Development of ultra-low optical and mechanical loss aSi coatings using novel ECR ion beam deposition

Optical absorption of amorphous silicon coatings

Stuart Reid / Iain Martin (UWS/GU)

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LIGO-G1601200

“Take home message”

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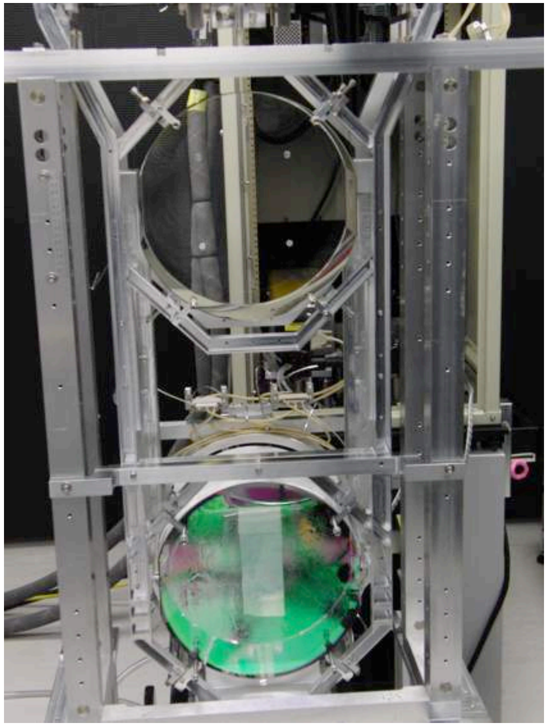
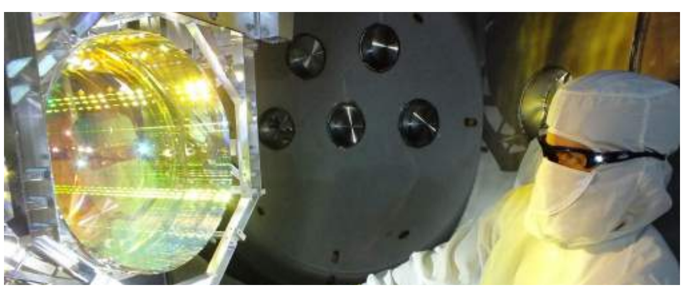
Recent results from UWS/UG now suggest:

- It is possible to reduce optical absorption in IBS aSi coatings, whilst maintaining low ϕ.

- Heated deposition of IBS aSi films likely to gain similar benefits in atomic structure/mechanical loss as heated e-beam deposition (as observed by Berkley group).

Background





Original requirements for aLIGO (at 1064nm):

Absorption < 0.5 ppm required (goal < 0.3 ppm)

Scatter < 2 ppm required (goal < 1 ppm)

ITM transmission: (5 ± 0.25) × 10-3.

IBS

ETM transmission: < 10 ppm (goal < 5 ppm)

Test Mass HR matching = 2 (T1-T2)/(T1+T2)

< 1 × 10-2 required (goal 5 × 10-3)

AR reflectivity: 200 ± 20 ppm

Mechanical loss: 3×10^{-5} (goal 1×10^{-4})

???

Likely requirements for aLIGO+ and beyond?

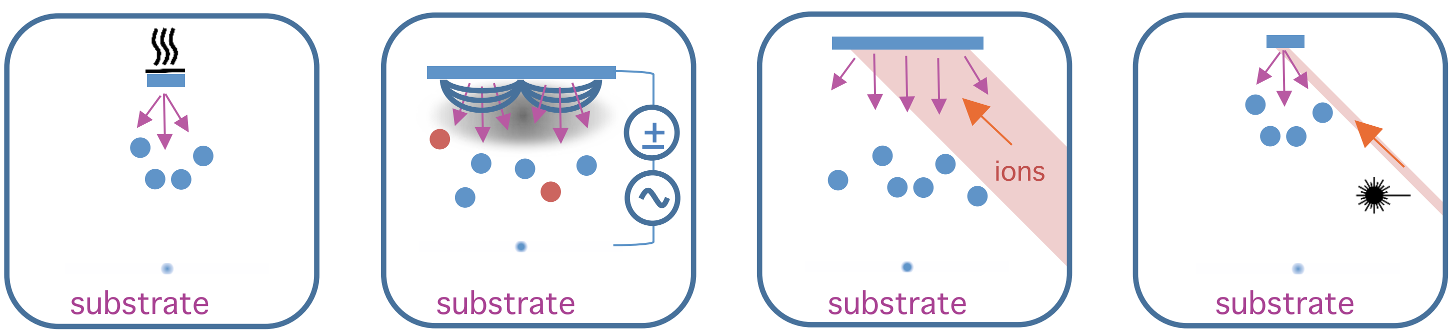
PVD (Physical vapour deposition)

The continued challenges in PVD technology

-> Uniform deposition on large area : difficult

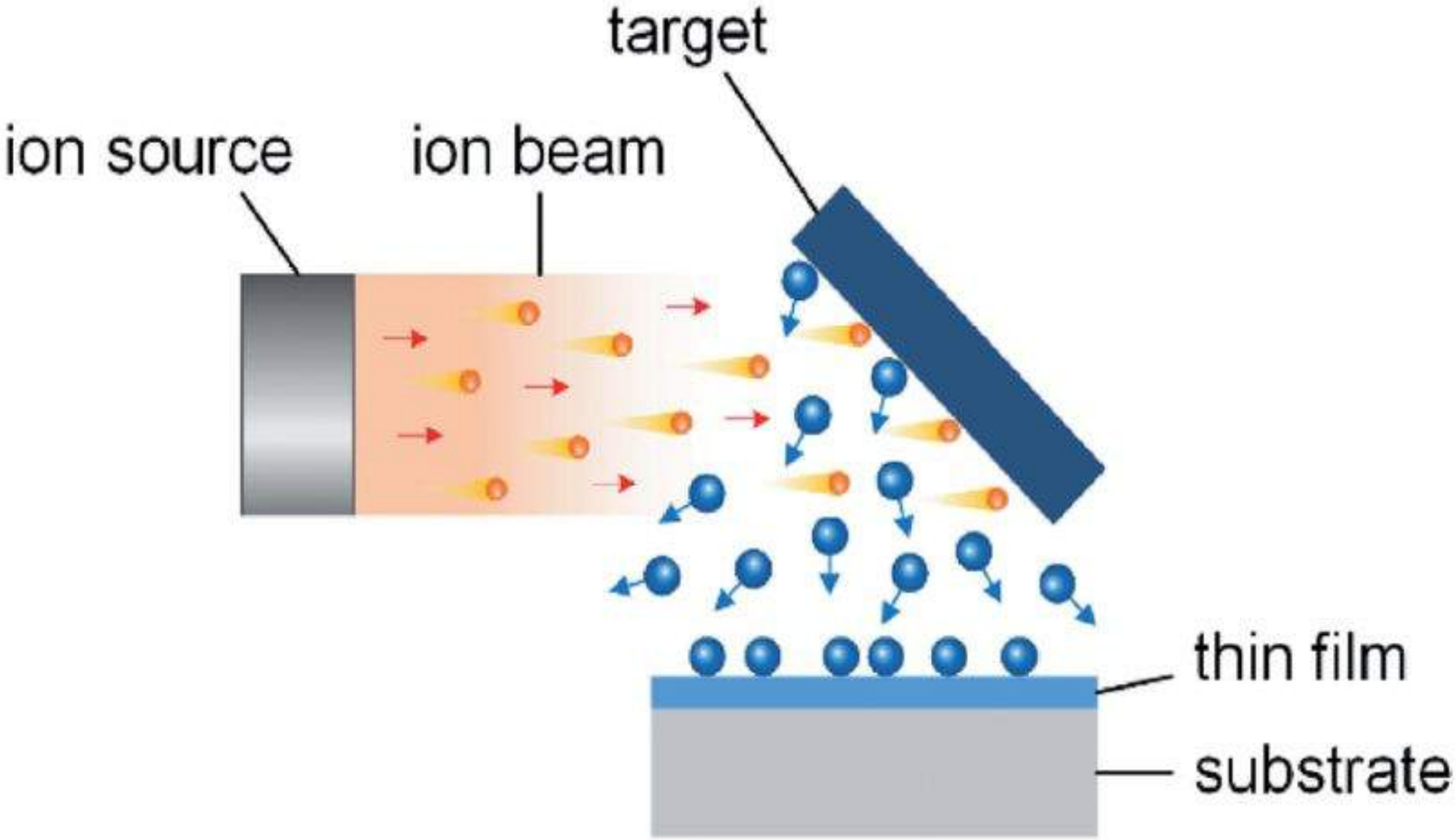
-> Multi component deposition: even more difficult

Evaporation | Magnetron sputtering | Ion Beam Deposition (IBD) | Pulsed Laser Deposition (PLD)

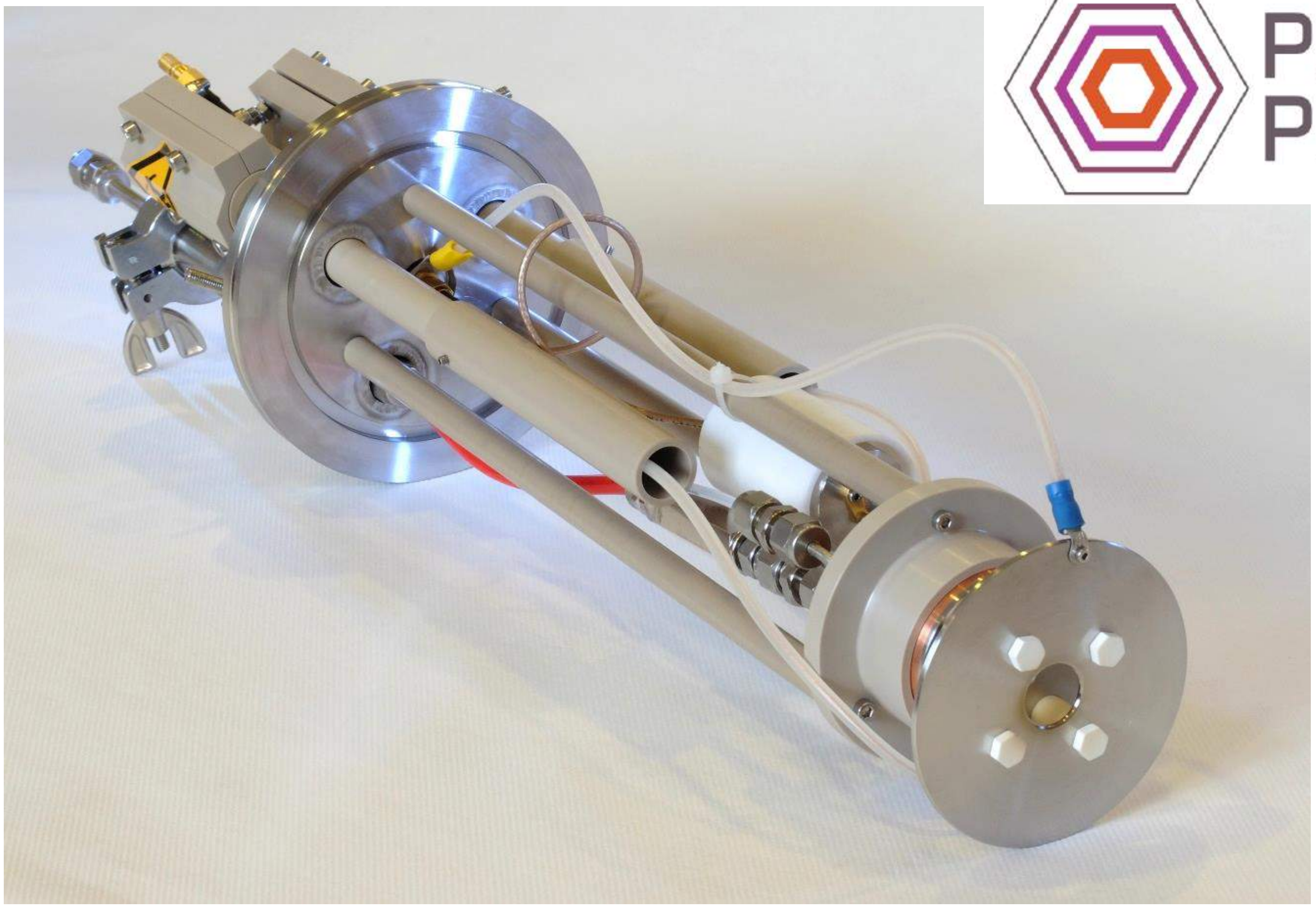


Deposition profile/conditions is somewhat fixed and limited by the geometry of the process

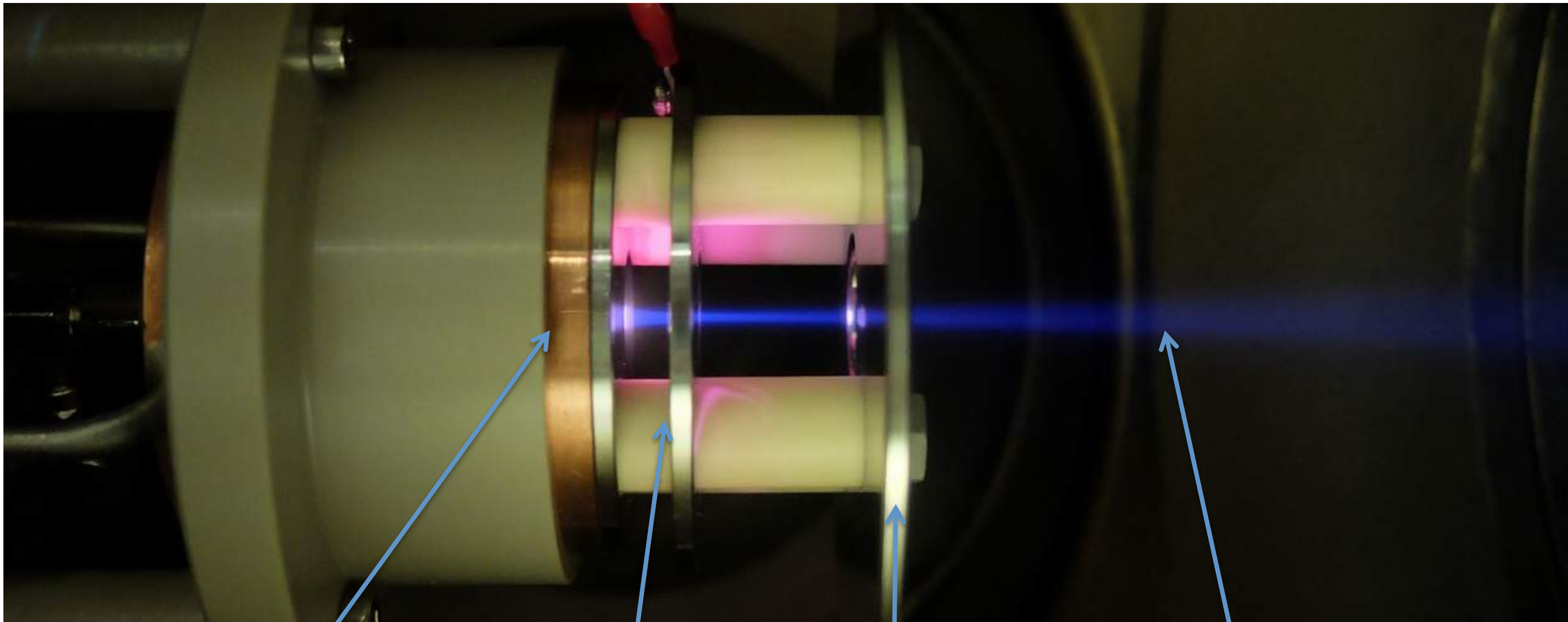
Ion beam deposition (IBD)



ECR ion source at UWS



Development of ECR-IBD



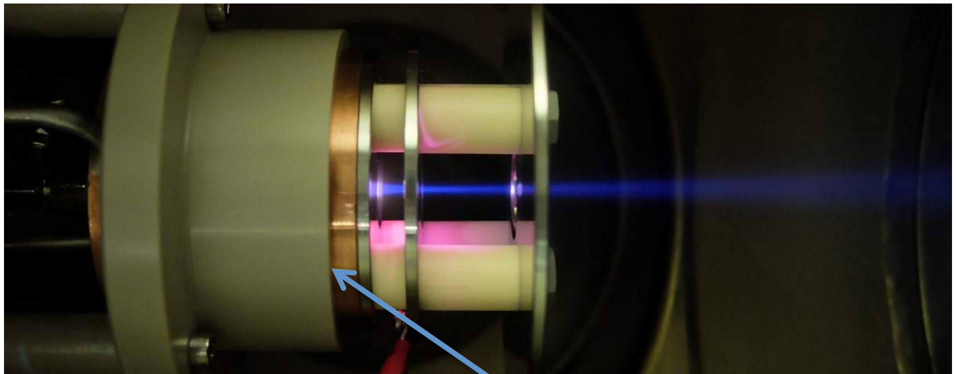
ECR plasma cavity
(microwave)

focus

ground

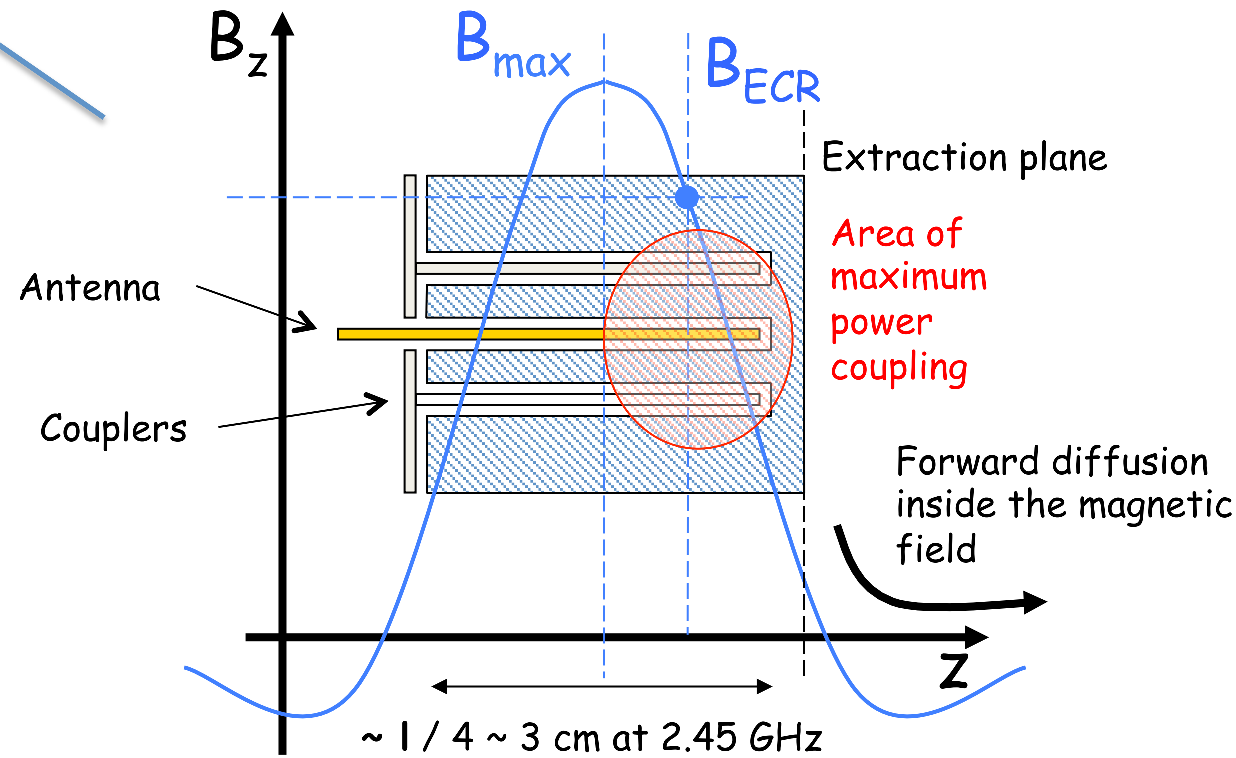
Divergent Ar ion beam

Development of ECR-IBD



Compact λ/4 microwave cavity

- filament-free
- maintenance free
- low current
- extraction potential 0-20 kV



Comparison to standard IBS

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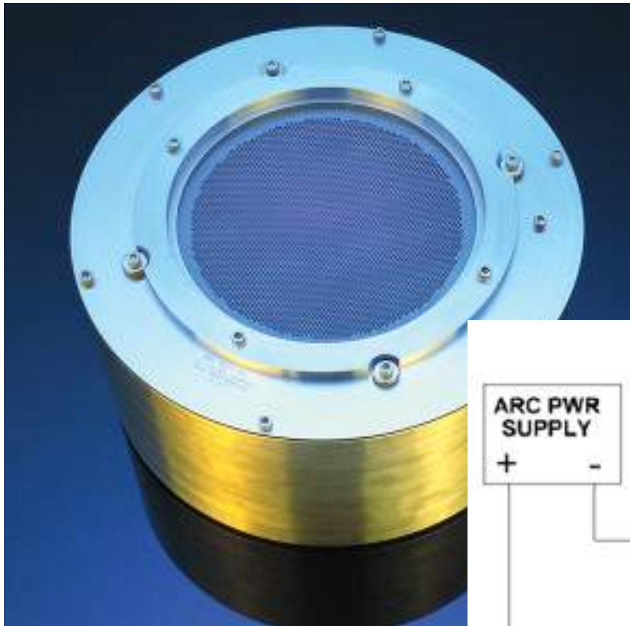
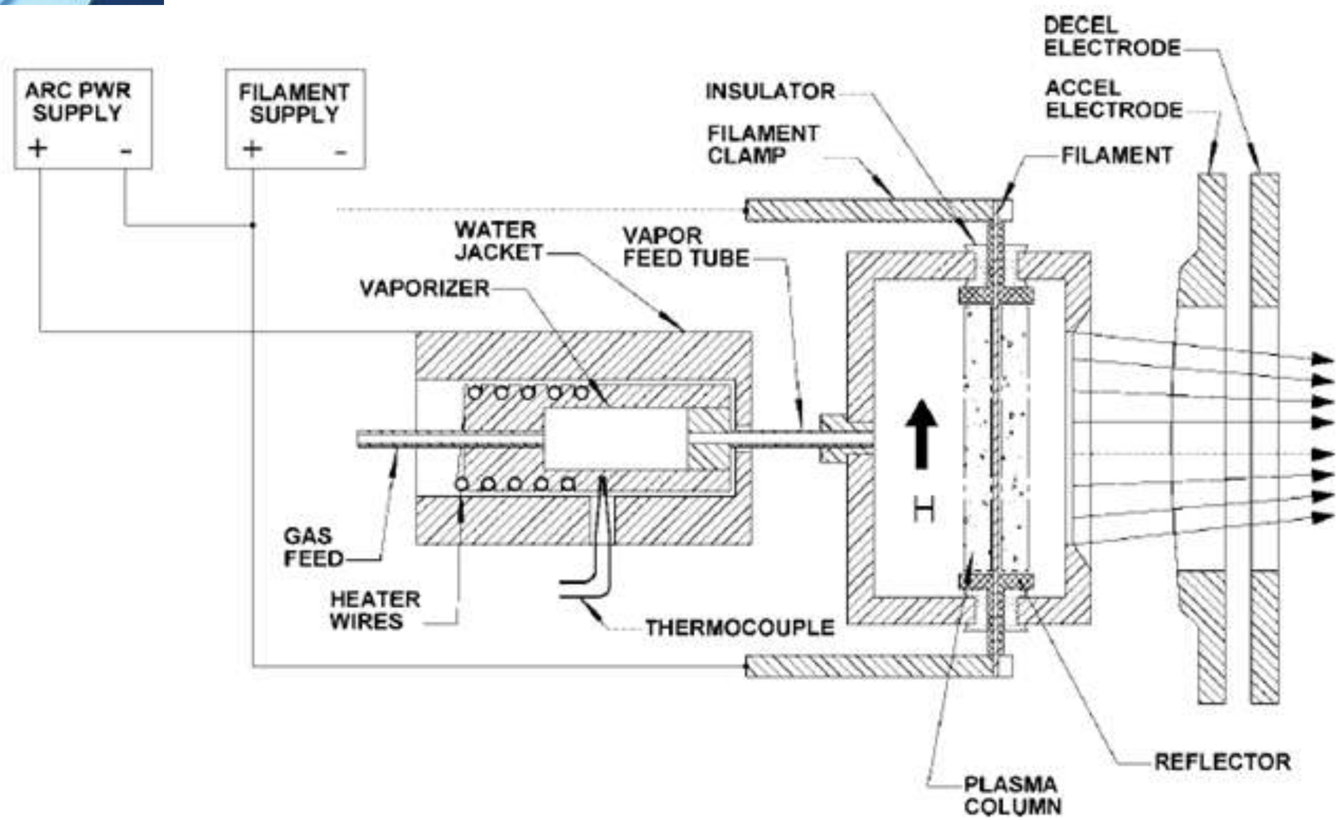


Filament and extractor grid provide high-current (possible contamination and expensive running costs)

50 to 1500eV and 75 to 700mA (for Veeco 16cm RF)



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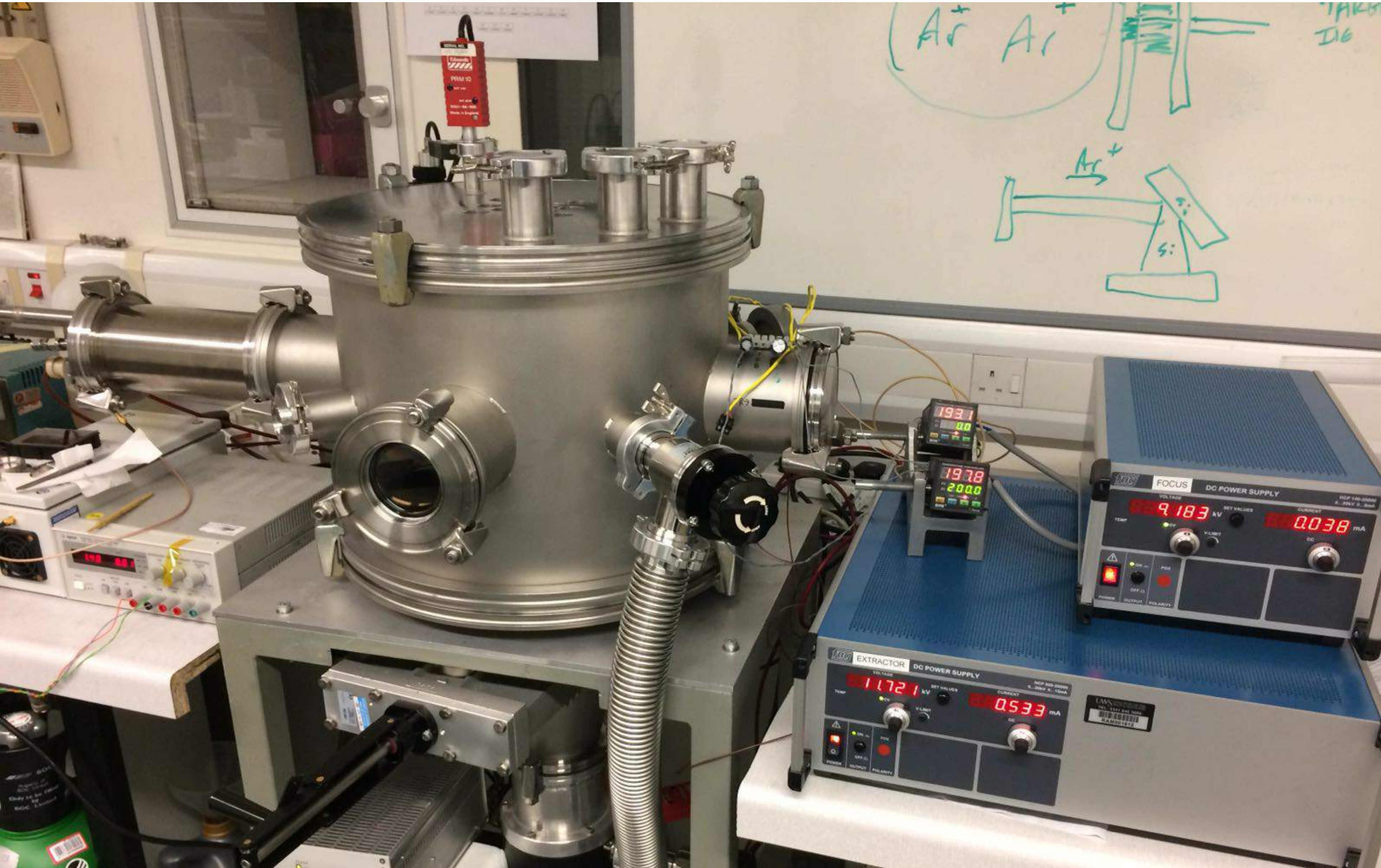

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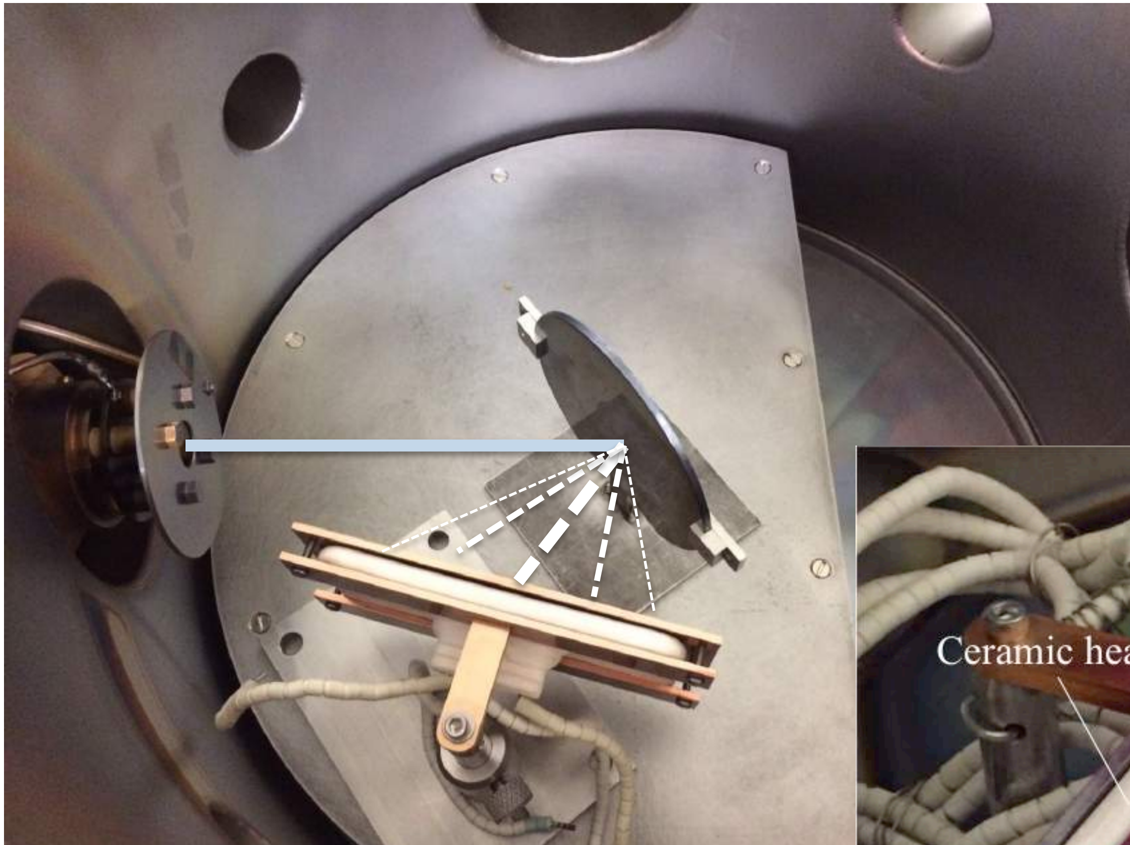
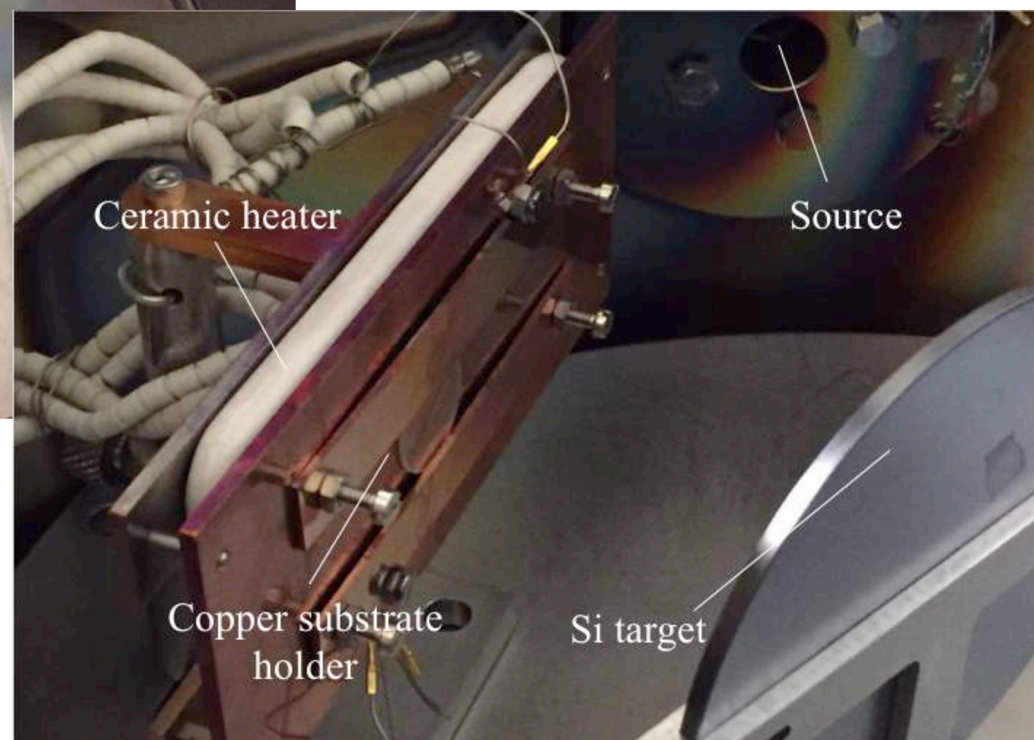
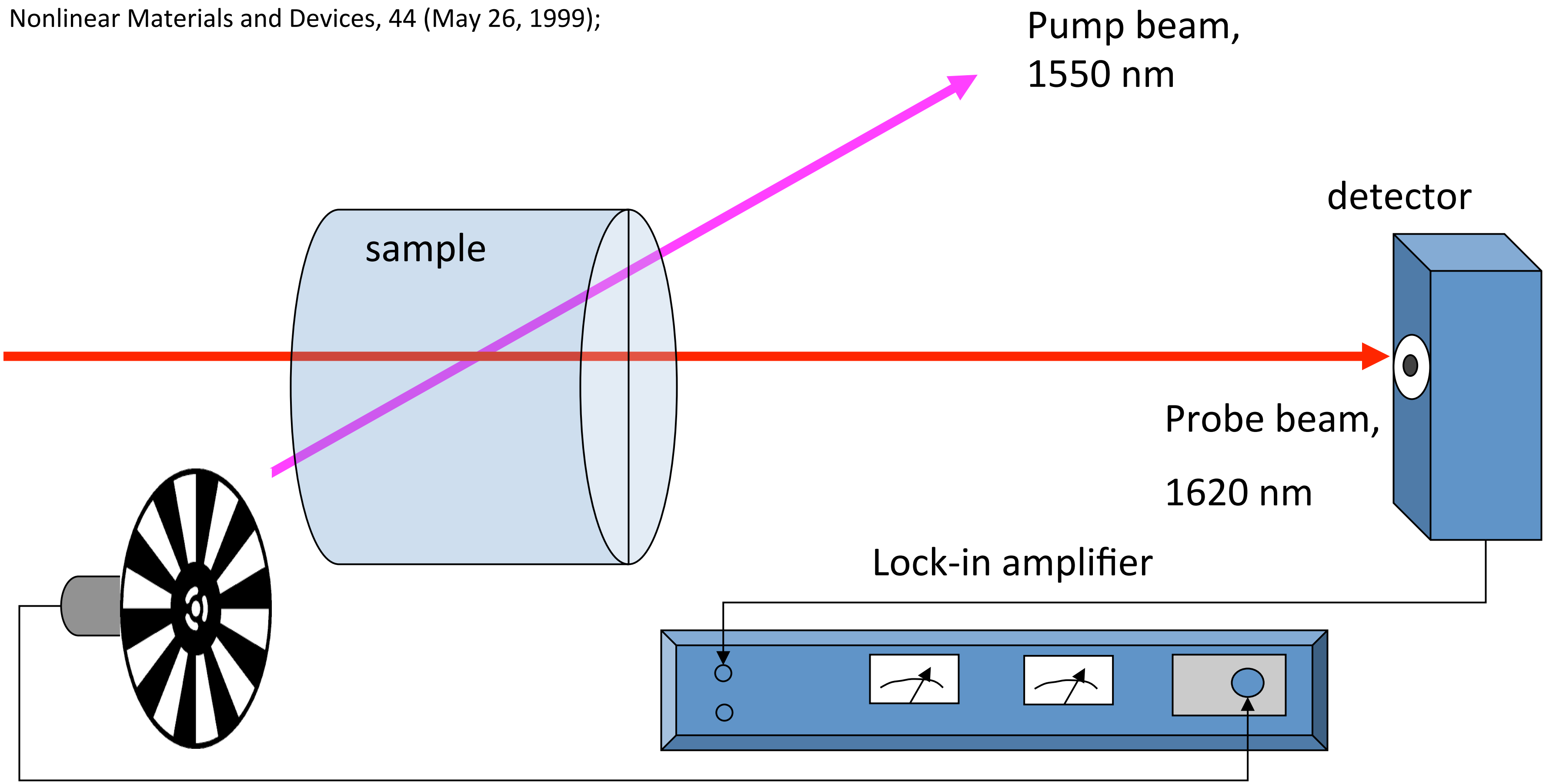




Absorption measurements - Glasgow

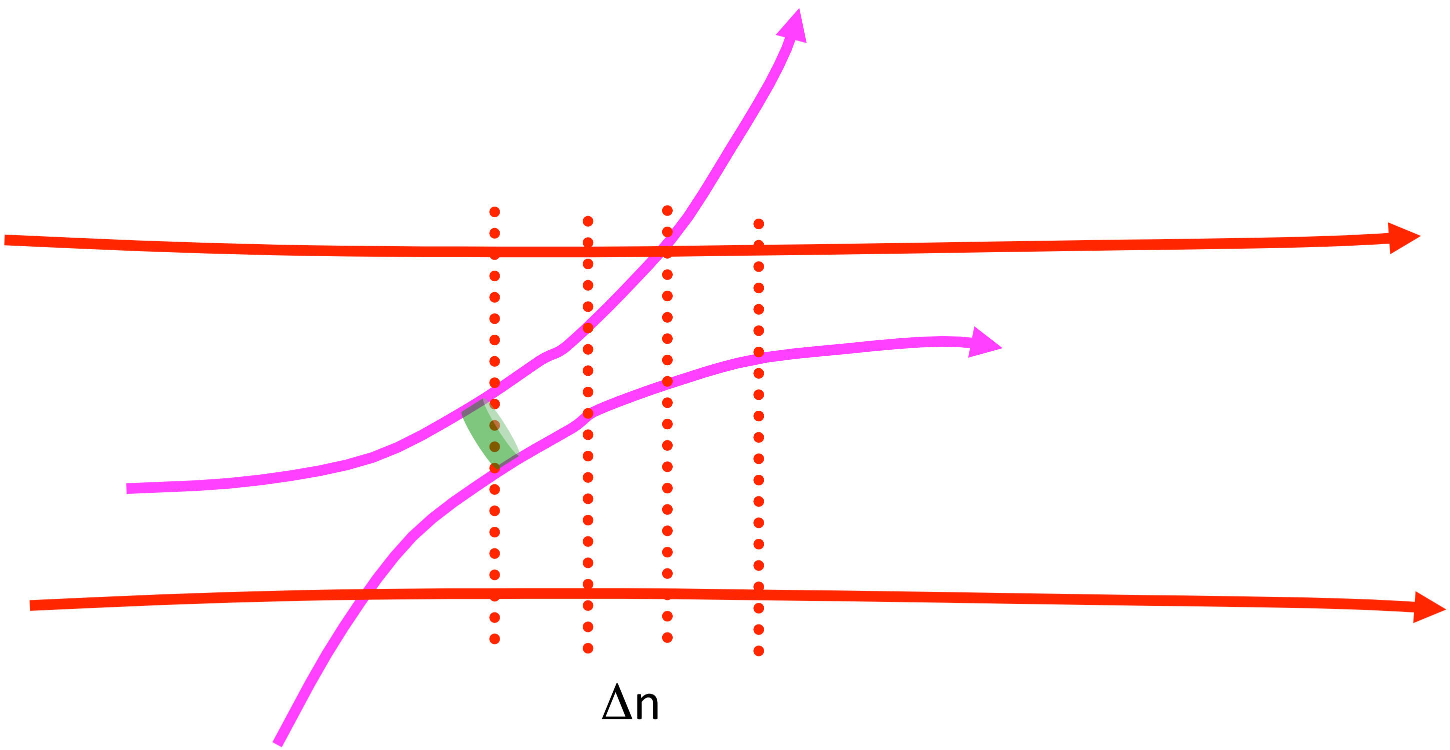
Photo-thermal commonpath interferometry (PCI)

A. Alexandrovski et al. *Proc. SPIE* 3610, Laser Material Crystal Growth and Nonlinear Materials and Devices, 44 (May 26, 1999);



Slides courtesy of J. Steinlechner (IGR, Glasgow)

Absorption measurements - Glasgow



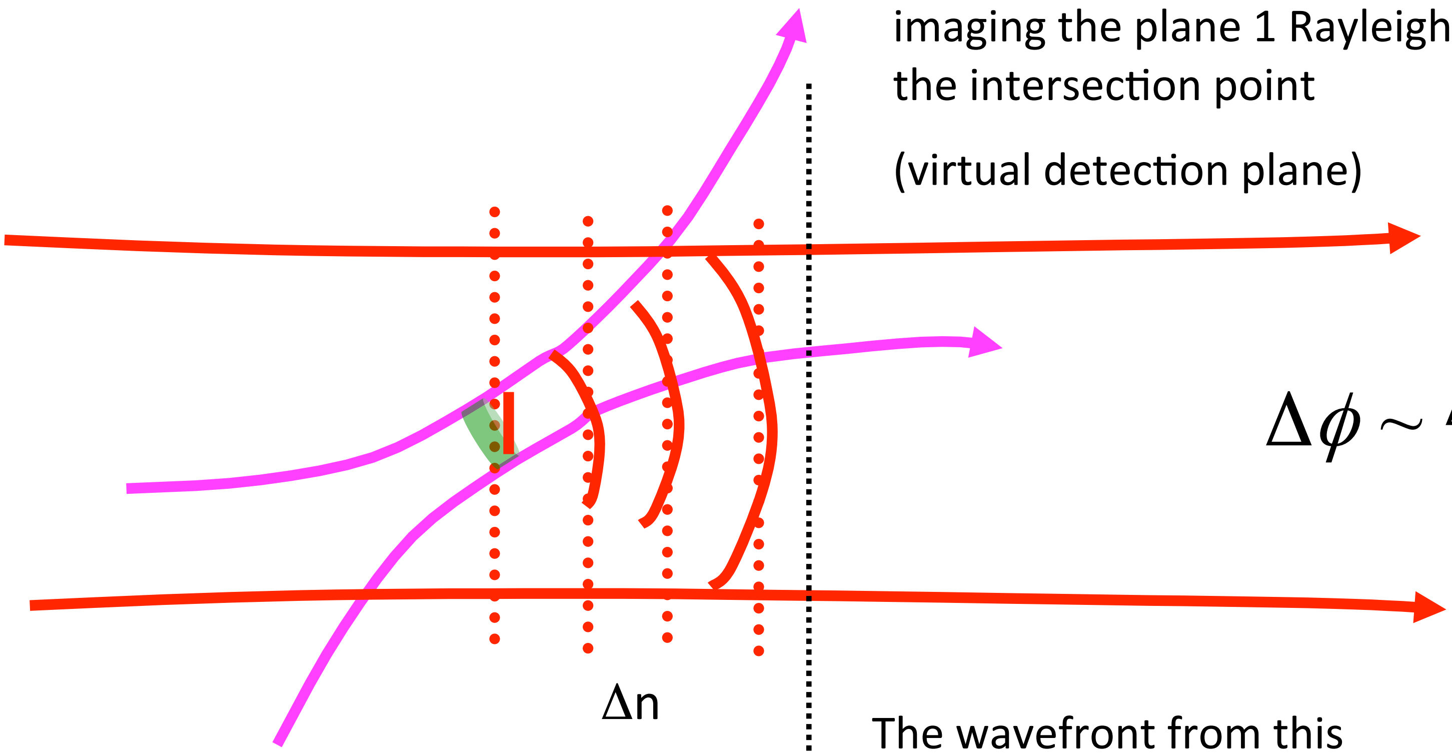
Pump beam changes refractive index of an element in the probe beam

Slides courtesy of J. Steinlechner (IGR, Glasgow)

Absorption measurements - Glasgow

We measure this phase difference by imaging the plane 1 Rayleigh range from the intersection point

(virtual detection plane)



$$\Delta\phi \sim \Delta I / I$$

Pump beam changes refractive index of an element in the probe beam

The wavefront from this element is different from the rest of the beam

Slides courtesy of J. Steinlechner (IGR, Glasgow)

Absorption measurements - Glasgow

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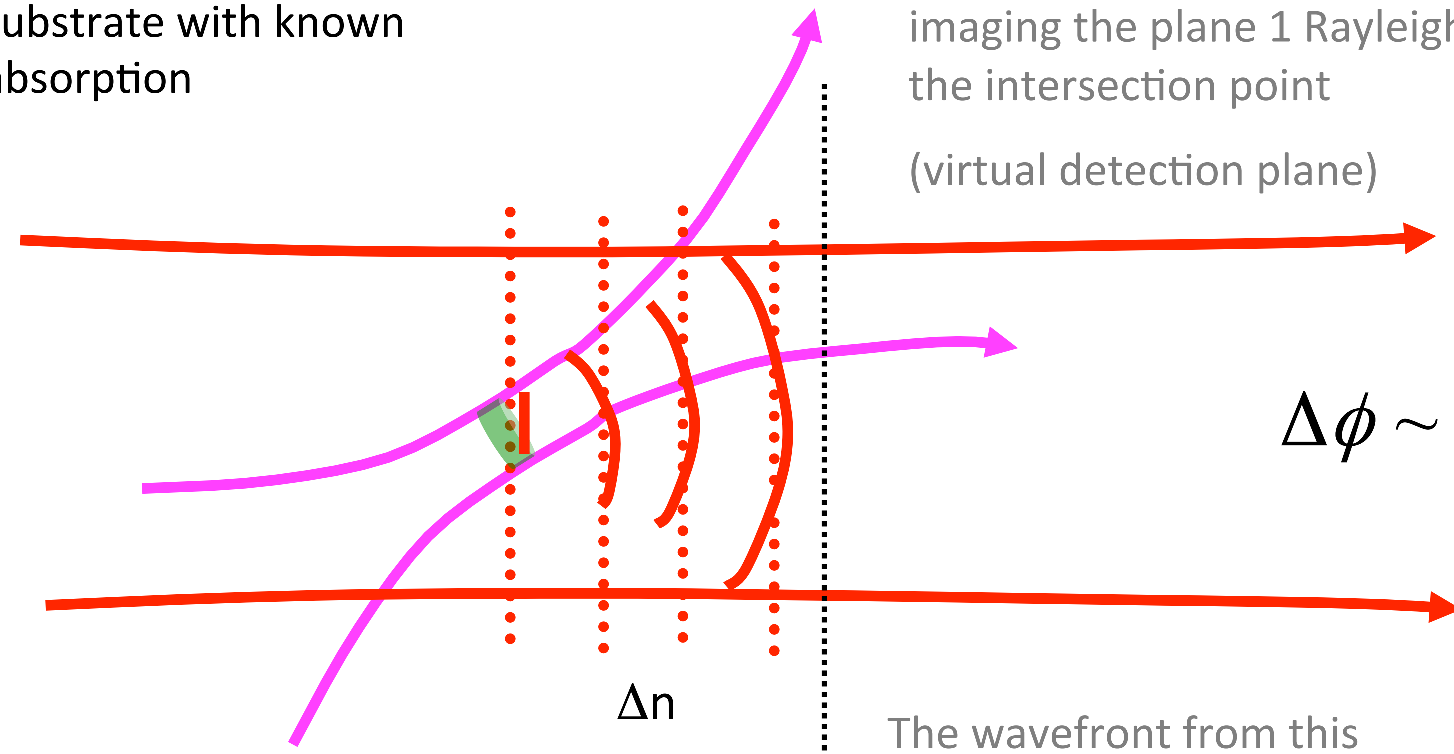
Getting absorption by comparing signal to calibration substrate with known absorption

We measure this phase difference by imaging the plane 1 Rayleigh range from the intersection point

(virtual detection plane)



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Pump beam changes refractive index of an element in the probe beam

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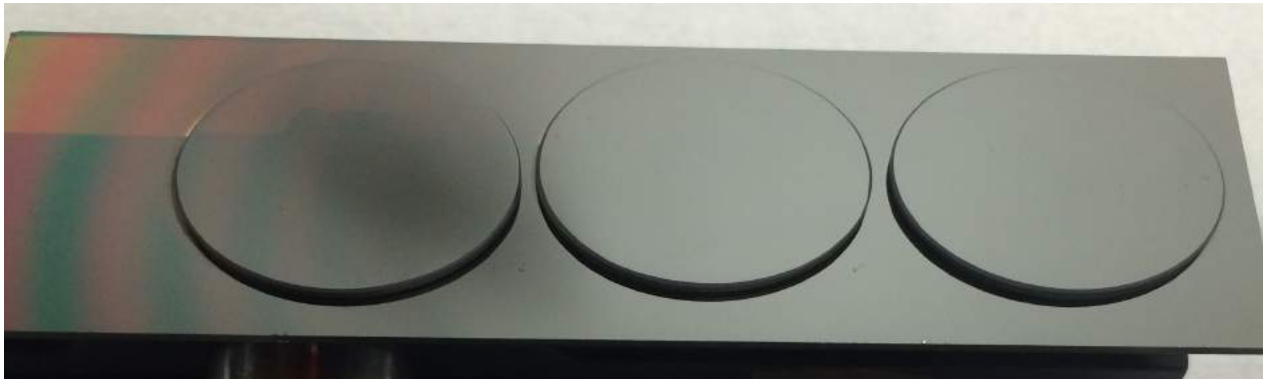
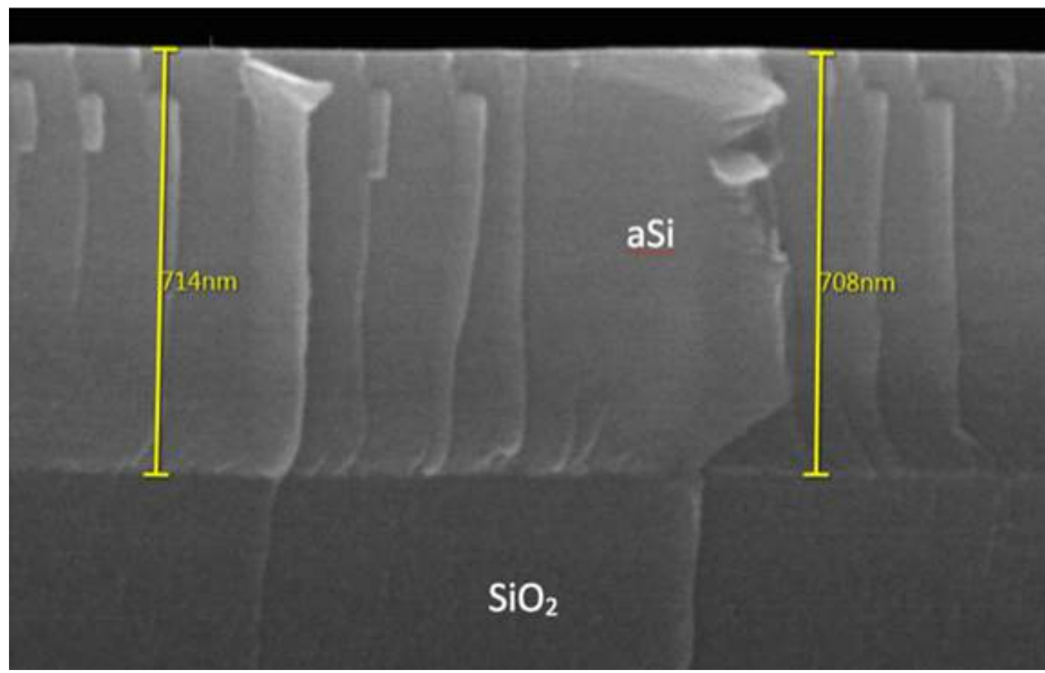
Slides courtesy of J. Steinlechner (IGR, Glasgow)

aSi coatings fabricated using ECR-IBD

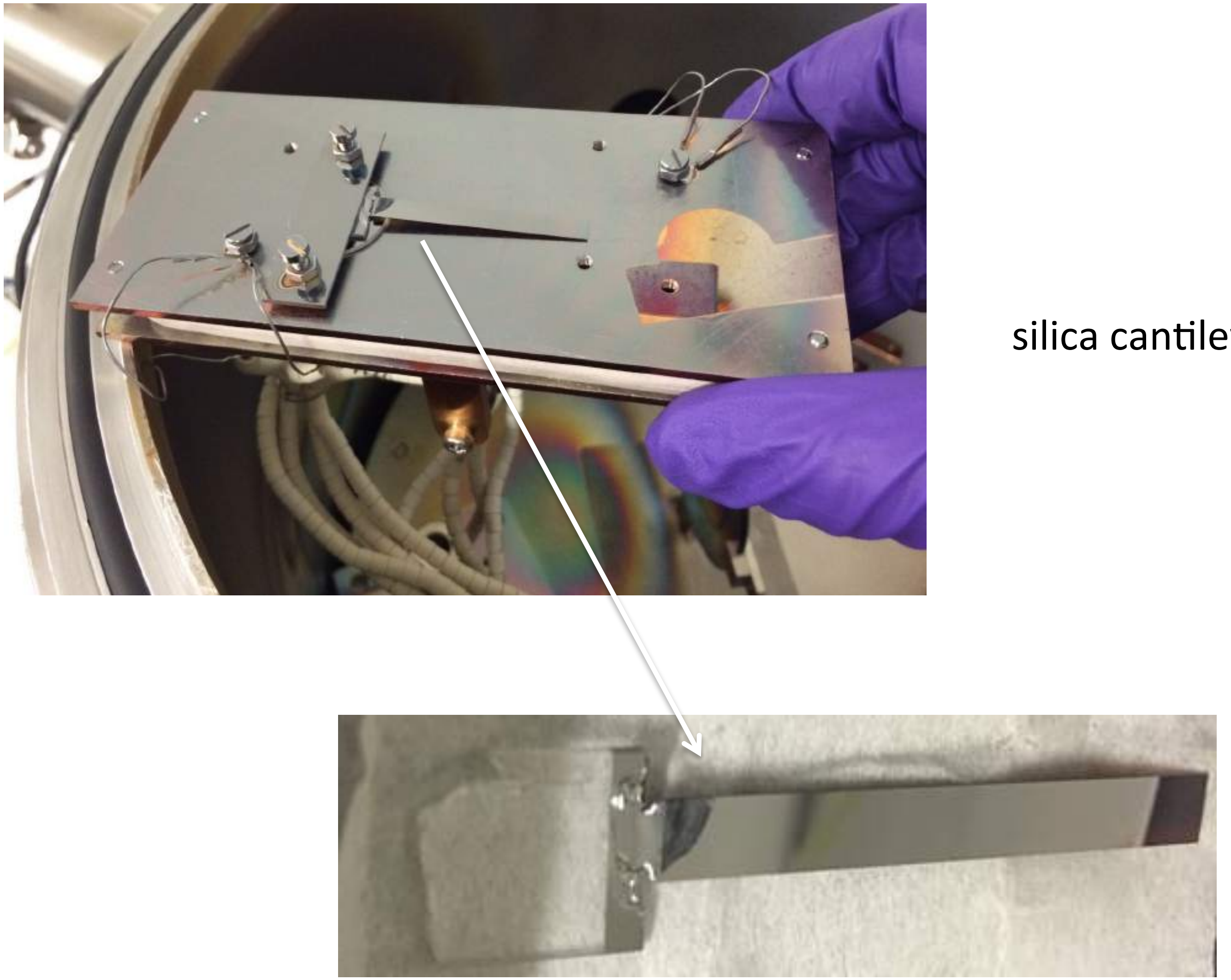


20mm JGS3 silica witness samples (optical characterisation and absorption)

Cross-section SEM image



aSi coatings fabricated using ECR-IBD



silica cantilevers, coated with aSi

Absorption measurements on aSi – 1550 nm

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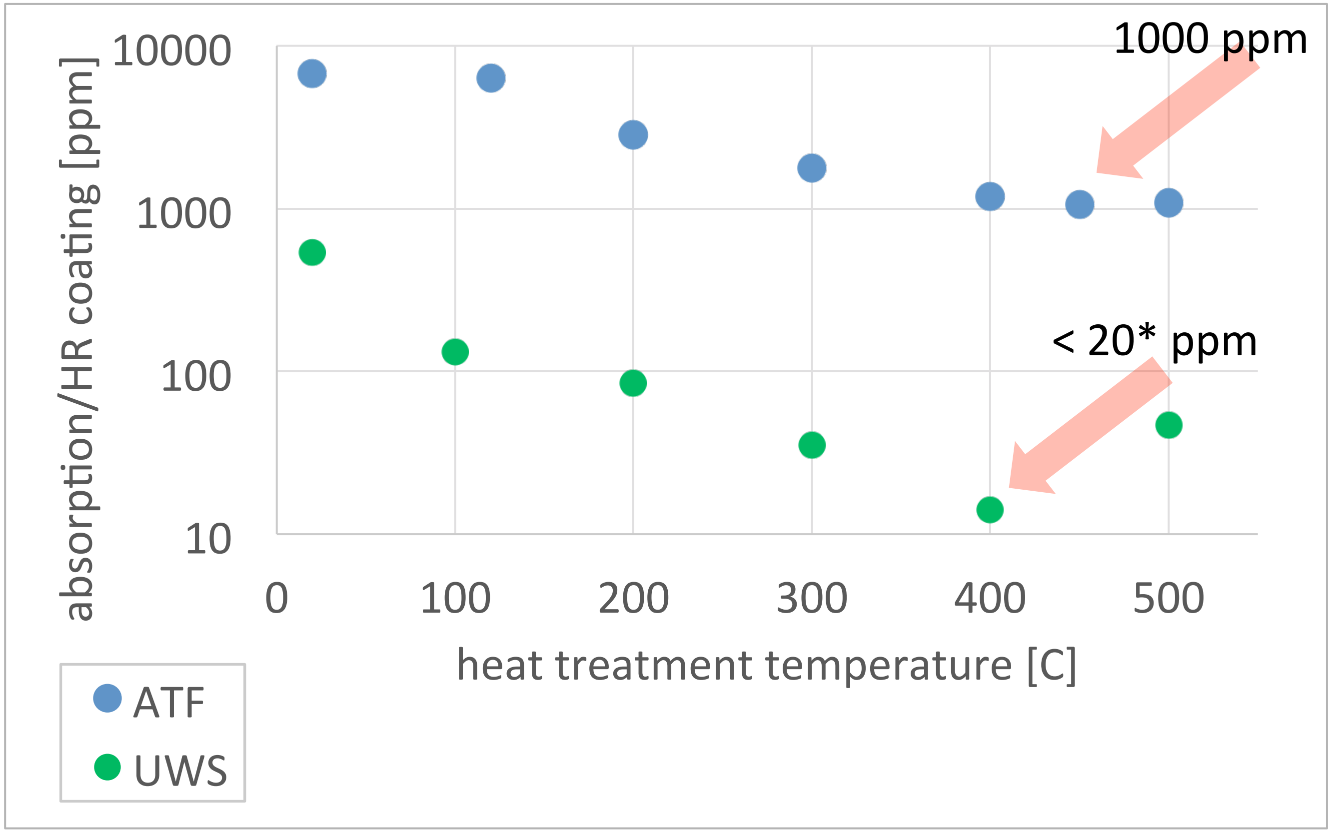
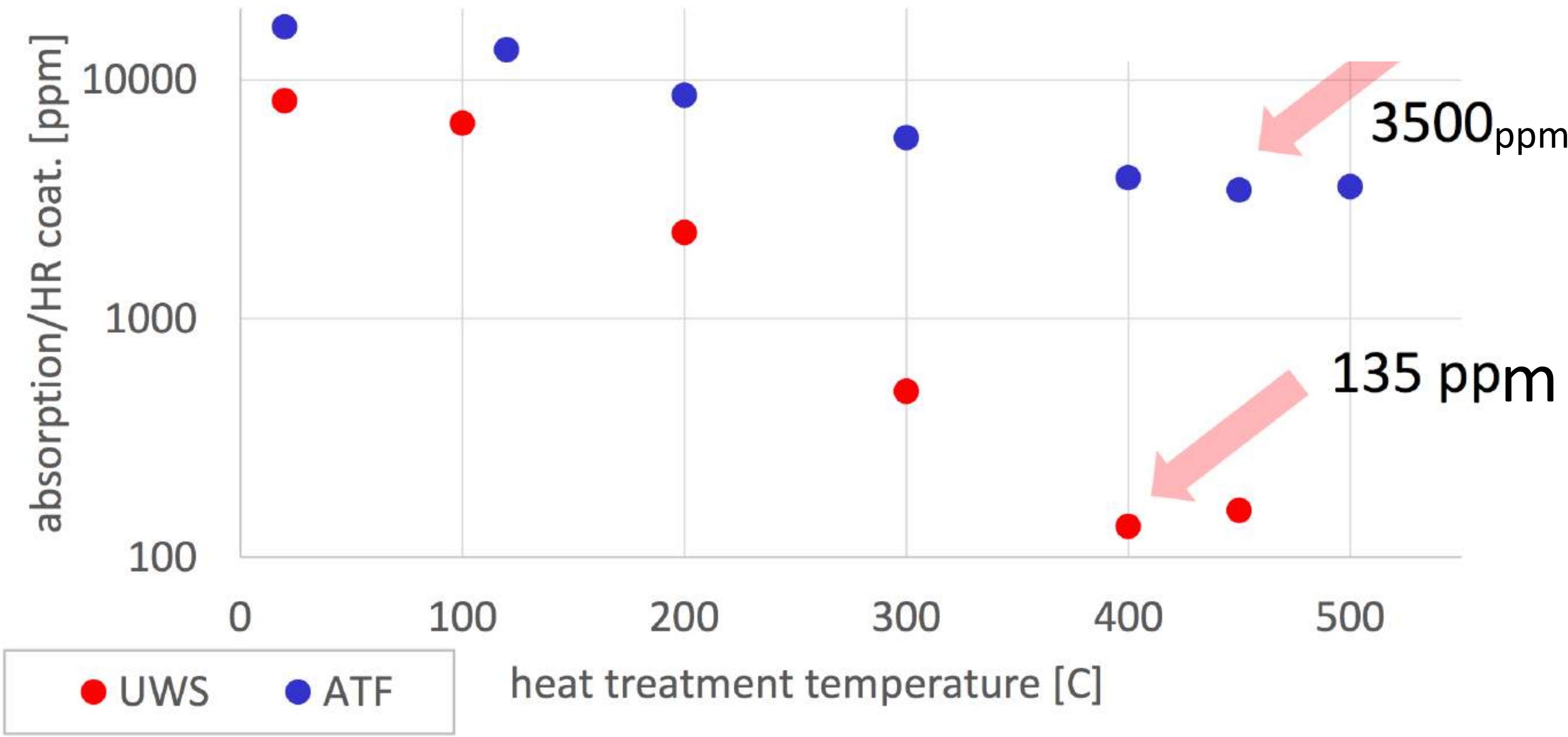


* measurement limited by substrate absorption

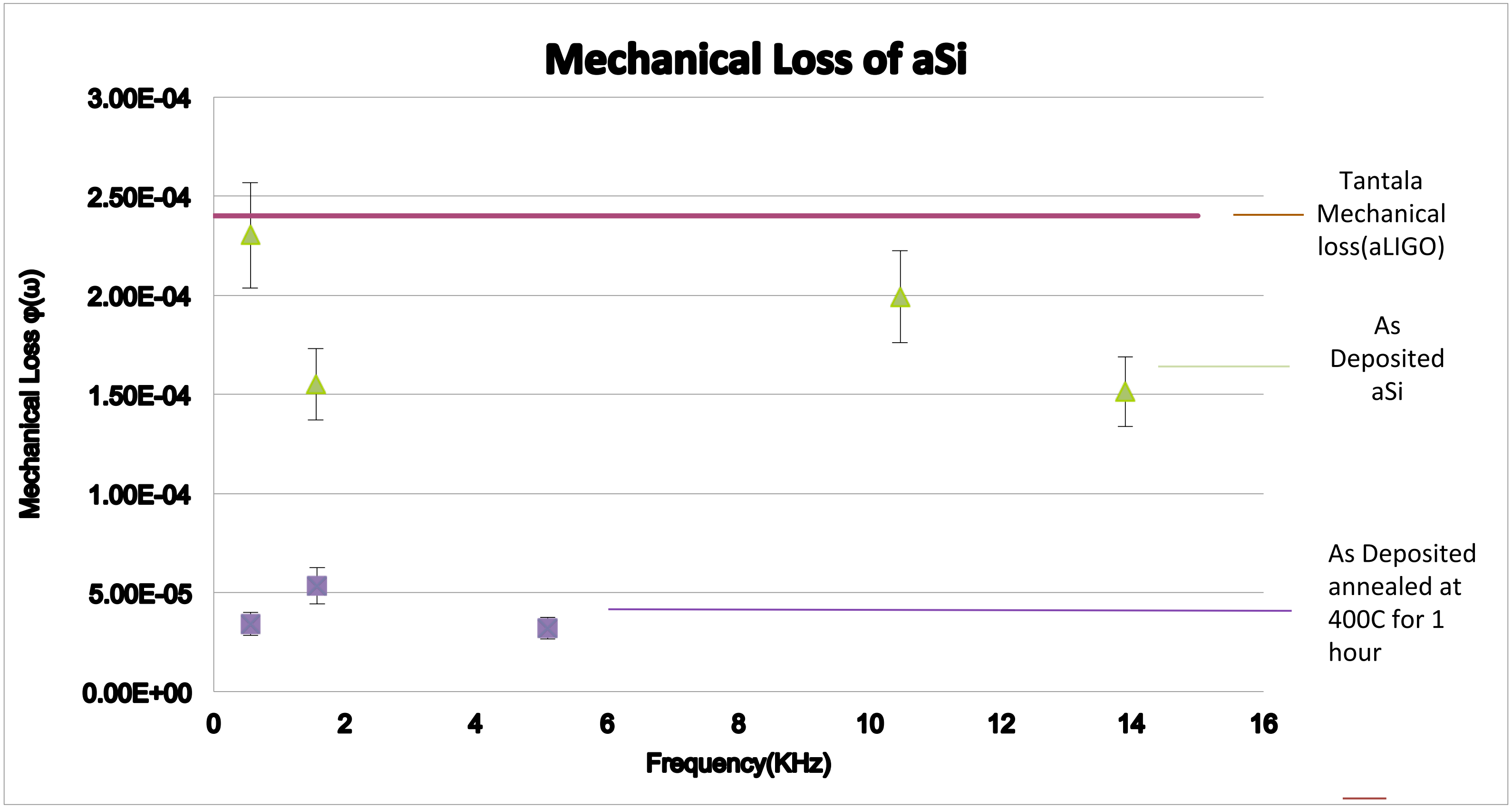
- 1550 nm
- Absorption significantly lower than for ATF coatings
- Refractive index ~3.4 from transmission measurements
- **UWS measured on a ~660 nm layer**
- **ATF measured on a 500 nm layer**

→ both scaled to HR coating

Absorption measurements on aSi – 1064 nm



Mechanical loss



Initial mechanical loss measurements on silica cantilevers

Berkeley high temperature deposition

- As discussed by M. Fejer yesterday (see G1601192-v1)
- Heated deposition reduces mechanical loss much further than post- heat treatment alone.

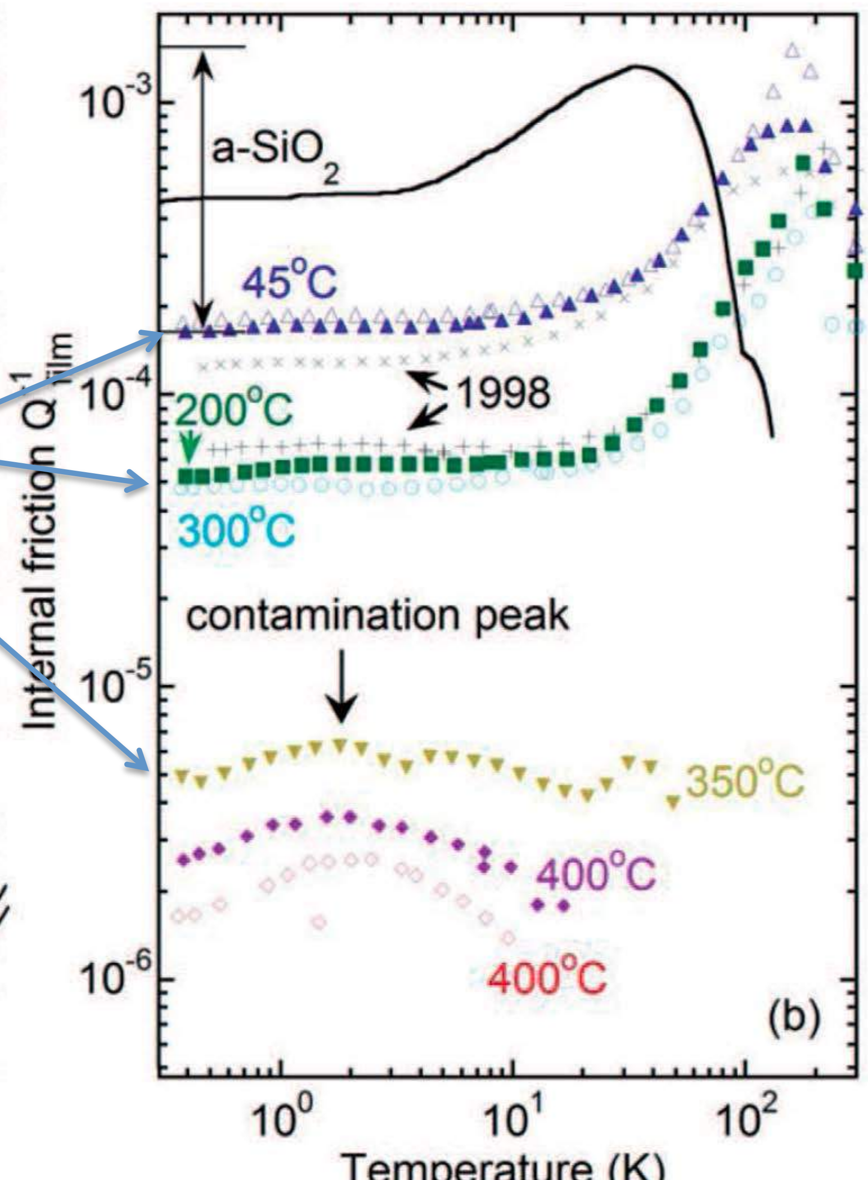
annealed 350C

deposited 350C

- ~10^{-4} vs ~10^{-6}

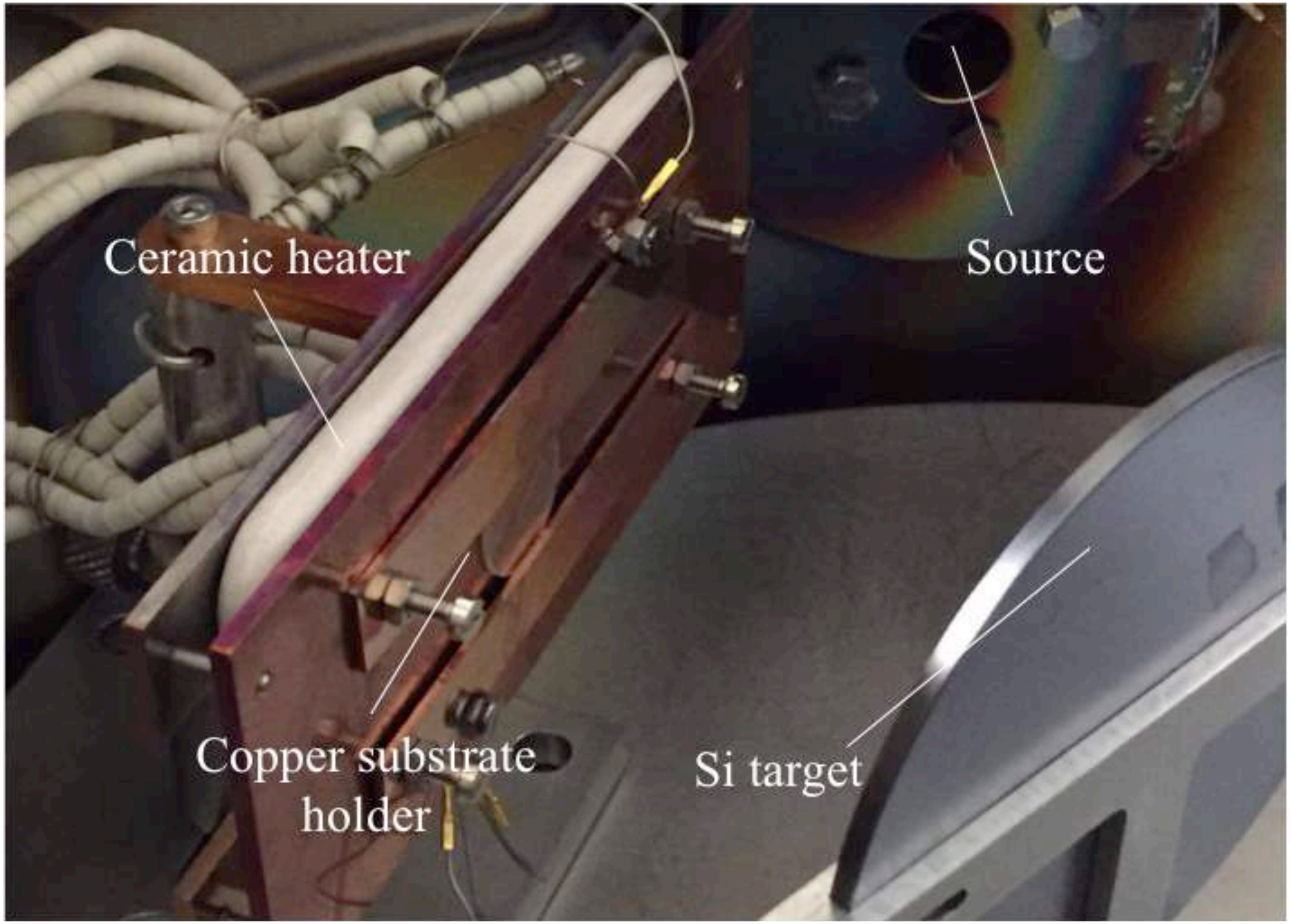
- Surface mobility during deposition:
  - sound velocity approaches asymptote
  - distribution of bond angles narrows
  - density increasing
  - Heat capacity approaches bulk silicon value

- Open question – similar benefits for IBS?

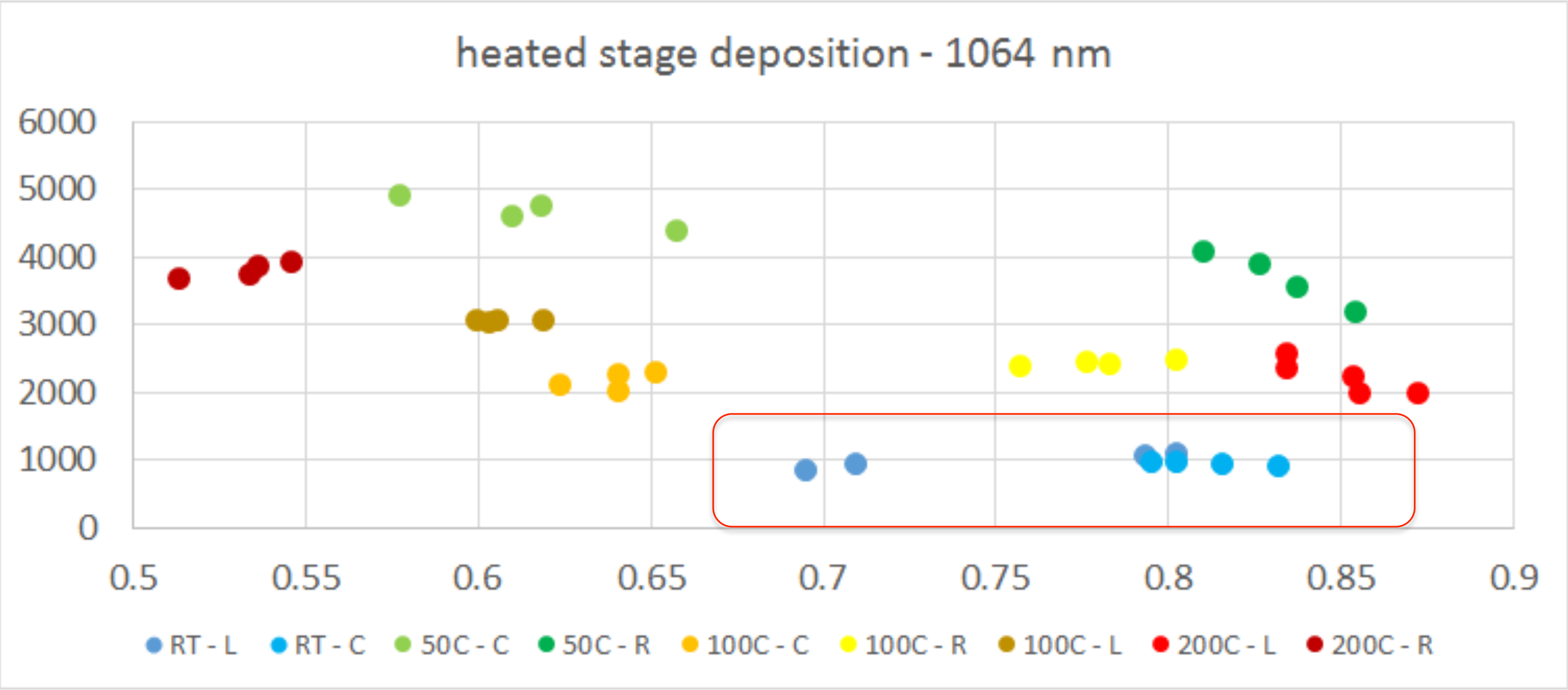


X. Liu, F. Hellman, et al, *PRL* **113**, 025503 (2014)

High-temperature deposition



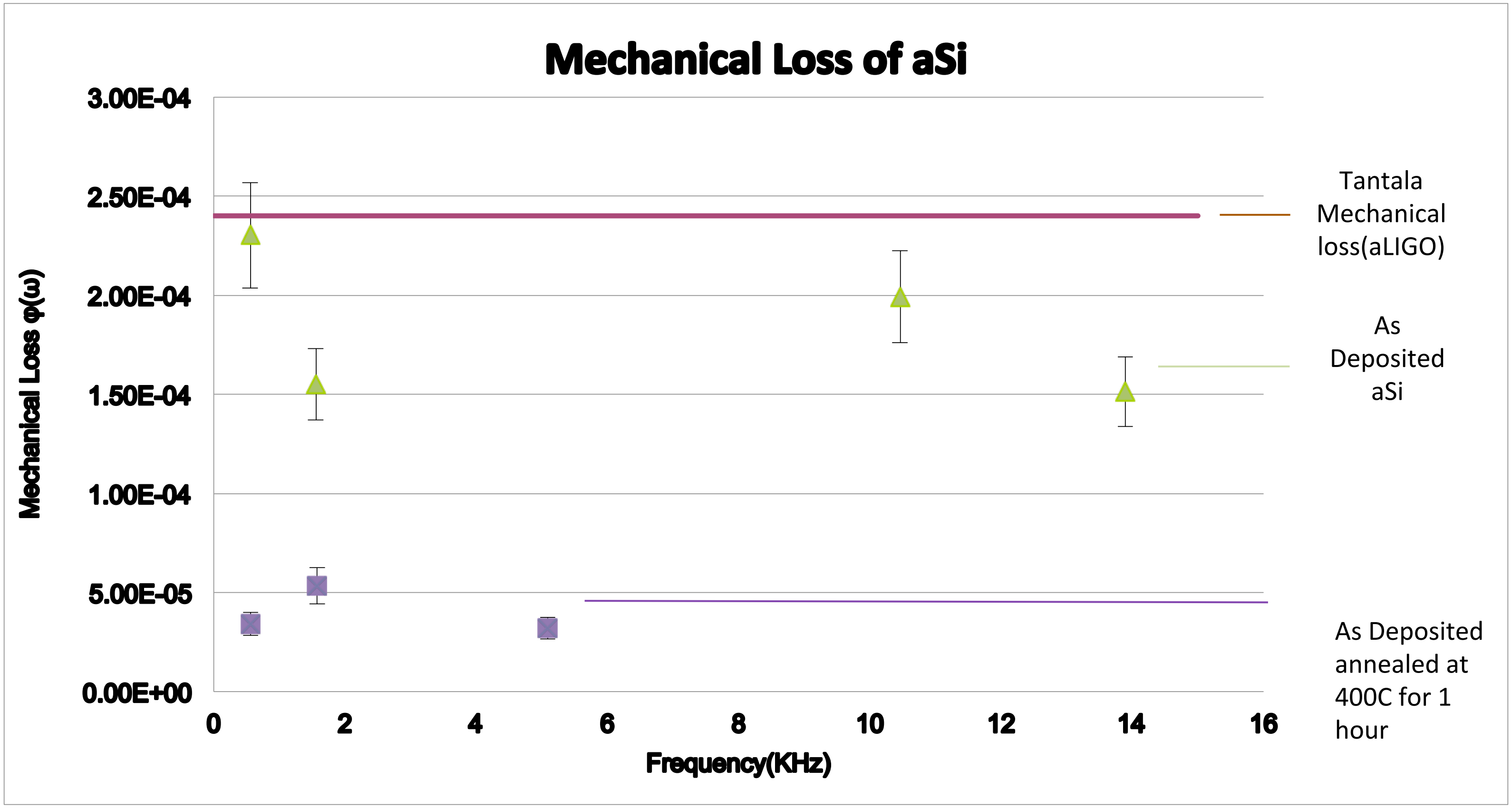
High-temperature deposition - absorption



Random spread in absorption – no clear benefit in heated deposition in initial tests

Strong evidence that room temperature coatings have been contaminated – strangely reducing the absorption further – however index also lower than expected

High-temperature deposition – mechanical loss



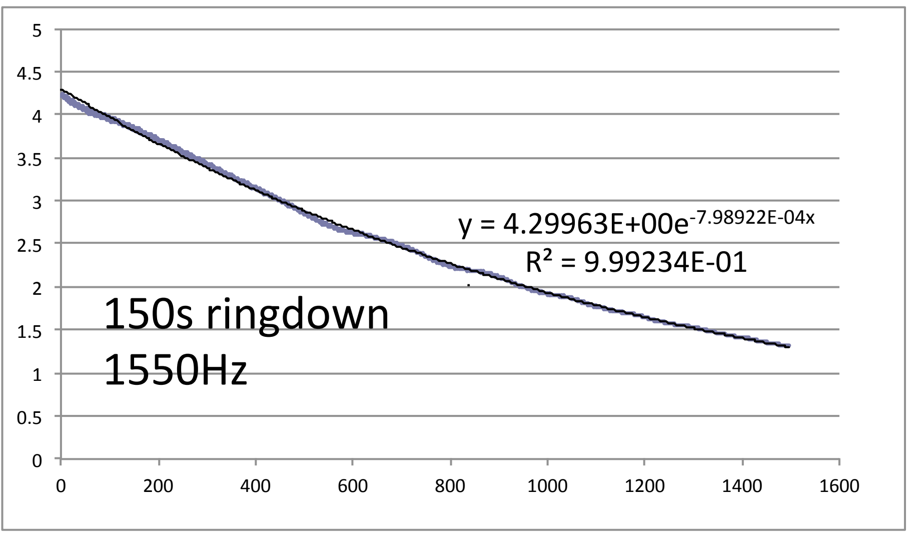
So what happens???

High-temperature deposition – mechanical loss

Difficult (but good!) problem:

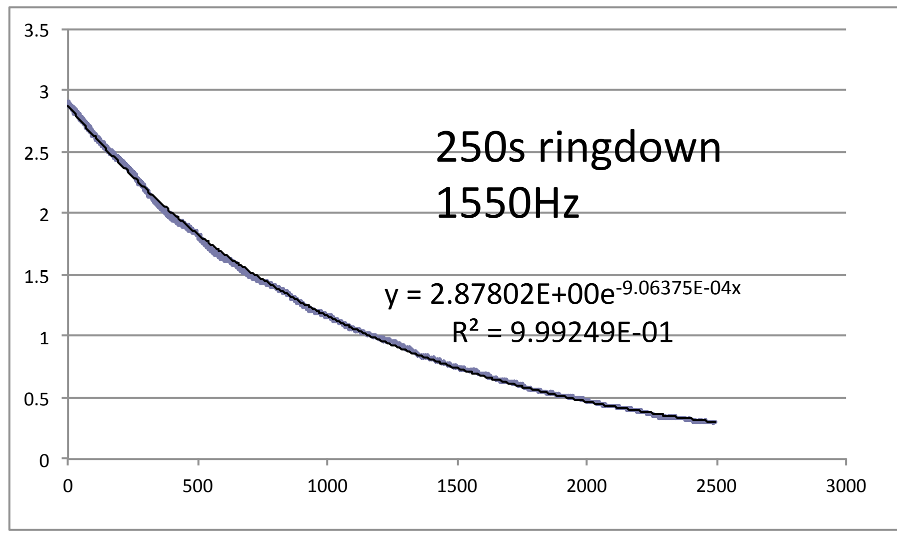
uncoated cantilever – annealed twice at 400C

$\phi_{uncoated} = 1.64 \times 10^{-6}$



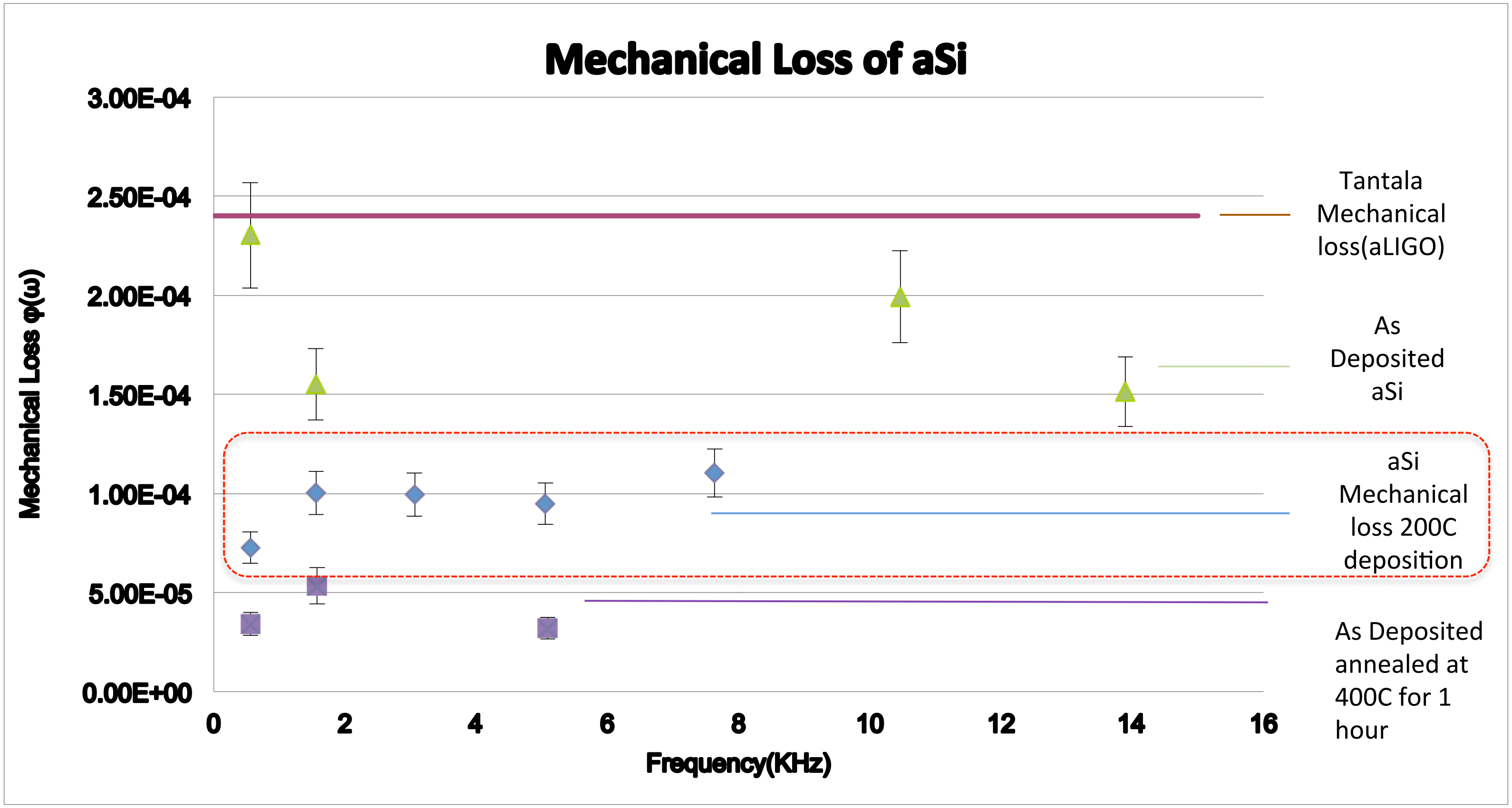
coated cantilever – annealed at 400C

$\phi_{coated} = 1.86 \times 10^{-6}$

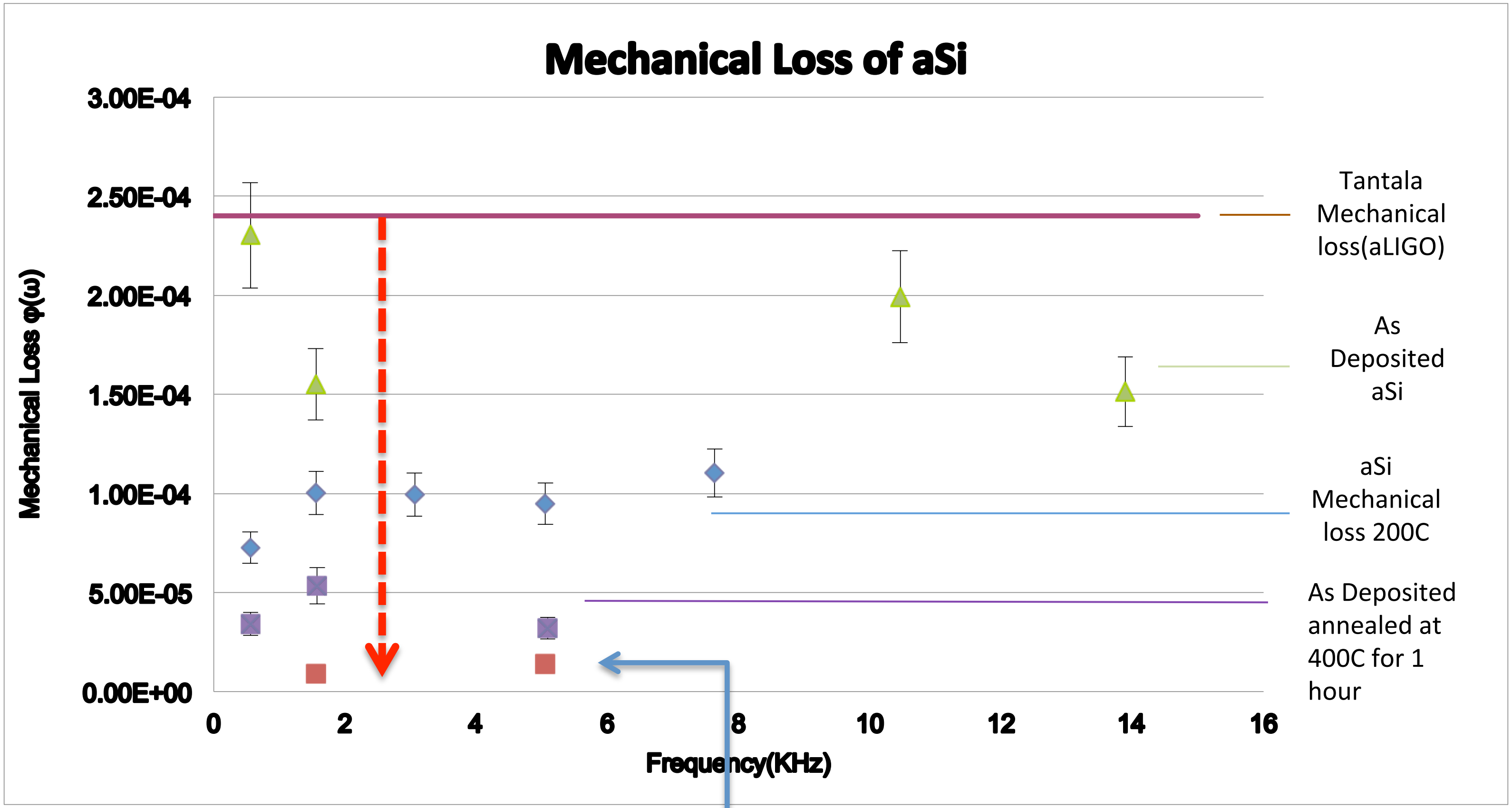


$\phi_{coating} = 8.6 \times 10^{-6}$

High-temperature deposition – mechanical loss



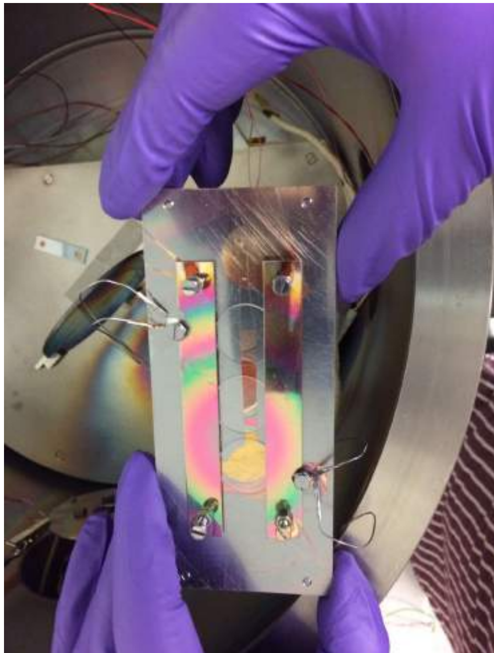
High-temperature deposition – mechanical loss

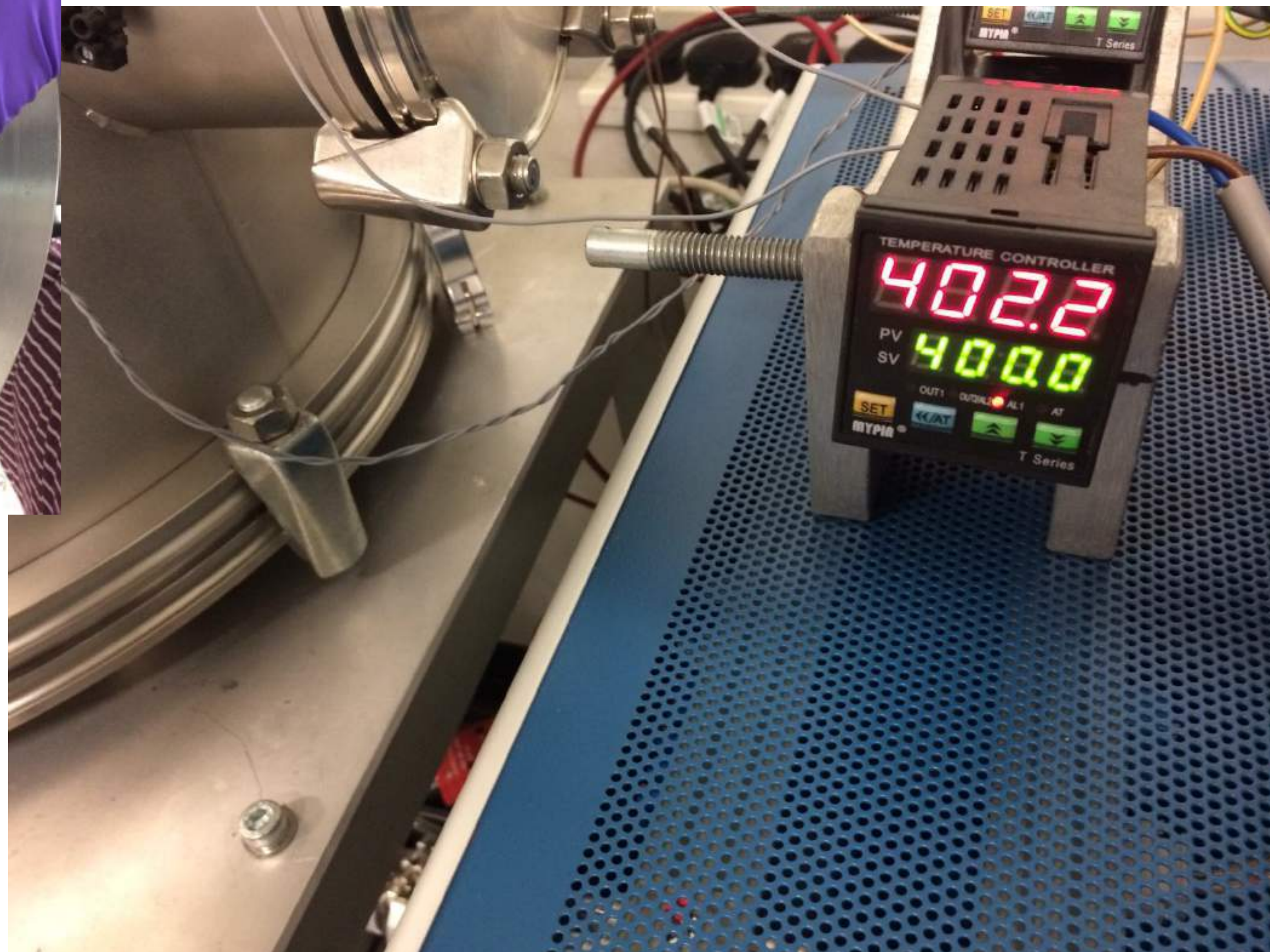


Likely factor 25 reduction in loss achievable

Annealing the 200C aSi coating at 400C, measurement approaching experimental uncertainty, at the level of 1×10^{-5}.

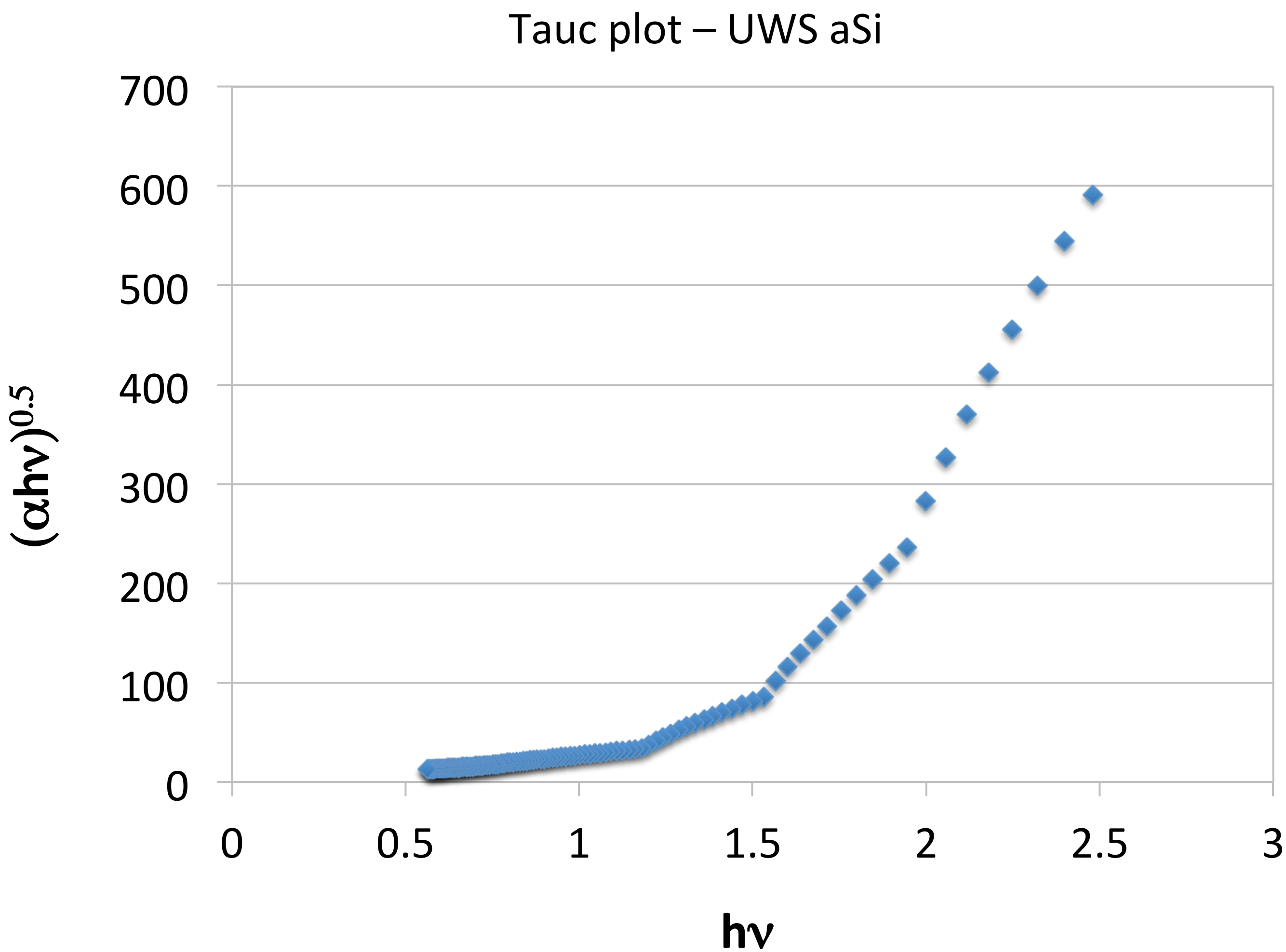
High-temperature deposition – mechanical loss



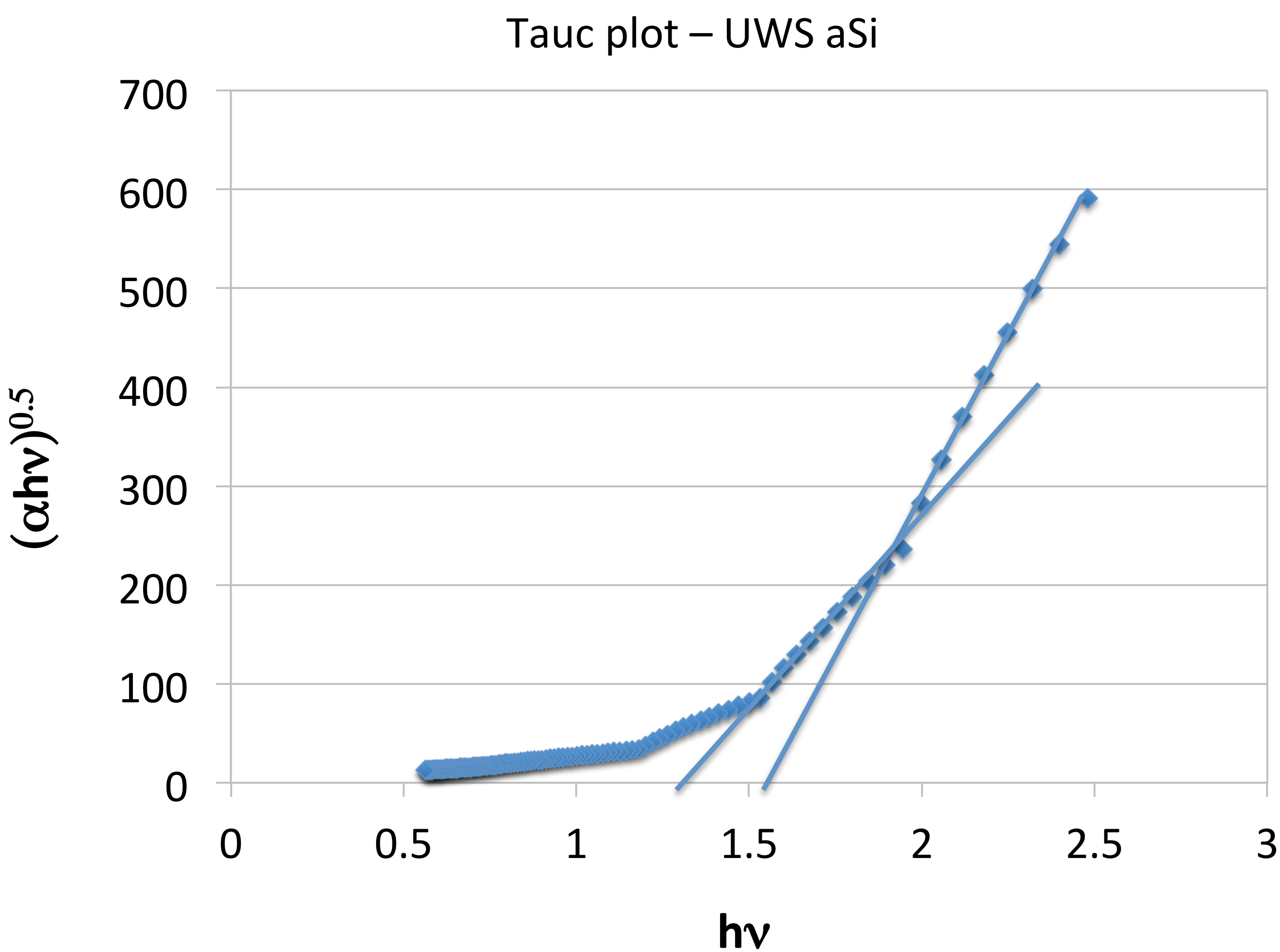


Results are on the way!

Characterisation – bandgap associated absorption

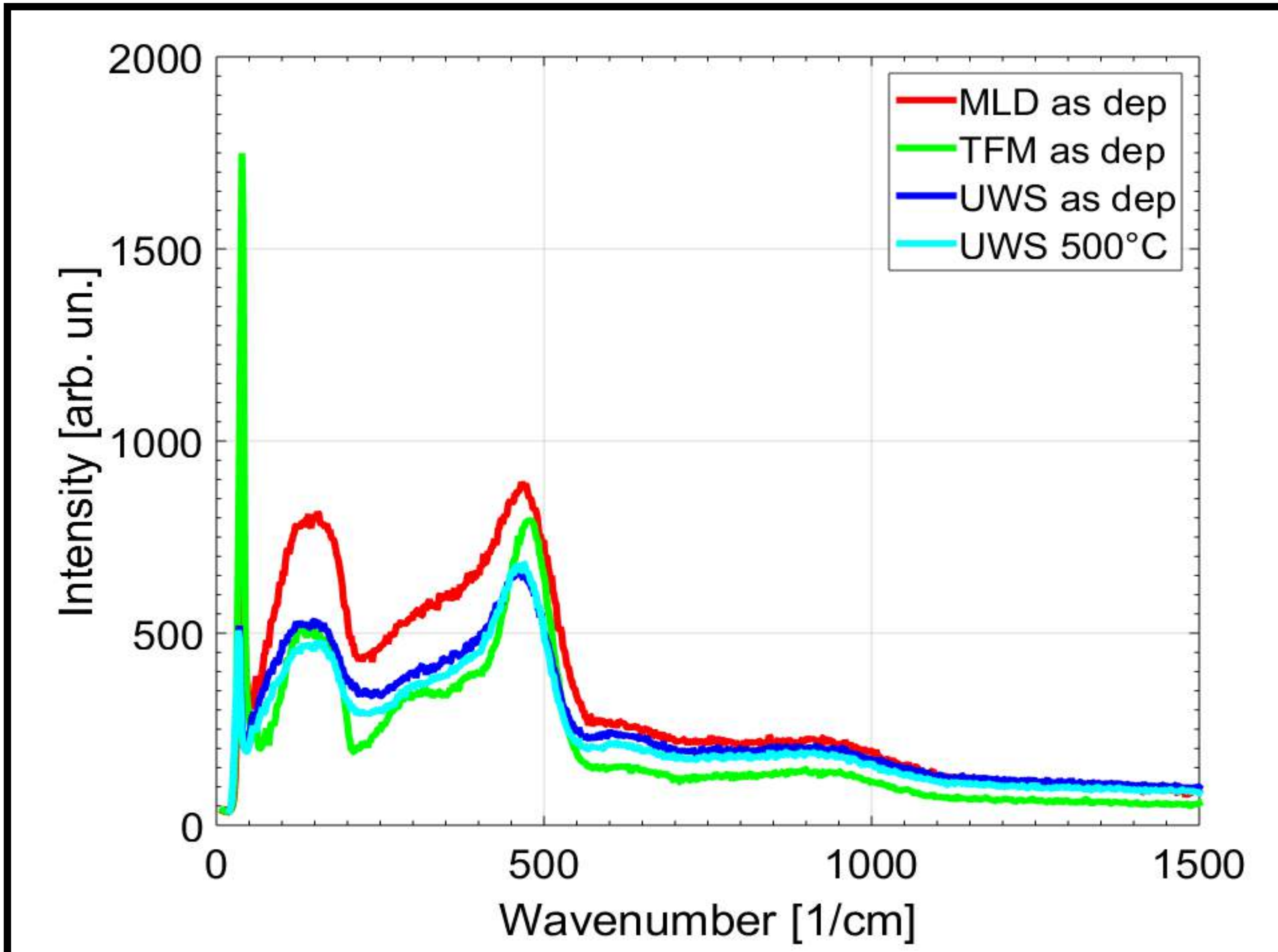


Characterisation – bandgap associated absorption



Average bandgap energy 1.4eV (commonly reported 1.1-1.5eV for a-Si)

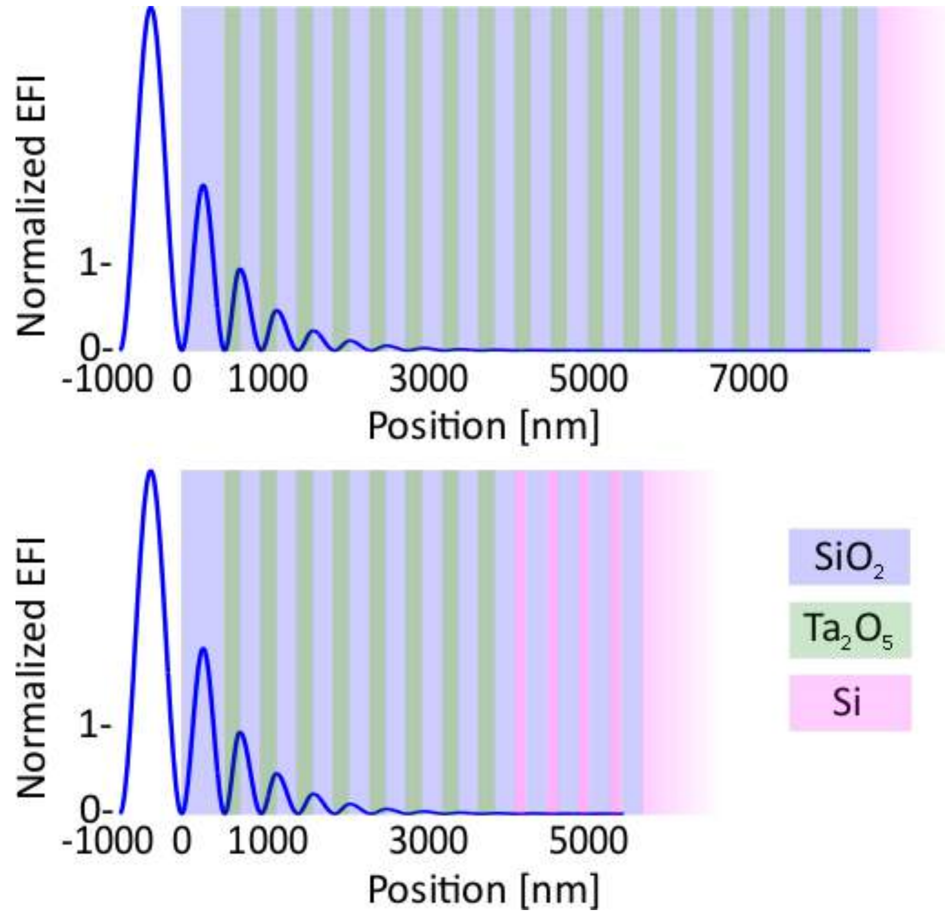
Characterisation – Raman



See poster by Zeno Tornasi (Glasgow)

Thermal noise

- We can use a multi material design
- Some bilayers of SiO_2 and Ta_2O_5 are used to reduce the laser power
- In lower layers amorphous silicon can be used to improve thermal noise due to a high refractive index and low loss

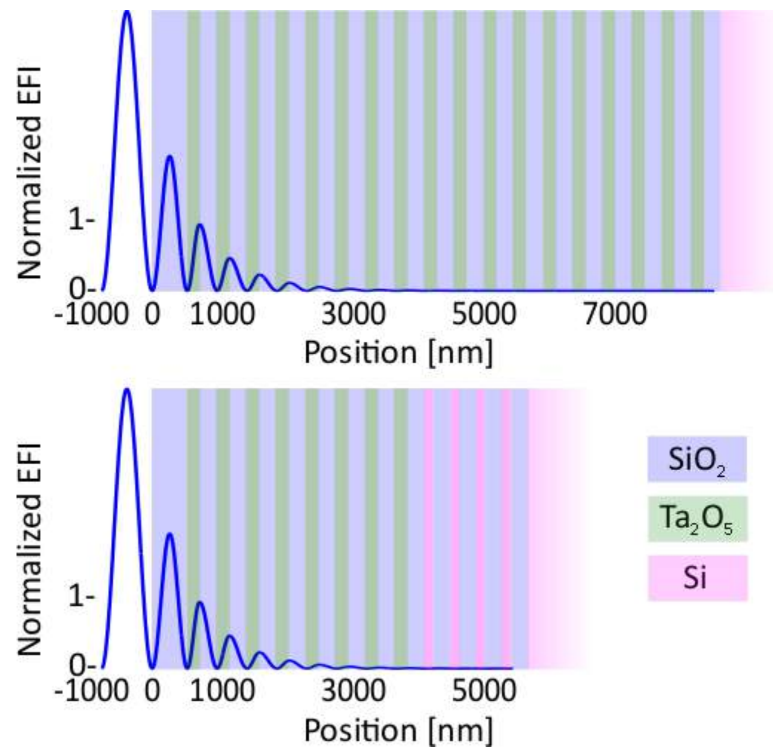


Jessica Steinlechner

What does this mean for thermal noise?
… if we want less than 1ppm absorption from the aSi:

At 1064 nm RT:

- We need 8 bilayers of SiO_2 and Ta_2O_5 to reduce the laser power
- For an ITM with T= 1.4% we can't improve the coating using aSi in lower layers
- For an ETM with T = 6 ppm we need 4 bilayers of SiO_2 and aSi



- Thermal noise improvement* compared to a pure SiO_2 and Ta_2O_5 coating:

Room temperature:
ITM: - 0%
ETM: - 28%
~~total: -18%~~ 21.5%

Almost no improvement by reducing mechanical loss further (limited by silica loss and ITM thermal noise)

*Loss for aSi: ~~1.2e-4~~ 5×10^{-5} measured on UWS aSi coatings at room temperature

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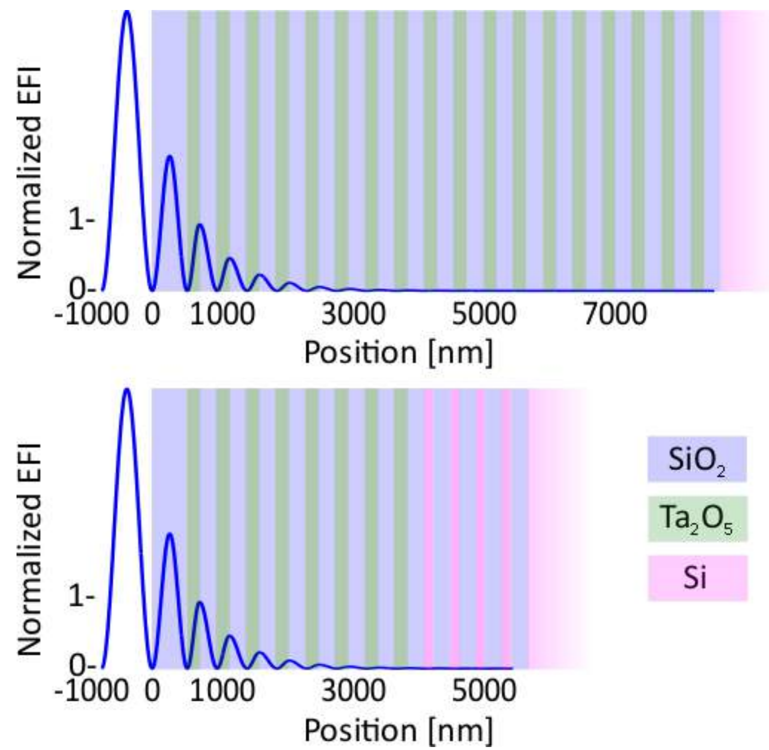
What does this mean for thermal noise?
… if we want less than 1ppm absorption from the aSi:

At 1550nm RT:

- We need 5 bilayers of SiO_2 and Ta_2O_5 to reduce the laser power
- For an ITM with T= 6000 ppm we need 2 bilayers of SiO_2 and aSi
- For an ETM with T = 6 ppm we need 5 bilayers of SiO_2 and aSi



- Thermal noise improvement* compared to a pure SiO_2 and Ta_2O_5 coating:

	120 K	20 K
ITM:	-21%	-20%
ETM:	-38%	-36%
total:	-32%	-31%

Jessica Steinlechner

*Loss for aSi: values from commercial coatings; no cryogenic measurements on UWS coatings

Conclusion from UWS + GU investigations using ECR-IBD

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aSi attractive high-index material choice for aLIGO+ and beyond

- Optical absorption of 20ppm for HR stack feasible
  (reason due to unique dep parameters – low dep rate + high ion energy)
- Mechanical loss ~ $5x10^{-5}$ (room temp deposition + heat treatment at 400C)

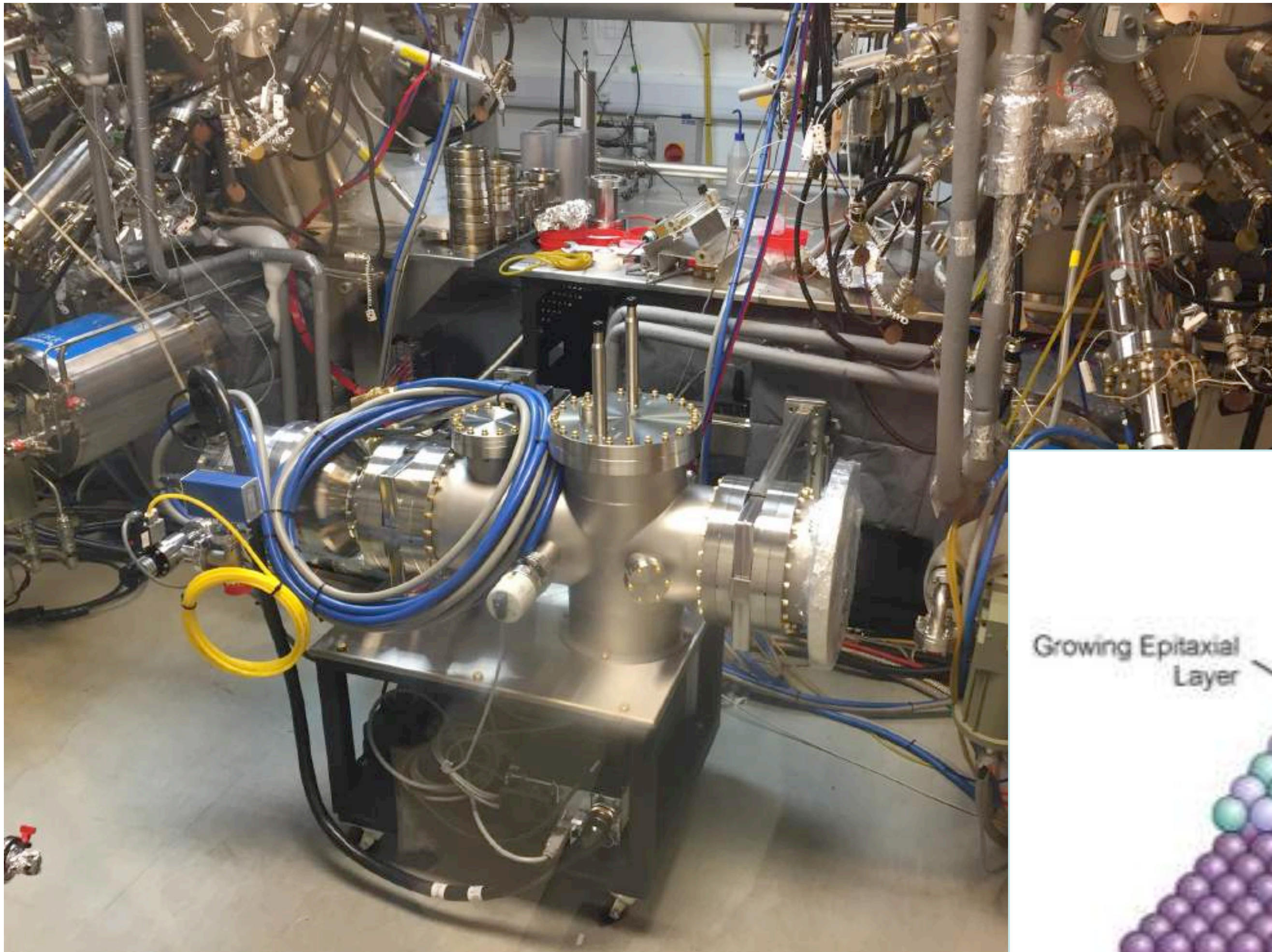
Heated deposition

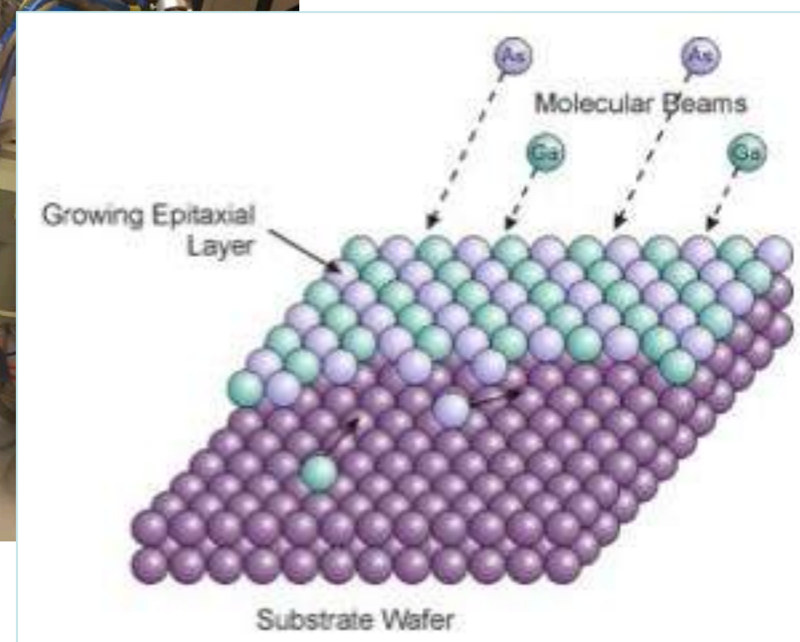
- First evidence that heated substrates + ion-beam deposition can reduce mechanical loss below that achievable through same temperature post-deposition annealing
- Mechanical loss ~$1x10^{-5}$ for aSi deposited at 200C then heat treated to 400C

Future work

- Complete studies on aSi deposited at elevated temperatures
- Investigate effect of elevated temperature on Ta_2O_5
- Investigate effect of shifting bandgap absorption edge in aSi through doping (H, Al, N etc) – with particular relevance to 1064nm use.

Towards a more ordered future…



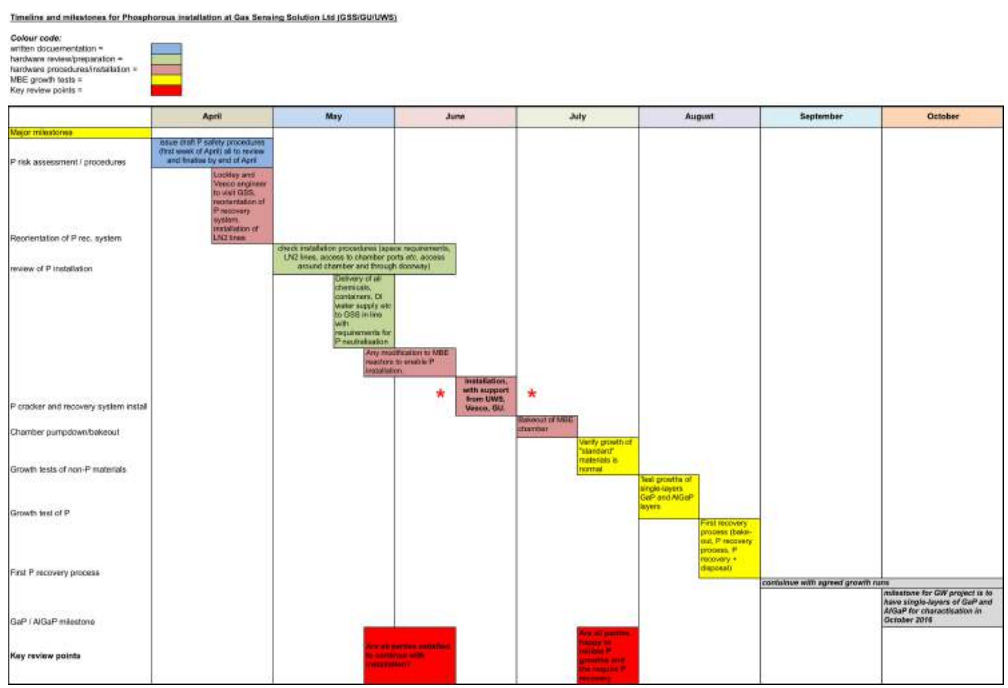


MBE developments (UWS+GU+Stanford+GSS)

Plan to develop AlGaP interference coatings on silicon

Key milestones:

- March 2016: all equipment delivered (P cracker, P recovery system, auxillary equip.)
- June 2016: installation of P cracker and recovery system
- August 2016: test growths of AlGaP begin



Conclusion from UWS + GU investigations using ECR-IBD

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University of Glasgow

aSi attractive high-index material choice for aLIGO+ and beyond

- Optical absorption of 20ppm for HR stack feasible
  (reason due to unique dep parameters – low dep rate + high ion energy)
- Mechanical loss < 1×10^{-4} (room temp deposition + heat treatment at 400C)

Heated deposition

- First evidence that heated substrates + ion-beam deposition can reduce mechanical loss below that achievable through same temperature post-deposition annealing
- Mechanical loss ~1×10^{-5} for aSi deposited at 200C then heat treated to 400C

Future work

- Complete studies on aSi deposited at elevated temperatures
- Investigate effect of elevated temperature on Ta_2O_5
- Investigate effect of shifting bandgap absorption edge in aSi through doping (H, Al, N etc) – with particular relevance to 1064nm use.
- Further low temperature absorption and thermal noise evaluation.