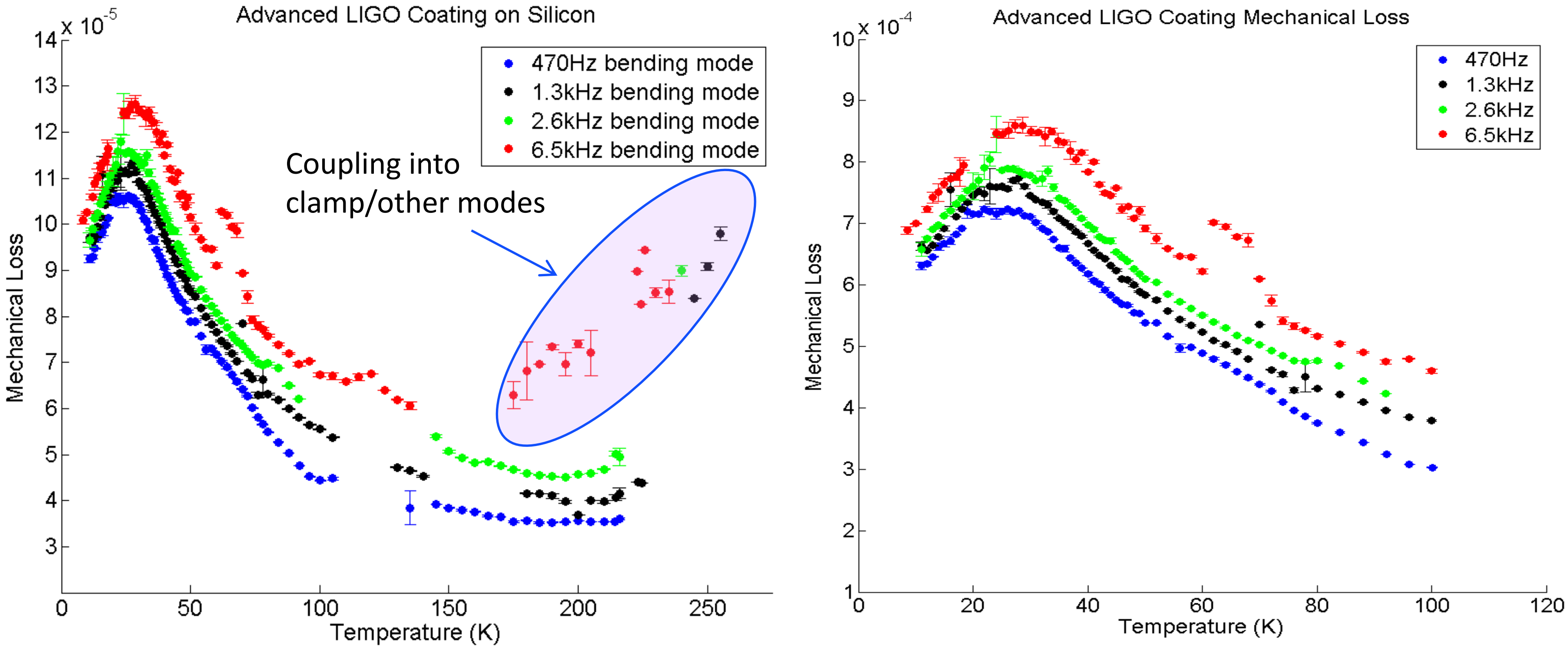
- Cryogenic loss peaks in tantala and silica films suggest a factor of ~1.9 reduction in coating thermal noise from cooling to 20K (for a constant beam radius of 6.2 cm)
- Evidence that low-temperature loss can be altered by heat-treatment and doping – evidence of correlations between loss, structure and doping level

Heat-treatment of highly-doped tantala

- High TiO_2 doping may suppress low temperature loss peak in coatings heat-treated at 600°C
- Studies of effect of heat-treatment on the 25% and 55% TiO_2-doped samples in progress

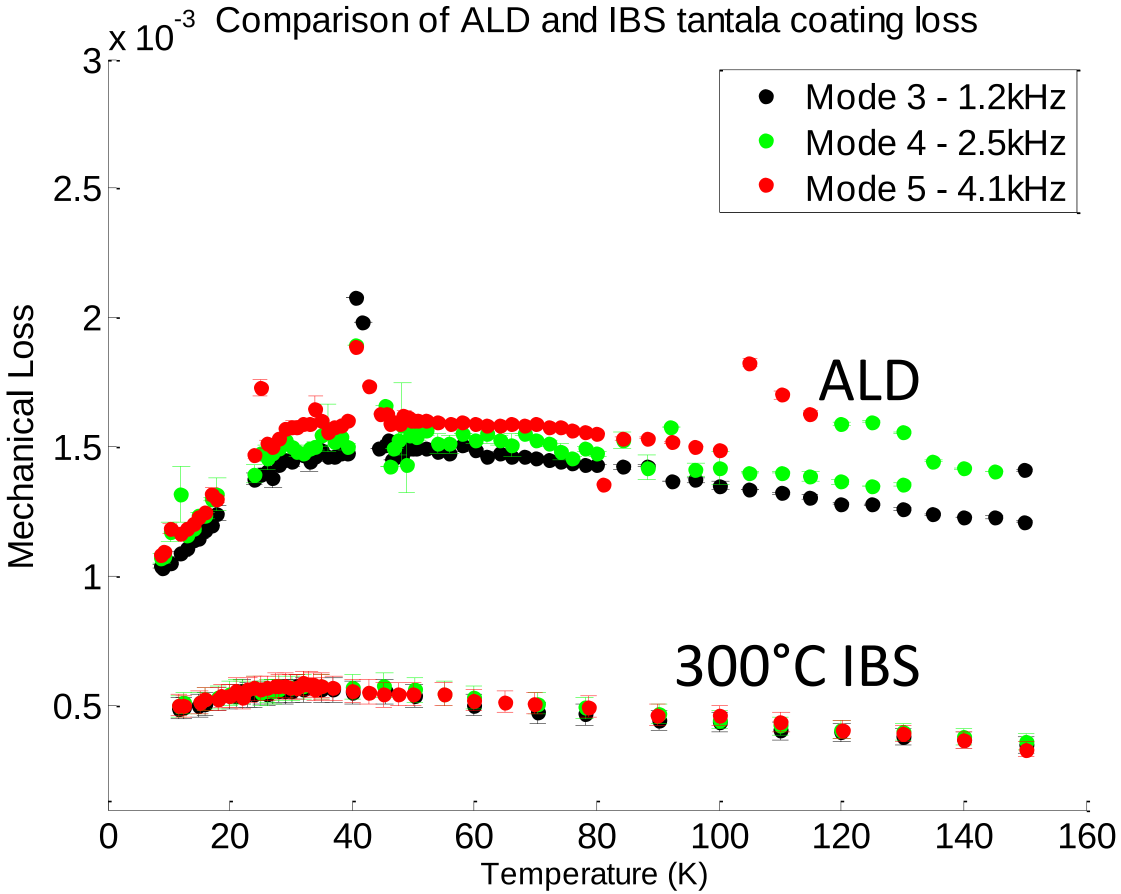


Advanced LIGO mirror coating witness sample studies



- Coating loss upper limit (right) makes reasonable assumption that the substrate does not contribute to the loss below 100K
- Loss peak between 20 and 30 K (frequency dependent) as expected from previous single layer measurements
- Paper in preparation - M. Granata et al.
- Work done in collaboration with M. Granata, G. Cagnoli, R. Flaminio et al (LMA)

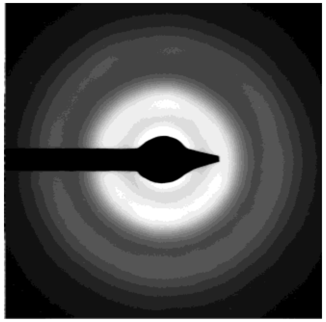
Atomic Layer Deposition (ALD) tantala



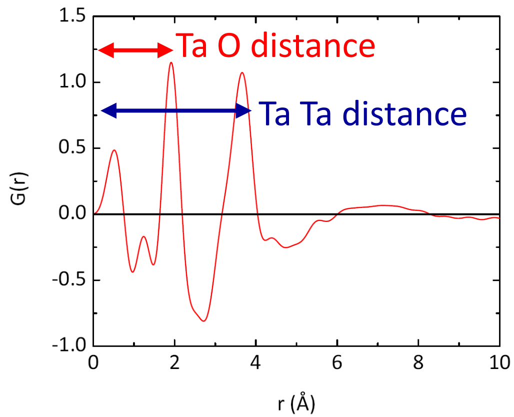
- Of interest to compare different deposition methods
- ALD tantala dissipation measured on silicon cantilevers
- ALD compared to IBS tantala heat treated at 300°C
- Structural studies underway

- ALD loss shown assumes no loss in the substrate under 150K and is therefore only an upper limit

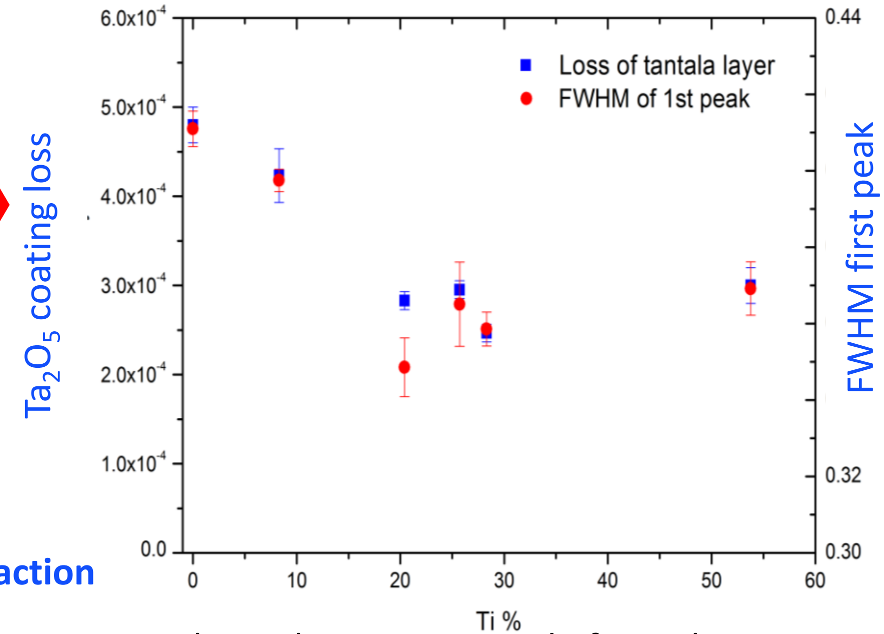
Correlations between loss and atomic structure



Azimuthal averaging of electron diffraction pattern



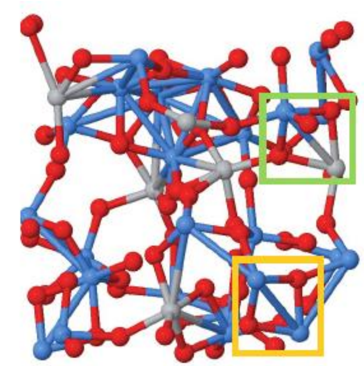
Typical RDF



Correlation between spread of metal-oxygen distance, loss and doping concentration

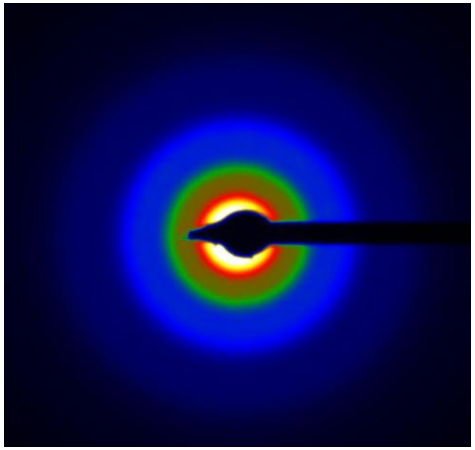
Reduced Density Function (RDF) analysis of electron diffraction data to study local structure in amorphous coatings

- Tantala room temperature loss is well correlated with the spread of metal-oxygen nearest-neighbour distances (FWHM of RDF peak)
- First evidence of correlation between structural properties and loss in tantala. Low losses appear to occur when the local structure is more ordered
- Ongoing structural measurement and atomic modelling to understand microscopic loss mechanisms – Riccardo Bassiri

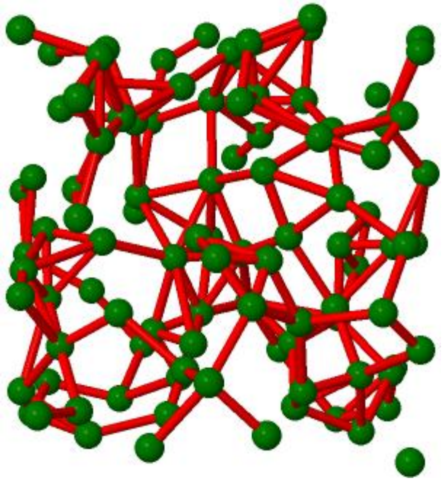


Alternative coating materials amorphous silicon

- Particularly high refractive index (n=3.5), of interest for 1550nm operation
- Literature shows e-beam / magnetron amorphous Si has relatively low loss[1], ~ 1×10^{-4} at room temperature and as low as 1×10^{-6} at cryogenic temperatures
  - Hydrogenation of amorphous Si can reduce the loss by up to a factor of 10 –passivation of dangling Si bonds
- Studying ion-beam sputtered amorphous silicon
  - Initial measurements at Stanford show absorption at 1550 nm of several thousand ppm – further investigations ongoing
  - Structural studies (TEM electron diffraction) show a-Si heat-treated at 450°C remains amorphous
  - Measurements of loss versus heat-treatment temperature ongoing



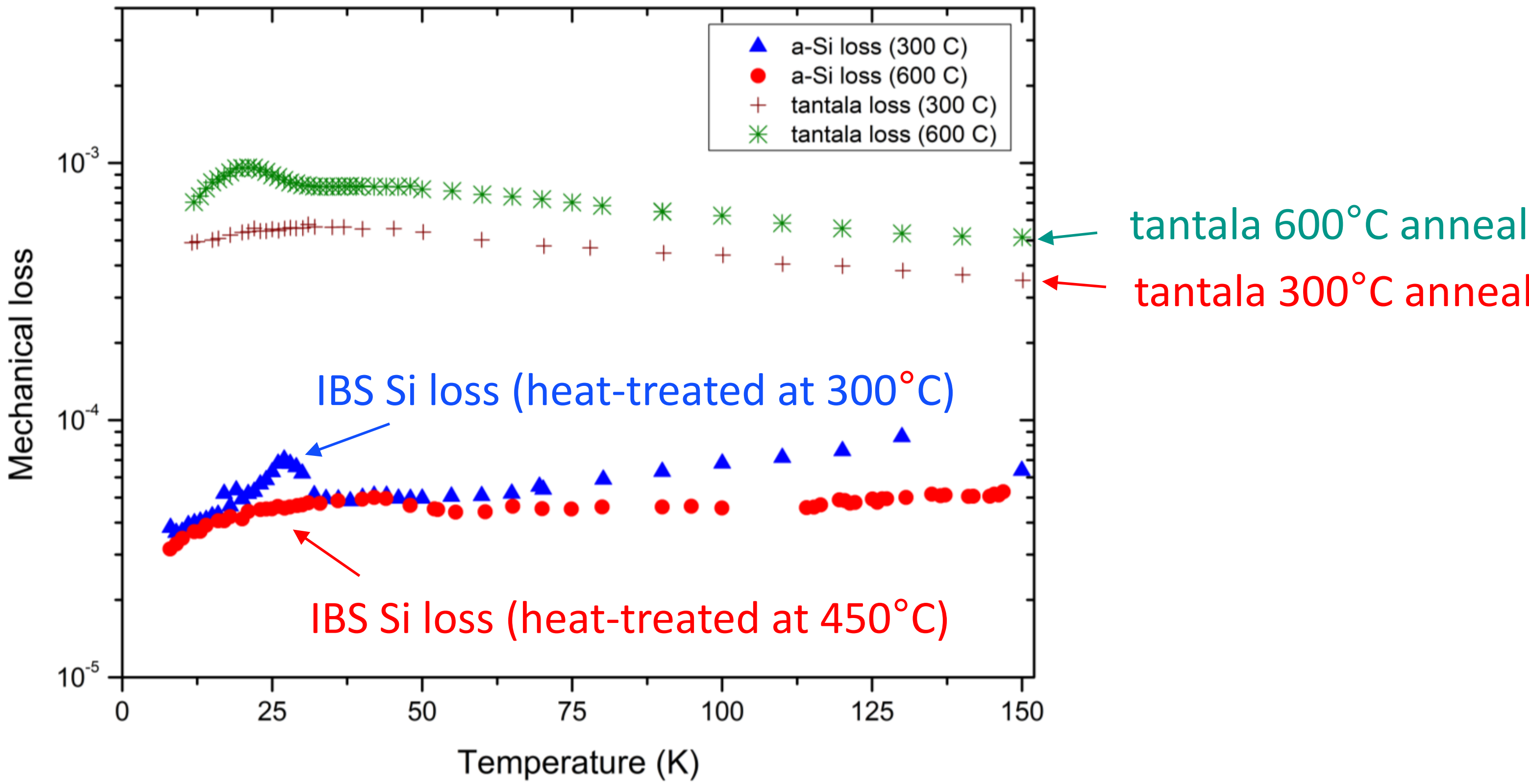
Electron diffraction pattern of a-Si



Atomic model of IBS a-Si film

[1] Liu and Pohl, Phys. Rev. B, 58 (1998)

IBS amorphous silicon coatings



- So far, only coated cantilevers studied
- A conservative upper limit to Si loss can be estimated, by assuming all of the loss originates in the coating. However, actual coating loss is highly likely to be lower than this as the cantilever substrate will be contributing to the measured loss
- Loss peak observed at 25 K in a-Si heat-treated at 300°C, but not at 450°C.

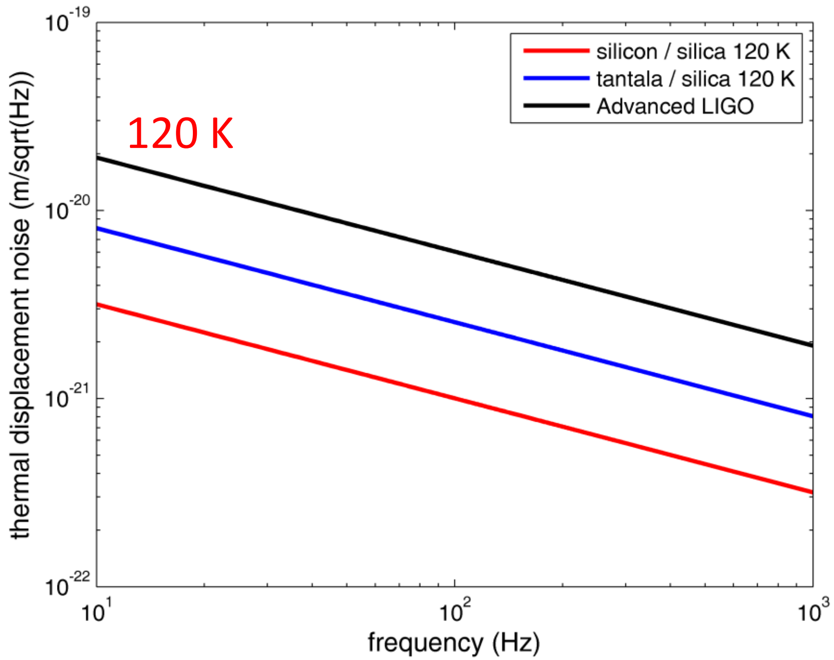
Comparison of coating Brownian noise

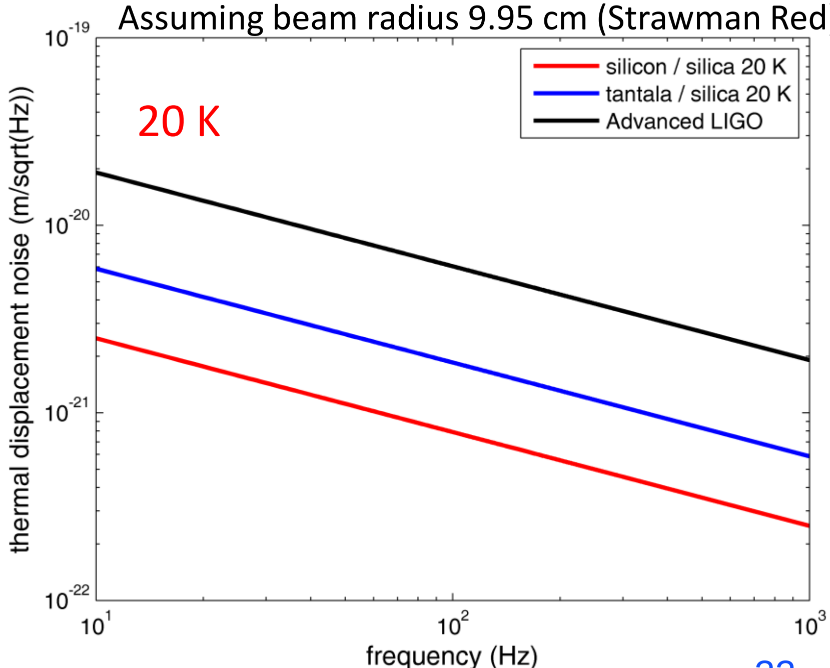
- SiO_2/Si requires 6 doublets for equivalent reflectivity as 15 doublets of SiO_2/Ta_2O_5)
- Loss of Si is significantly lower than Ta_2O_5 at cryogenic temperatures. Thermal noise limited by loss of silica layers at low temperature
- If lower optical absorption can be achieved, a-Si is a promising coating material

Thermal noise reduction in comparison to Advanced LIGO design*

	120 K	20 K
Ta_2O_5/SiO_2 (1064nm)	2.3	3.2
Si/SiO_2 (1550nm)	6.0	7.6

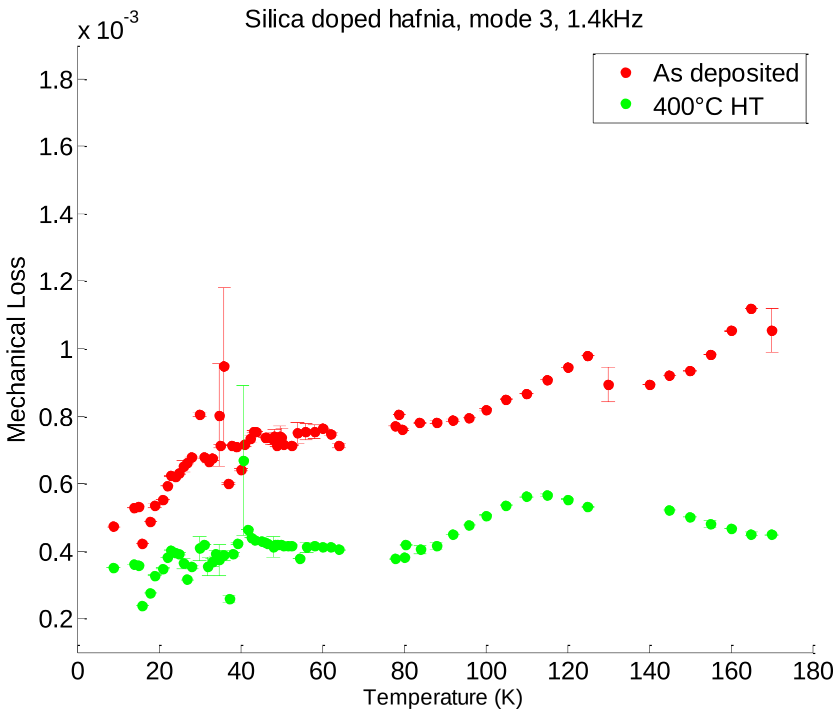
Assuming beam radius 9.95 cm (Strawman Red)

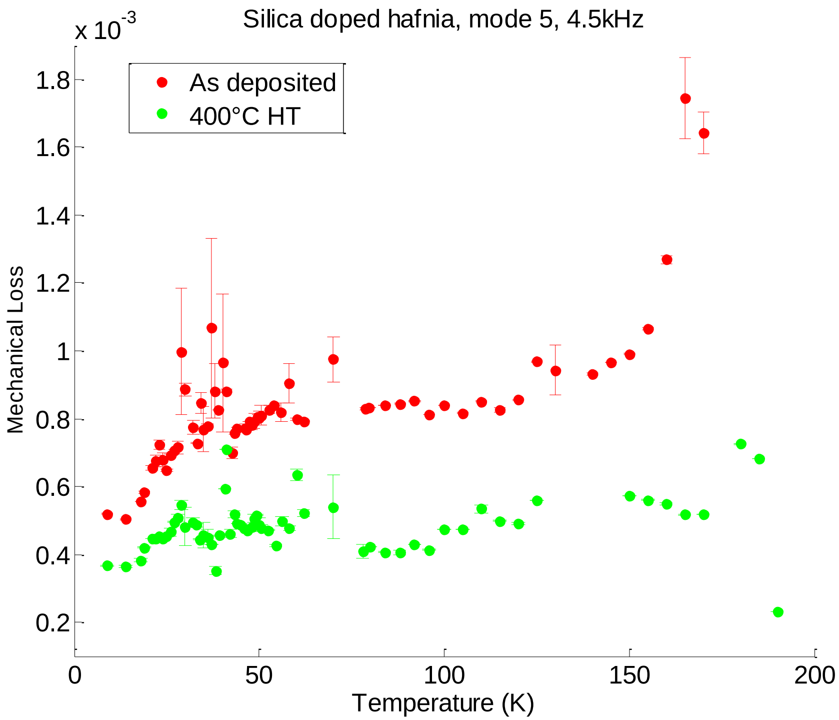




*λ=1064nm, T=300K, beam rad. 6.2cm

IBS silica doped hafnia



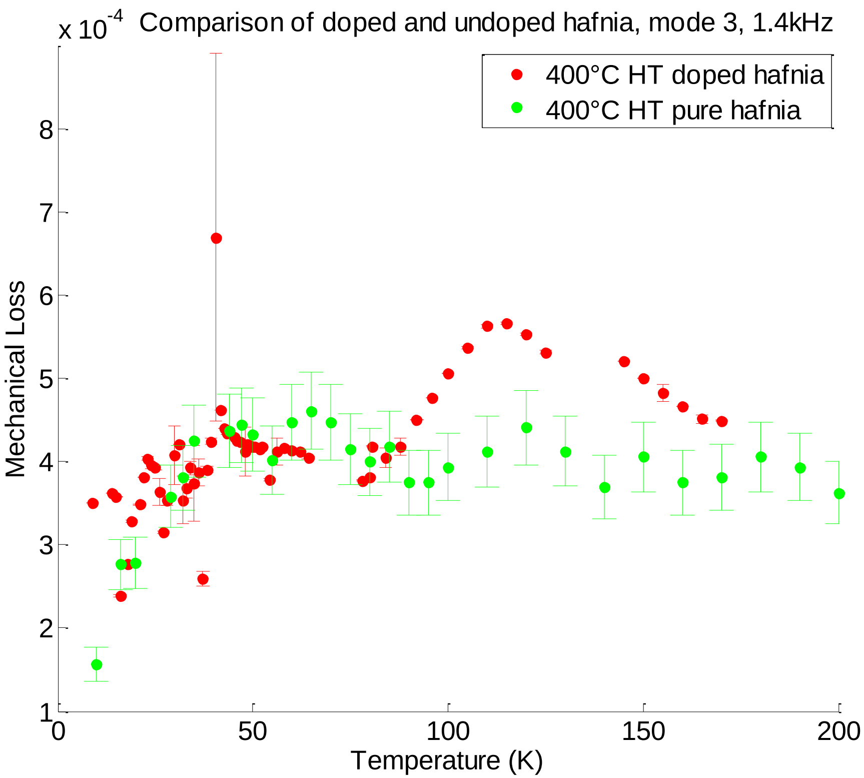


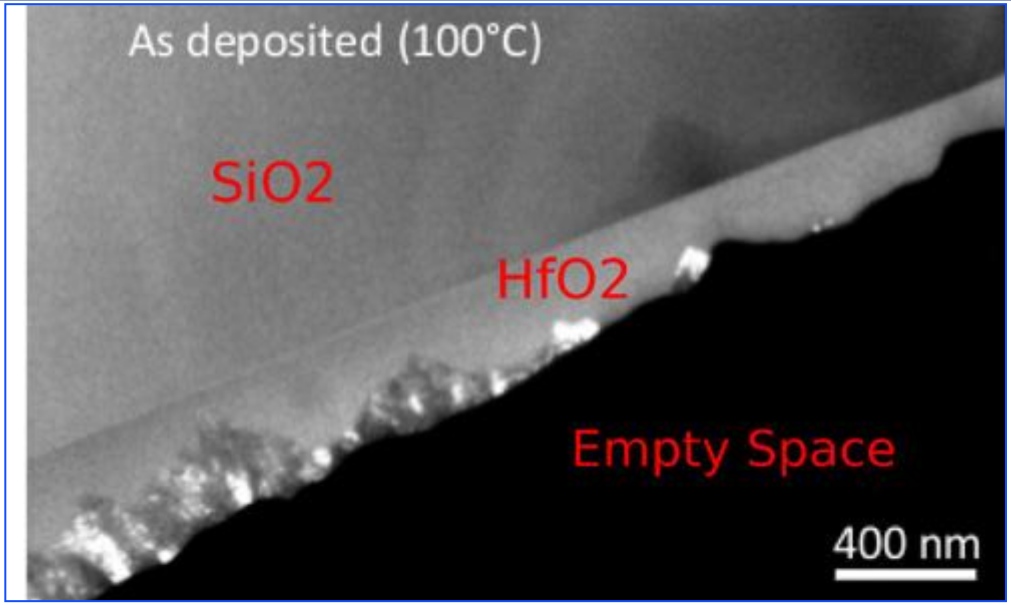
- Previously shown that deposition of pure hafnia partially crystallises coating[1] and that silica doping may prevent crystallisation[2]
- Heat treatment reduces loss - 400°C highest heat treatment measured so far
- Heat treated coating has lower loss than 600°C tantala at 20K – potentially good coating for cryogenic detectors

[1]Abernathy et al., CQG 28 (2011) 195017

[2]Ushakov et al., Phys. Status Solidi b 241 28 2268-78 (2004)

Comparison of pure and doped hafnia

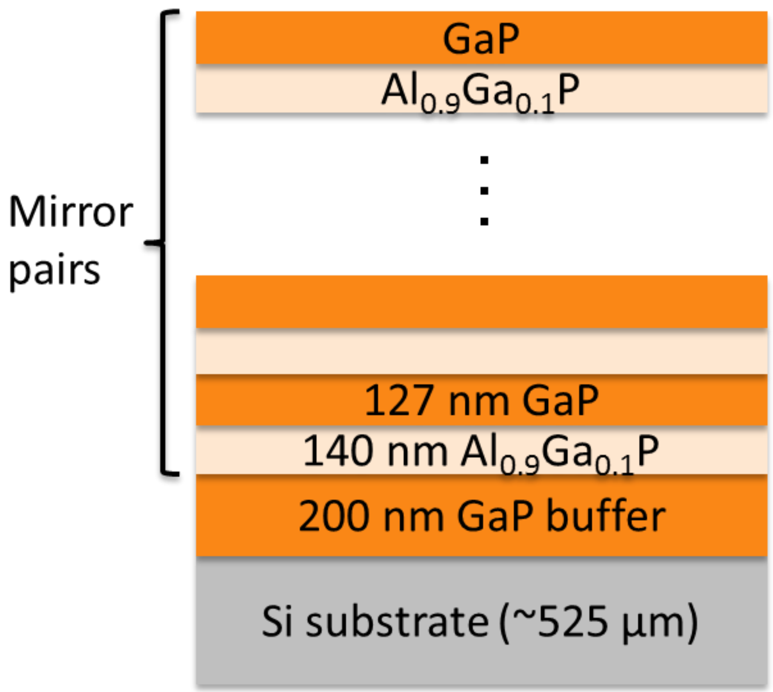




- Silica doping prevents crystallisation of hafnia, which is key for good optical properties
- Doping does not significantly increase the coating loss at low temperatures
- Investigations into the effects of both doping and heat treatment on going

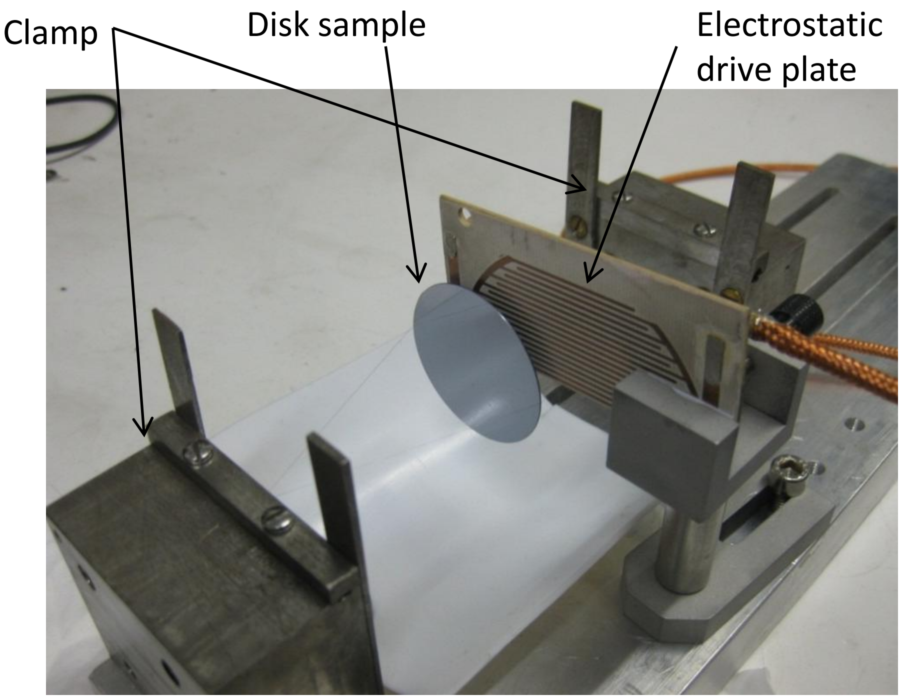
GaP/AlGaP Crystalline Coatings

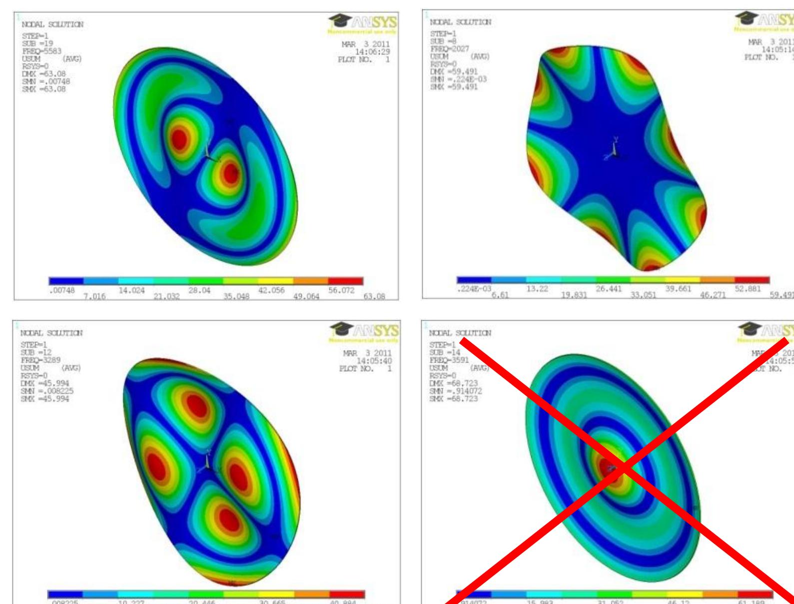
- Material is grown at Stanford on silicon and GaP
- Grown using Molecular Beam Epitaxy (MBE)
- GaP/AlGaP – lattice matched to silicon, can grow coatings directly on silicon substrates
- Experiments ongoing to measure the temperature dependence of the mechanical loss of substrates with and without crystalline GaP/AlGaP coatings
- Aim to study loss introduced by the coatings



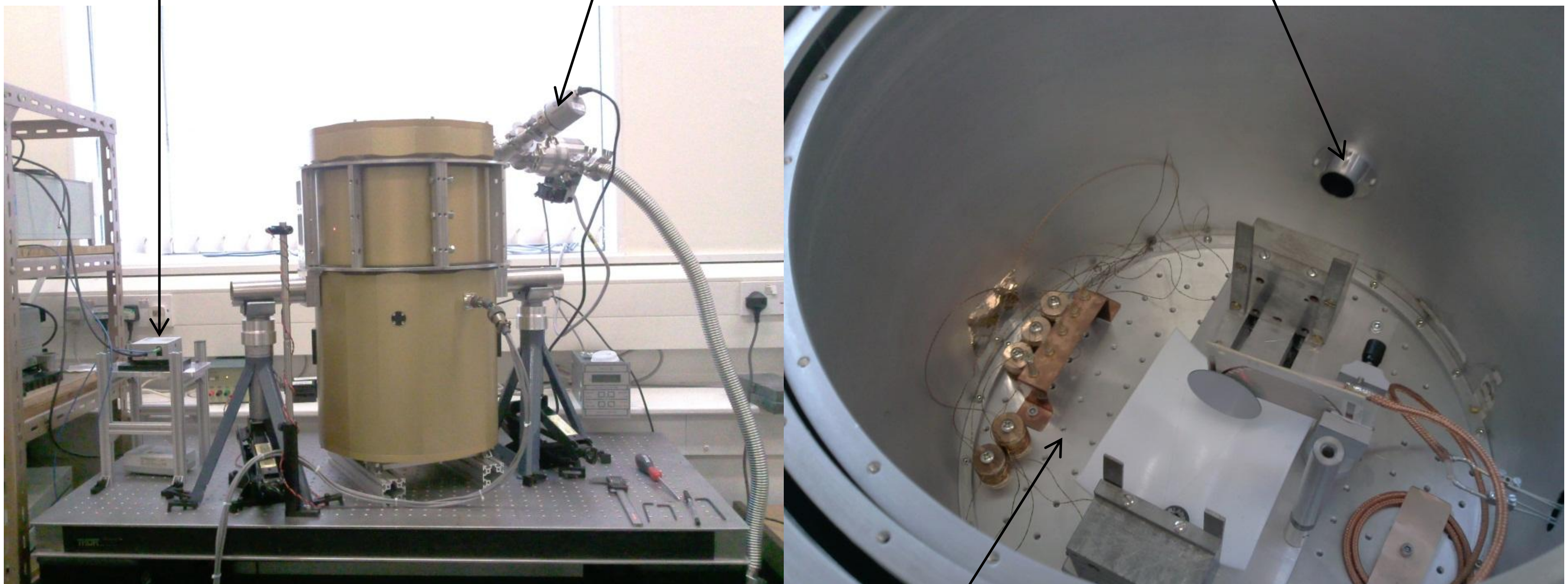
Nodal Support

- Coatings on silicon and GaP disks. Loss of various modes measured using a nodal support technique
  - Disk supported by two 50 micron wires
  - Accuracy of measurements at room temperature limited by thermoelastic loss in disk substrates





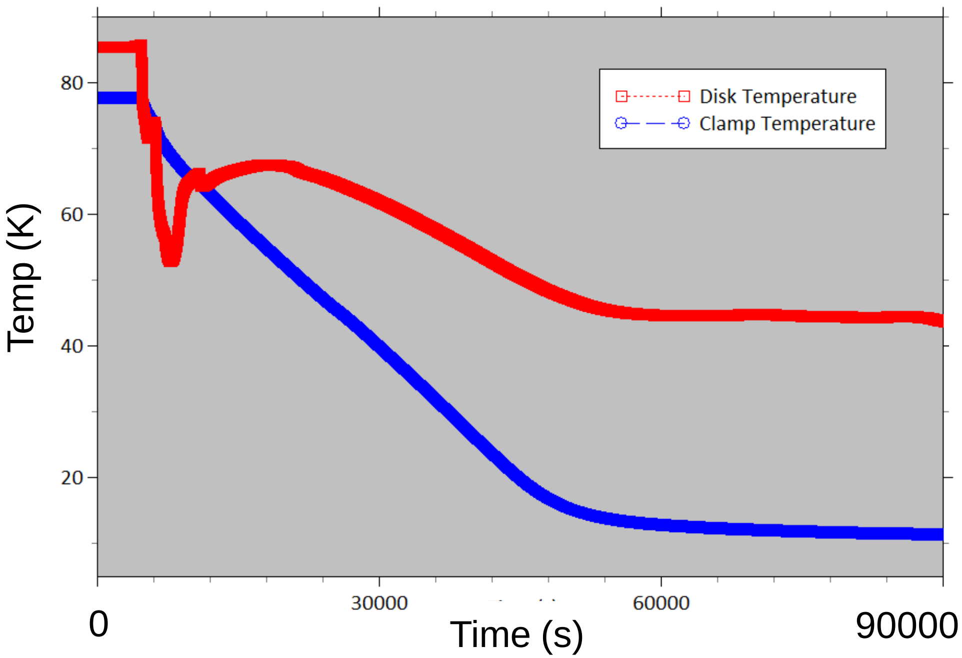
Experimental Setup



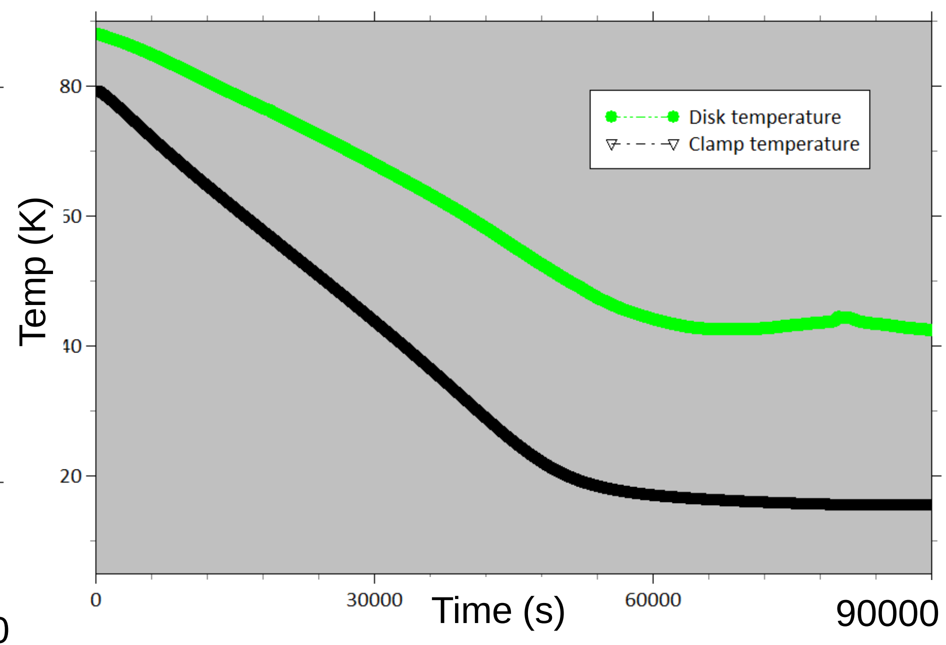
- Sample placed in cryostat and evacuated to ultra high vacuum
- Interferometer used for displacement measurements
- Cryostats designed to operate down to 4K using liquid cryogens
- Sample well thermally isolated from clamp/rest of setup
- Faster cooling/lower temperatures using exchange gas

Contact gas cooling curves

Cooling using contact gas



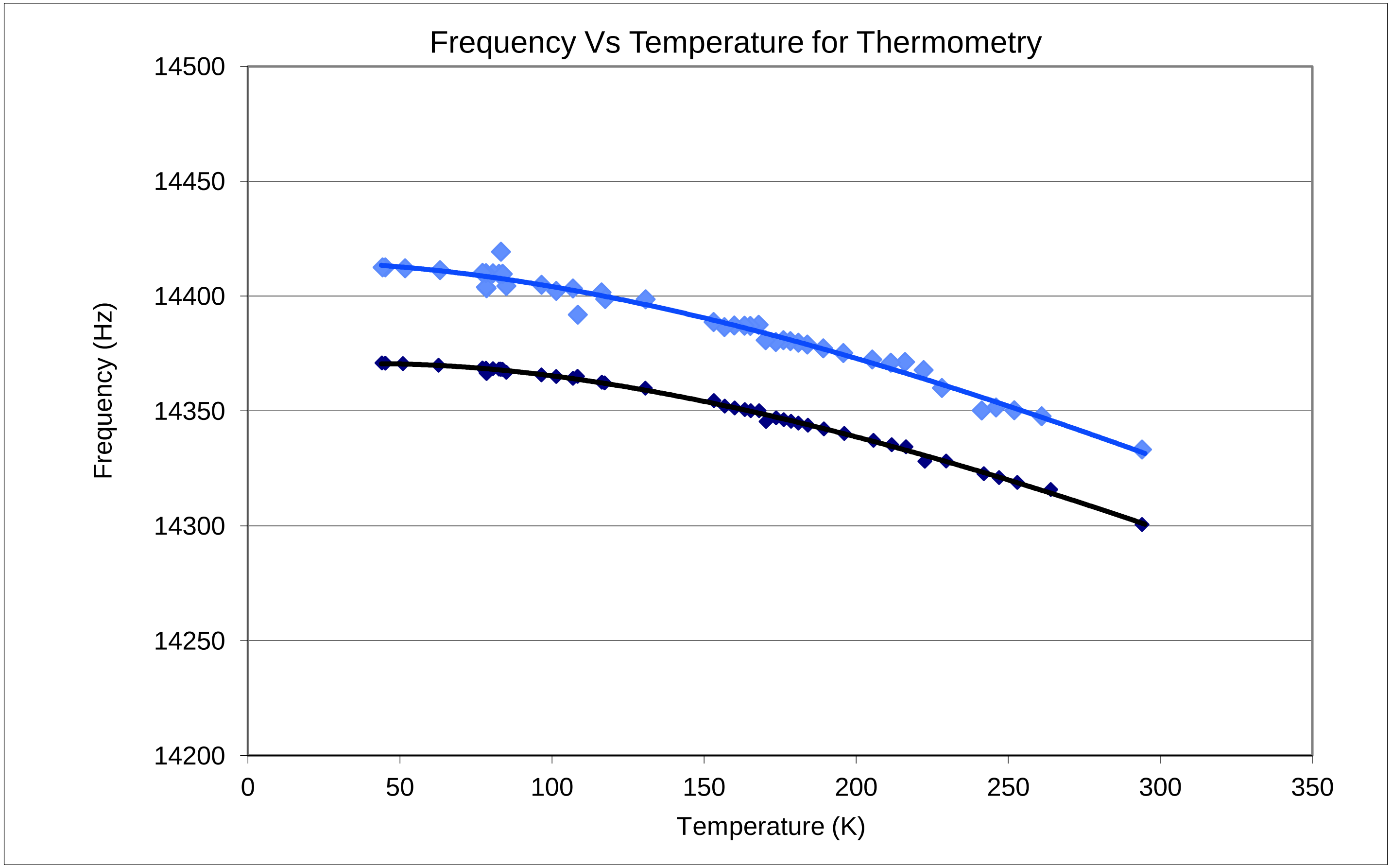
Cooling without contact gas



- Contact gas reduces cooling time
- Initial tests - not yet using optimum amount of cooling gas but cooling rate starting to improve

Thermometry

- Can measure frequency as a function of temperature with temperature sensor on disk
- Change in frequency then gives temperature without sensor



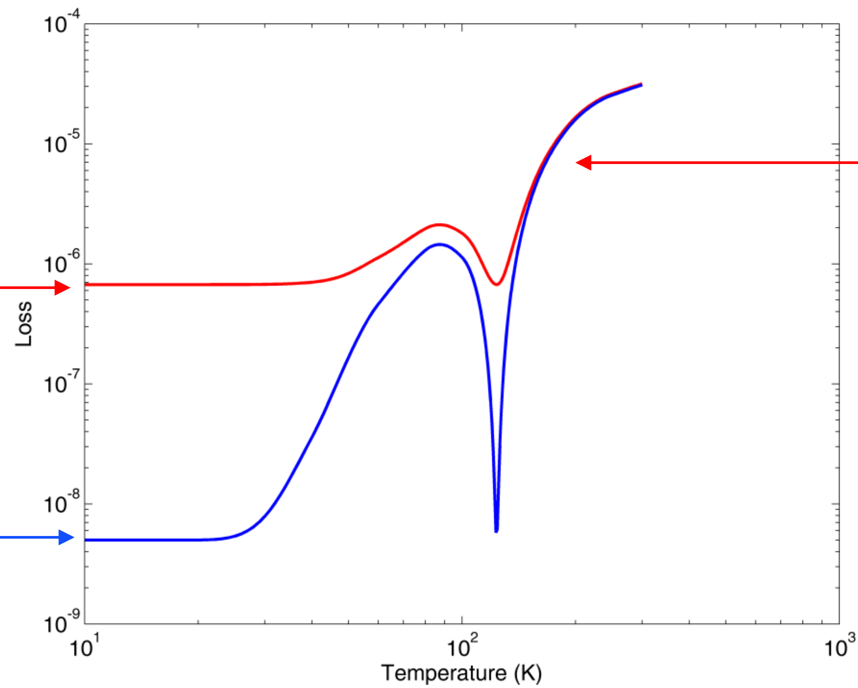
Frequency-Temperature dependence of two different modes

AlGaP on Si loss measurements

- Expect to be most sensitive to the coating loss below ~ 30K (likely to be limited by thermoelastic loss of disk at higher temperatures)
- Initial results of loss of disk reducing with temperature consistent with thermo-elastic limited loss
- Work on-going to calibrate temperature of disk, using exchange gas for thermal contact

Loss of coated disk

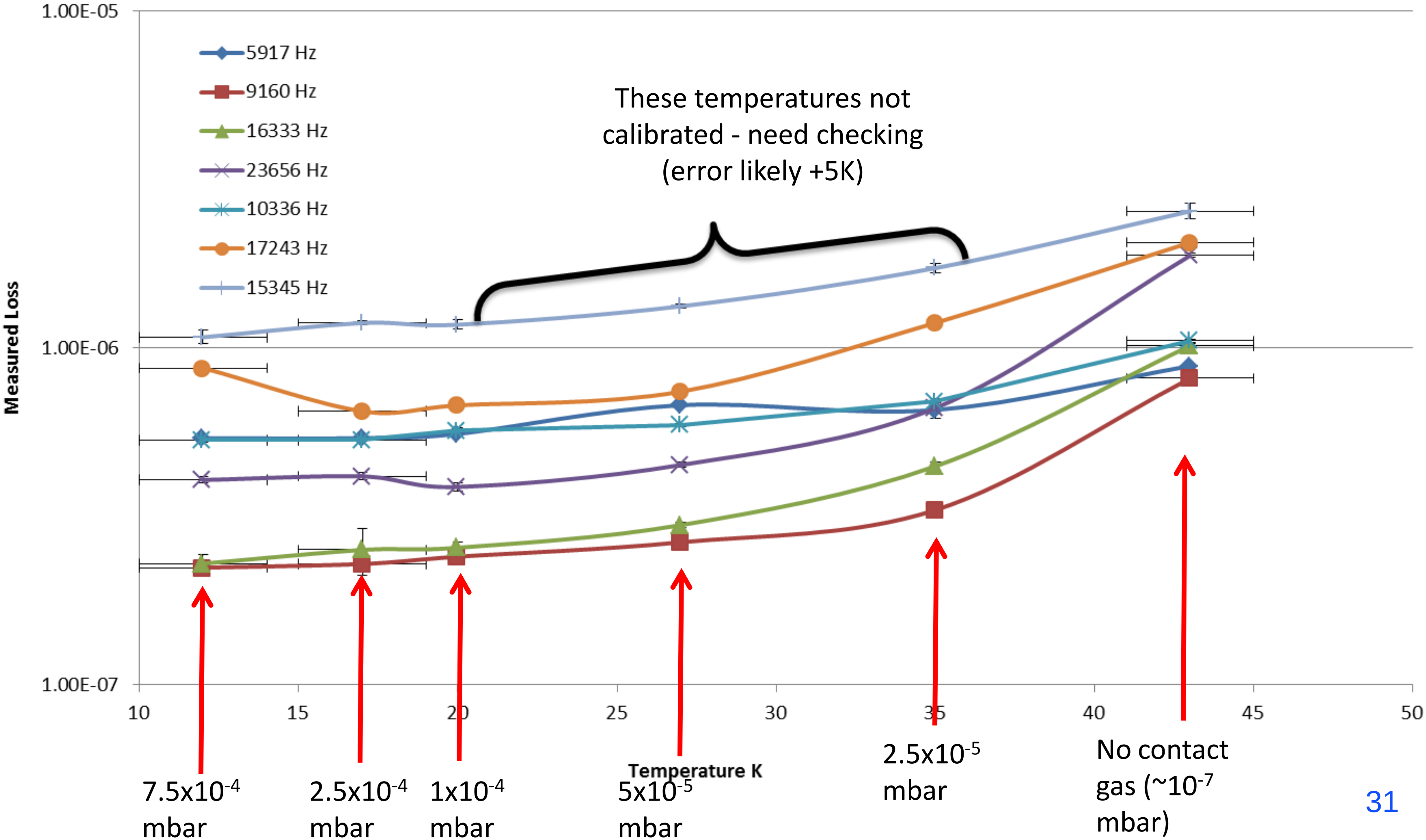
Loss of uncoated disk



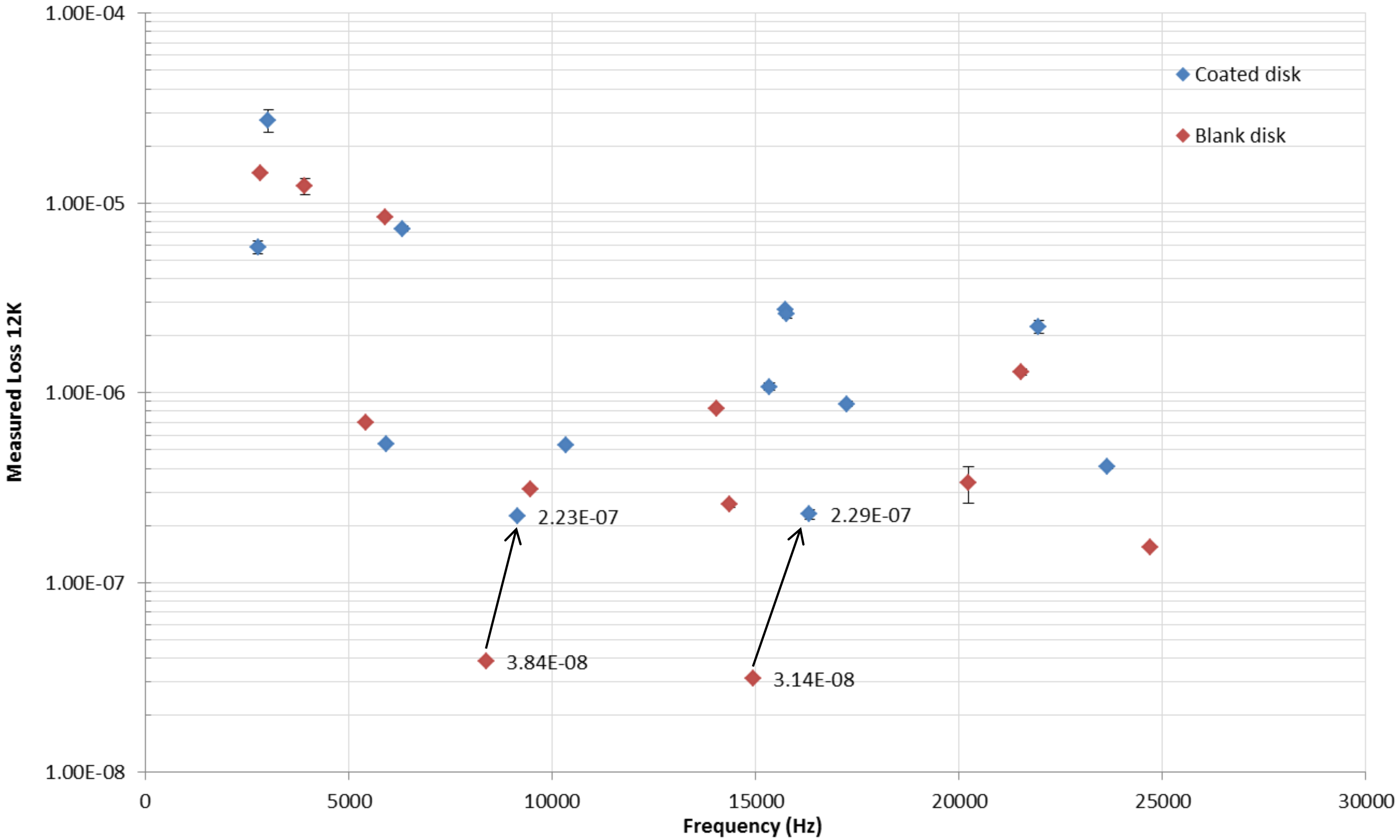
Close to room temperature, dominated by thermo-elastic loss in disk, very little sensitivity to coating loss

Coated Disk Low Temperature Loss

- AlGaP coated disk measured at different temperatures using He contact gas – different pressures balance input power of laser



Loss Measurements at 12±2K



Two lowest loss modes show possible difference in loss between coated and uncoated disk, otherwise coating loss again not visible

Preliminary coating loss analysis

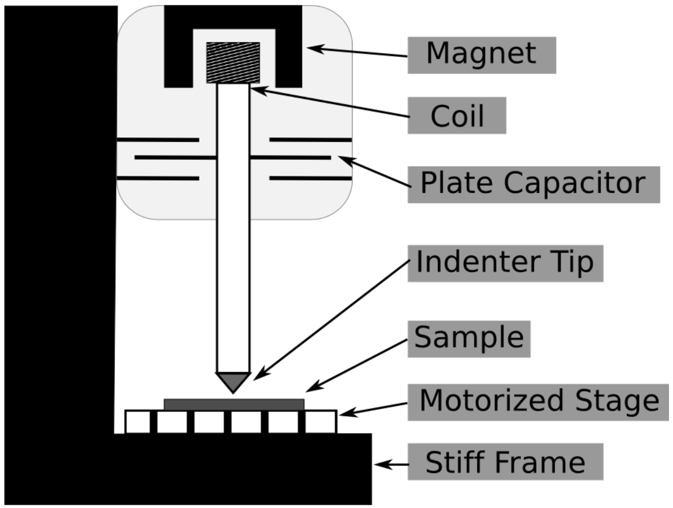
- Assuming the difference in loss for these two modes is due to the coating
- Coating loss is calculated:

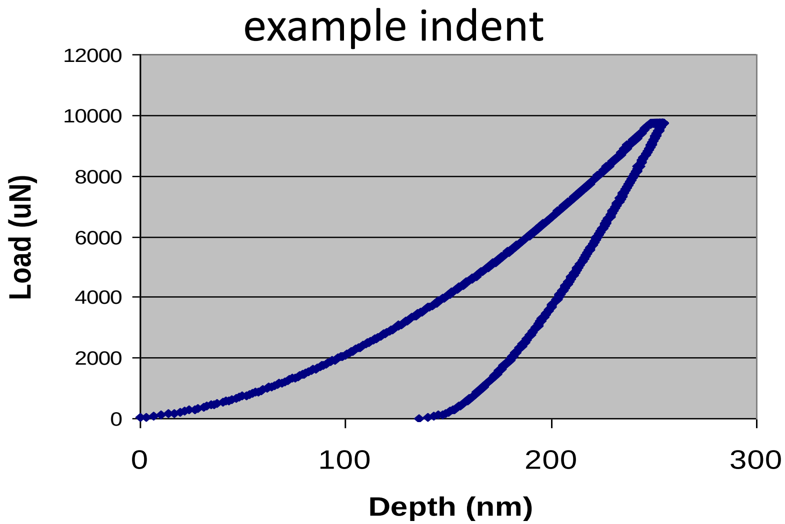
$$\phi(\omega_o)_{coating} = \frac{E_{Stored_{Substrate}}}{E_{Stored_{Coating}}}\left(\phi(\omega_o)_{Coated\,disk} - \phi(\omega_o)_{Uncoated\,disk}\right)$$

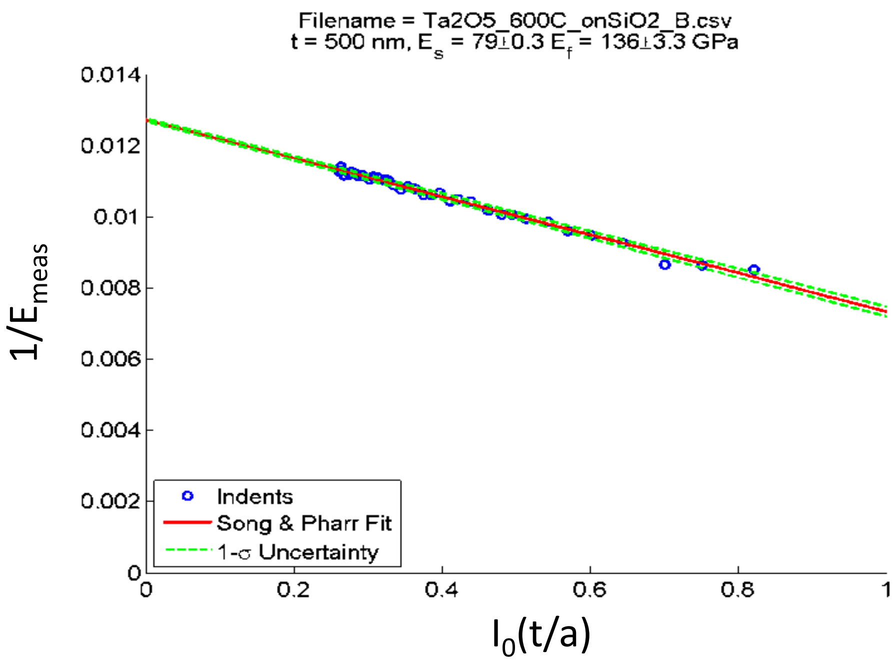
- $\frac{E_{Stored_{Substrate}}}{E_{Stored_{Coating}}}$ is an energy ratio which we can calculate either by approximating the disk as a bending beam – or through FEA models of the disk and coating

- Average coating loss (at 12K): 1.42×10^{-5}
  - This is a factor of 14x lower than a silica/doped tantala coating at room temperature and 45x lower than the Advanced LIGO coating loss at 12 K

Coating property characterisation
Young's modulus - nano-indentation



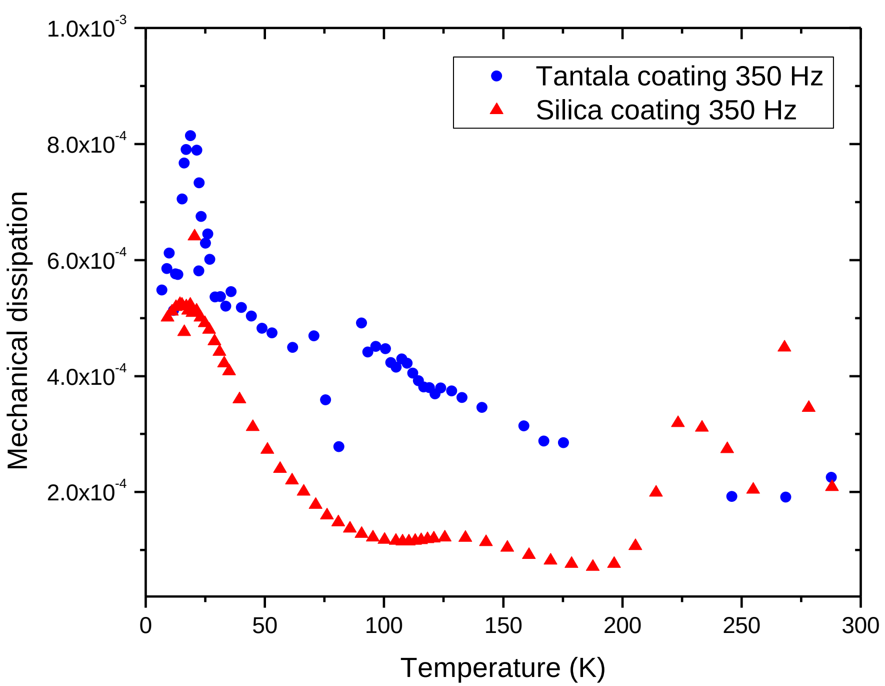


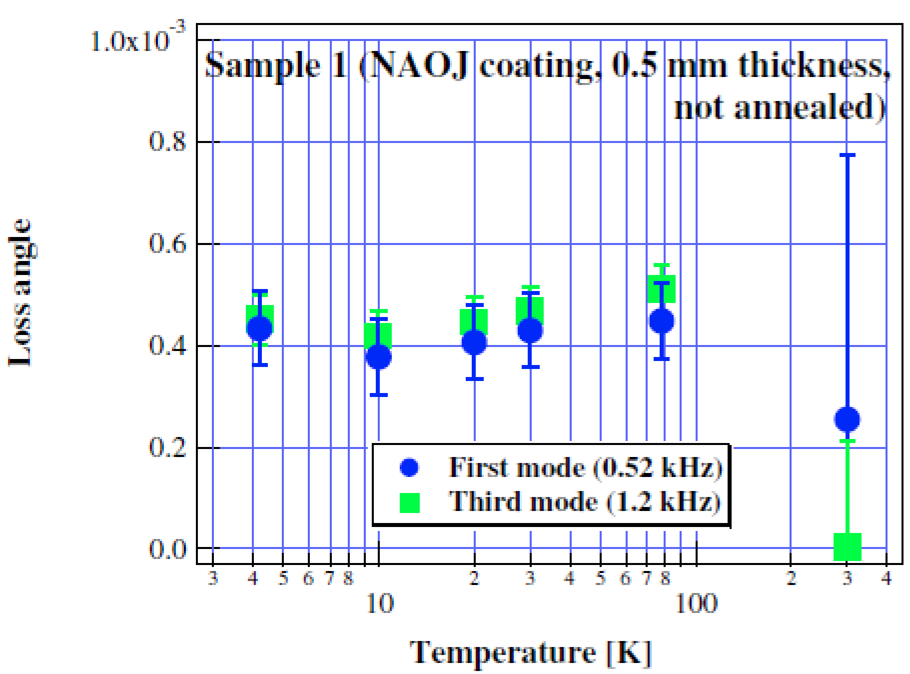


- Each indent produces a modulus containing information on coating and substrate
- Indent at many different depths and extrapolate to zero depth to get coating modulus

Work at the ICRR

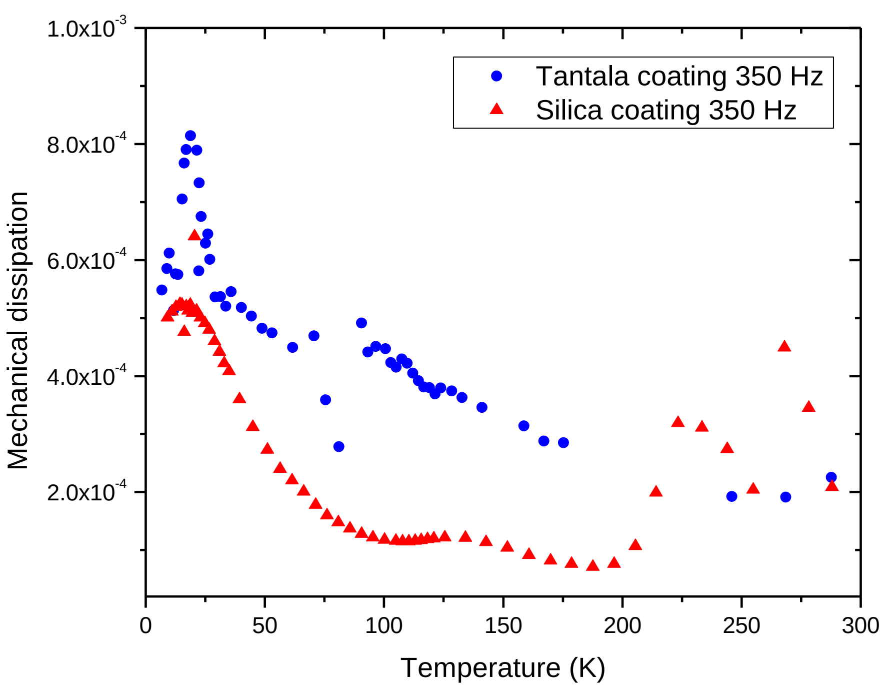
- Previous measurements at Glasgow (I. Martin et al.) show peaks in both silica and tantala single layer coatings at cryogenic temperatures
- Previous measurements on silica/tantala multilayers made at KEK do not (K. Yamamoto et al, Physical Review D 74, 022002 (2006))
- Need to clear up this apparent discrepancy
  - May stem from differences in substrate material, geometry, annealing conditions, coating vendor, coating thickness

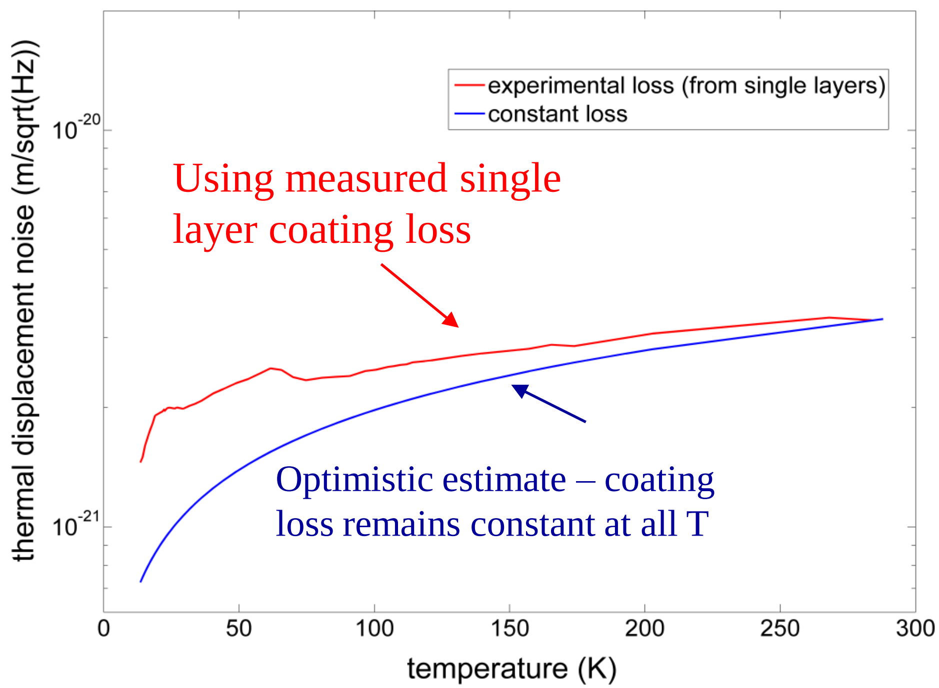




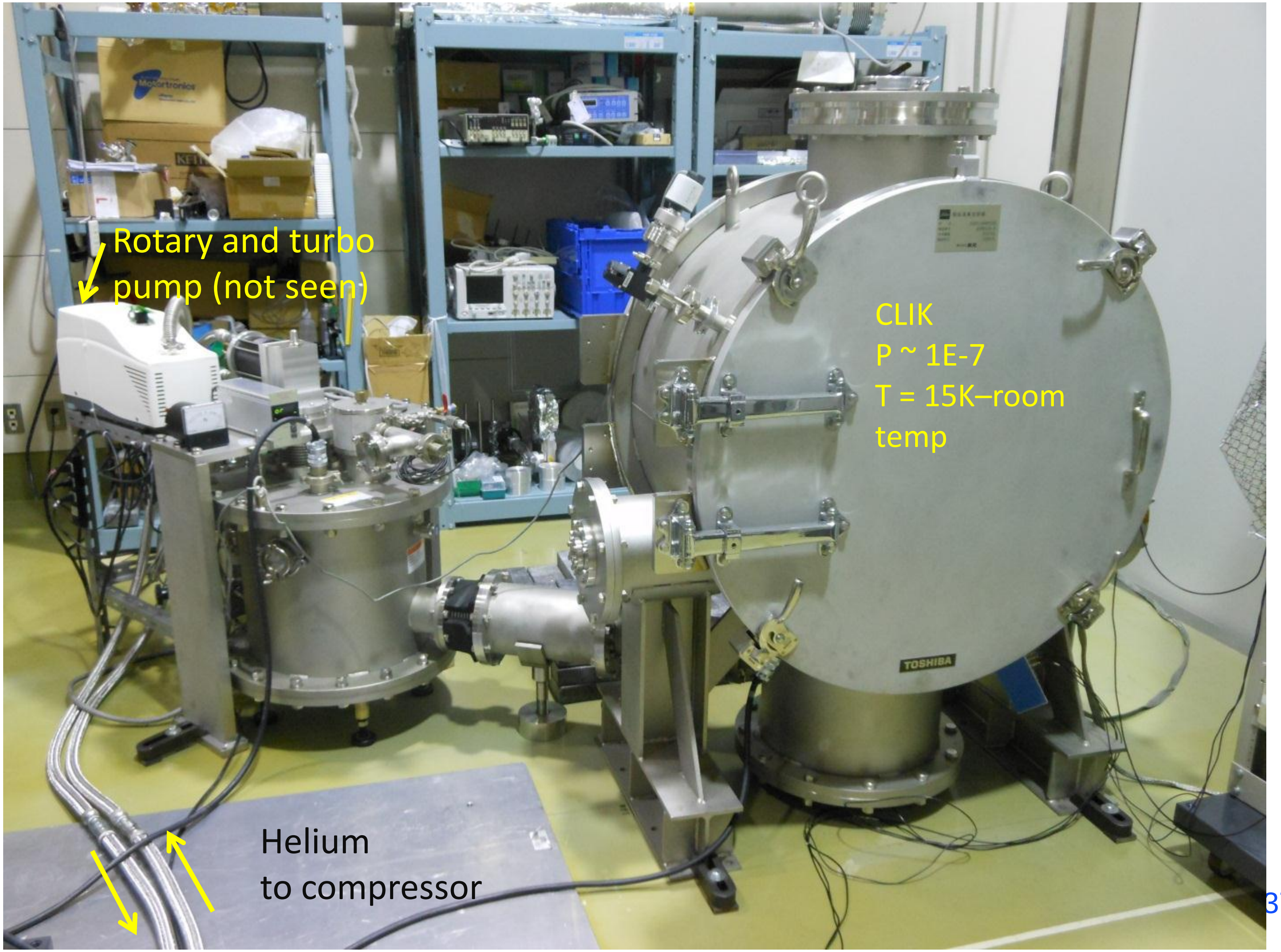
What impact do these results have?

- How much will sensitivity increase by moving to cryogenic temperatures?
- This is extremely important for cryogenic detectors such as ET/KAGRA
- Assuming loss is independent of temperature gives a more sensitive detector at cryogenic temperatures than the estimate from single layer measurements
- Disks to be re-measured with smaller temperature steps by ICRR and Glasgow members through ELiTES programme

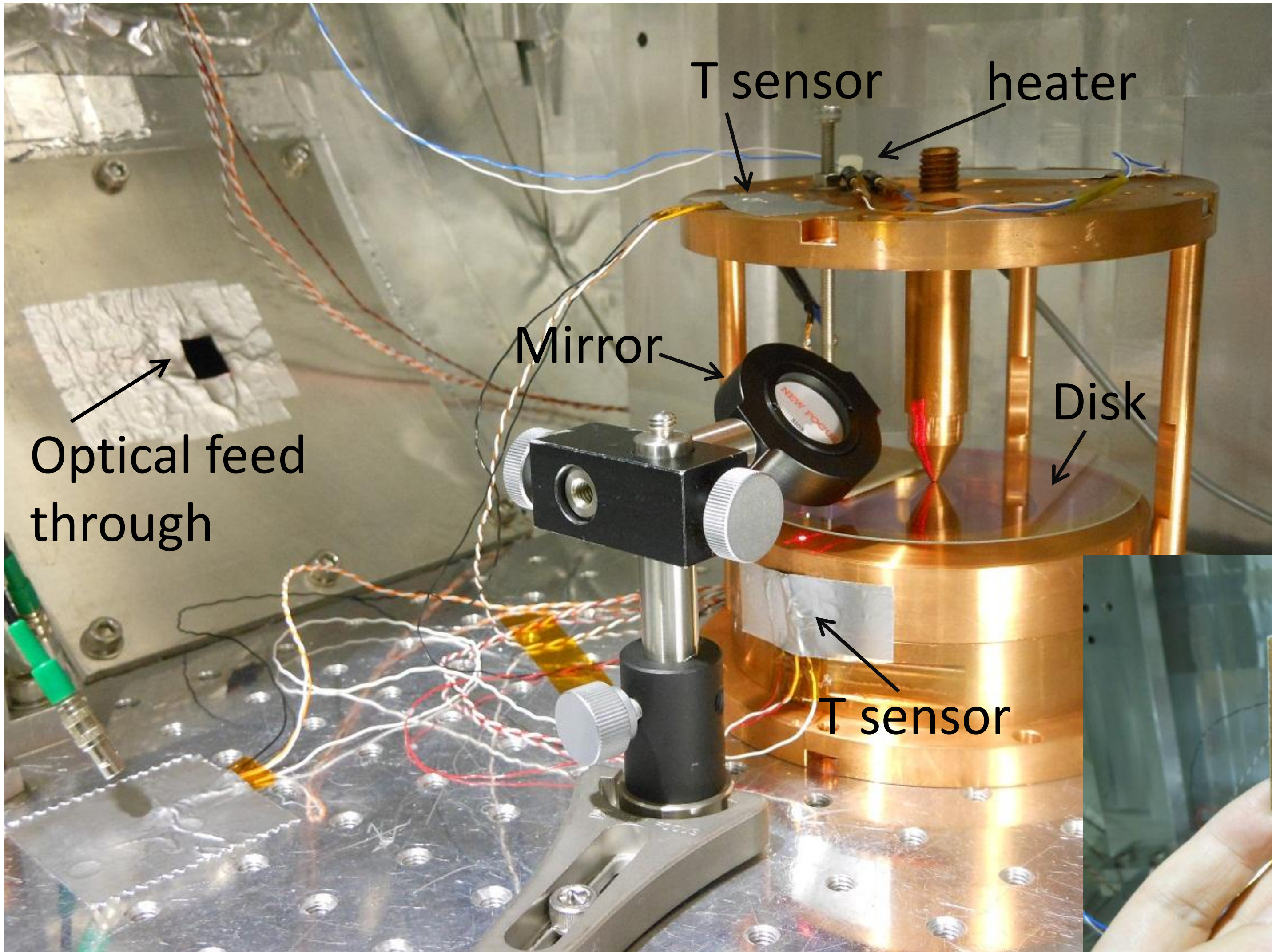




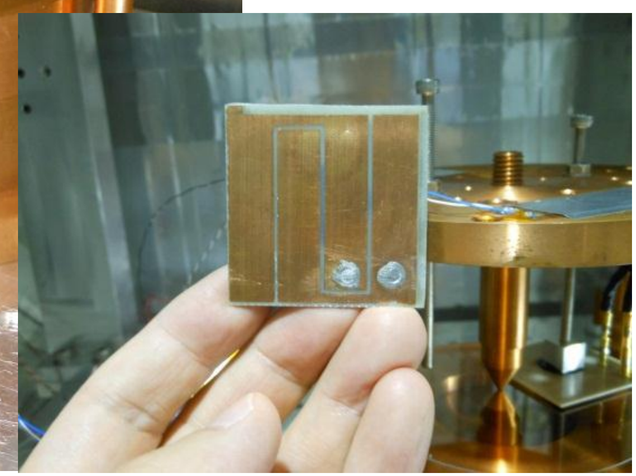
ICRR disk measurement setup



Inside CLIK

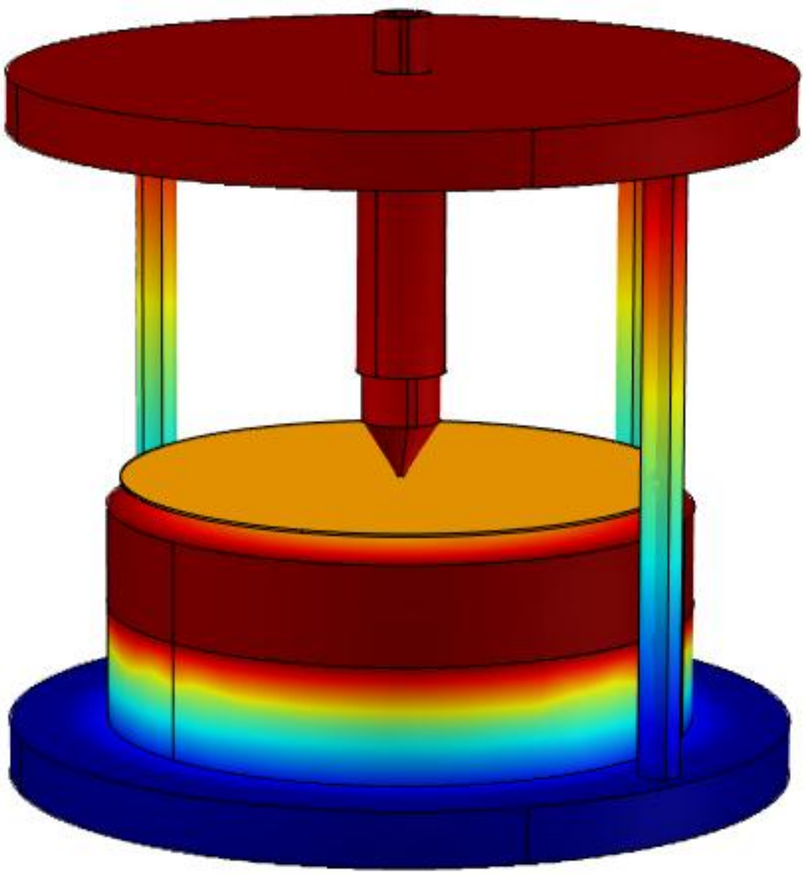


Electrode



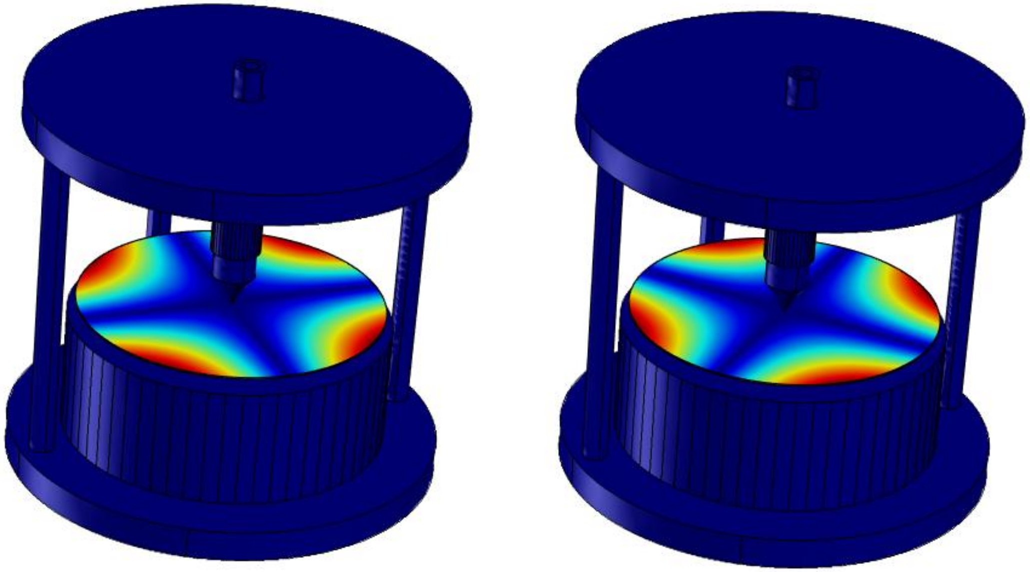
CLIK temperature

- Temperature measured by silicon diode sensors on the top and bottom of clamp structure
- Temperature also measured on baseplate
- Temperature of disk obtained using COMSOL model of structre
- Temperature control uses heater attached to the top of the clamp
- T steps 1K at low temperatures



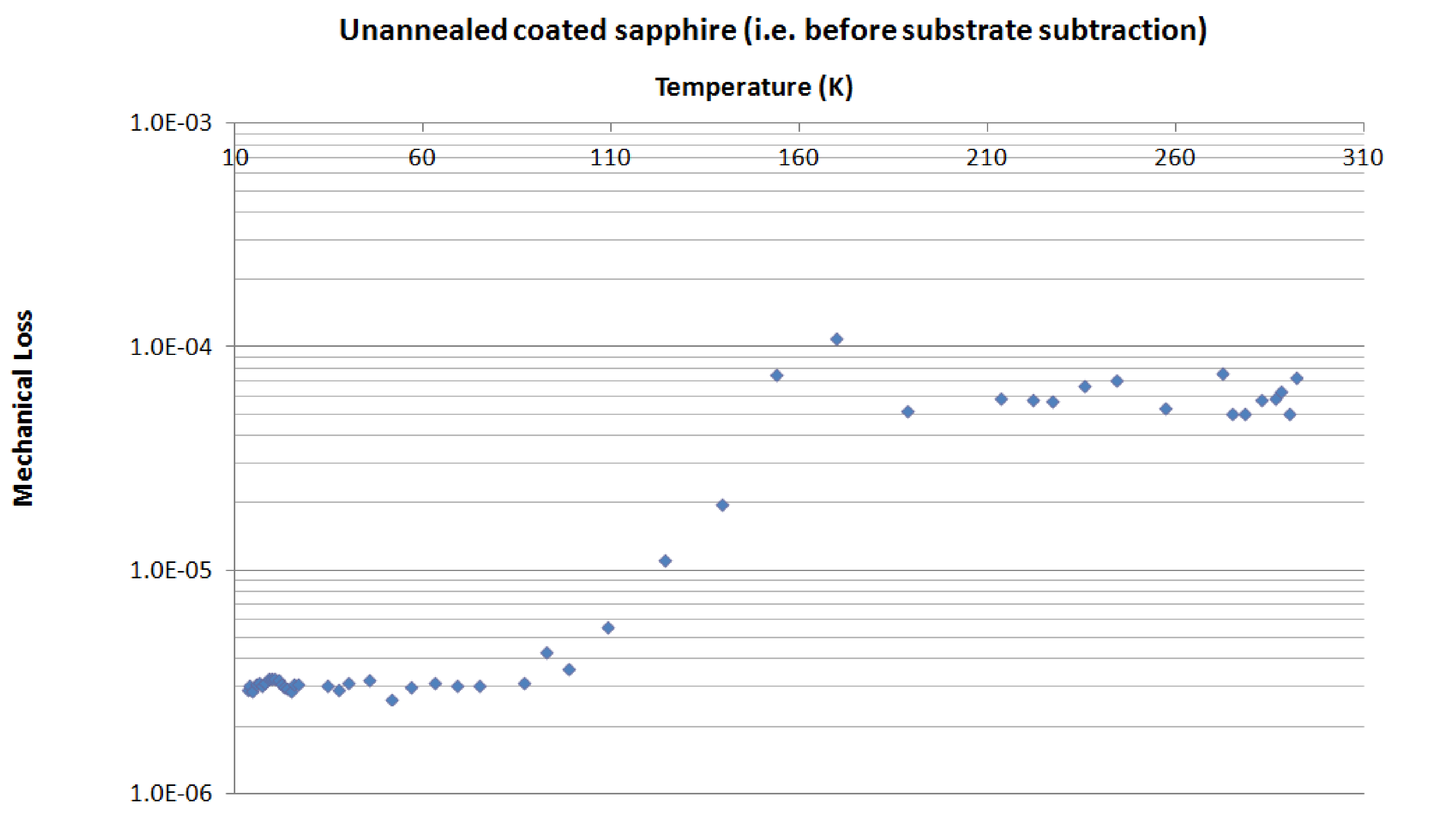
Coating loss measurement

- Electrostatic drive used to vibrate resonant frequencies of the disk
- Target mode looks like this:



- Optical lever approach with split photodiode used for vibration amplitude readout
- Signal fed into lock-in amplifier with reference frequency on resonance

CLIK Measurement – initial results



Summary

- Better amorphous coatings
  - Evidence that high titania doping concentrations may suppress low temperature loss peak in tantala
  - At cryogenic temperature, Si/SiO_2 coatings likely to give a factor of between 2 and 3 reduction in thermal noise compared to Ta_2O_5/SiO_2
  - Measurement of an Advanced LIGO multilayer coating at 20K shows an improvement in thermal noise of a factor of 2.1 compared to Ti:Ta_2O_5/SiO_2 at room temperature
  - Comparisons of coating deposition techniques on-going, with initial results suggesting ALD tantala has significantly higher loss than IBS
  - Heat treated silica-doped hafnia has been shown to have a lower loss at 20K than 600°C tantala at 20K.
  - Measurements of a range of amorphous coatings on-going

- Single crystalline coatings
  - Preliminary results suggest a loss of 1.42E-5 at approximately 12K for the first GaP/AlGaP multilayer stack on silicon grown by Stanford
  - Samples of a single layer of GaP on silicon cantilevers to be measured soon

Summary/Future work

- Glasgow will also investigate other crystalline coatings (AlGaAs)
- JAE coatings on sapphire to be measured at cryogenic temperatures

- At the ICRR:
- As deposited NAOJ coating already measured
- Currently measuring annealed coated sapphire disk
- JAE coatings also to be re-measured at Glasgow
- KAGRA optics group interested in measuring coatings from different vendors
- Work done as part of ELiTES exchange

Thanks for listening

Questions?

Feel free to come to rm 523 for anything that wasn’t covered today