

Impact (and potential sources) of carbonaceous species on lifetime testing of Ru-capped optics

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Degradation of EUV projection optics

Industry Problem

Development of novel capping layers capable of extending the lifetime of multi-layer optics in production environment

Required: $\Delta R < 1-2\%$ over 30,000 hr lifetime

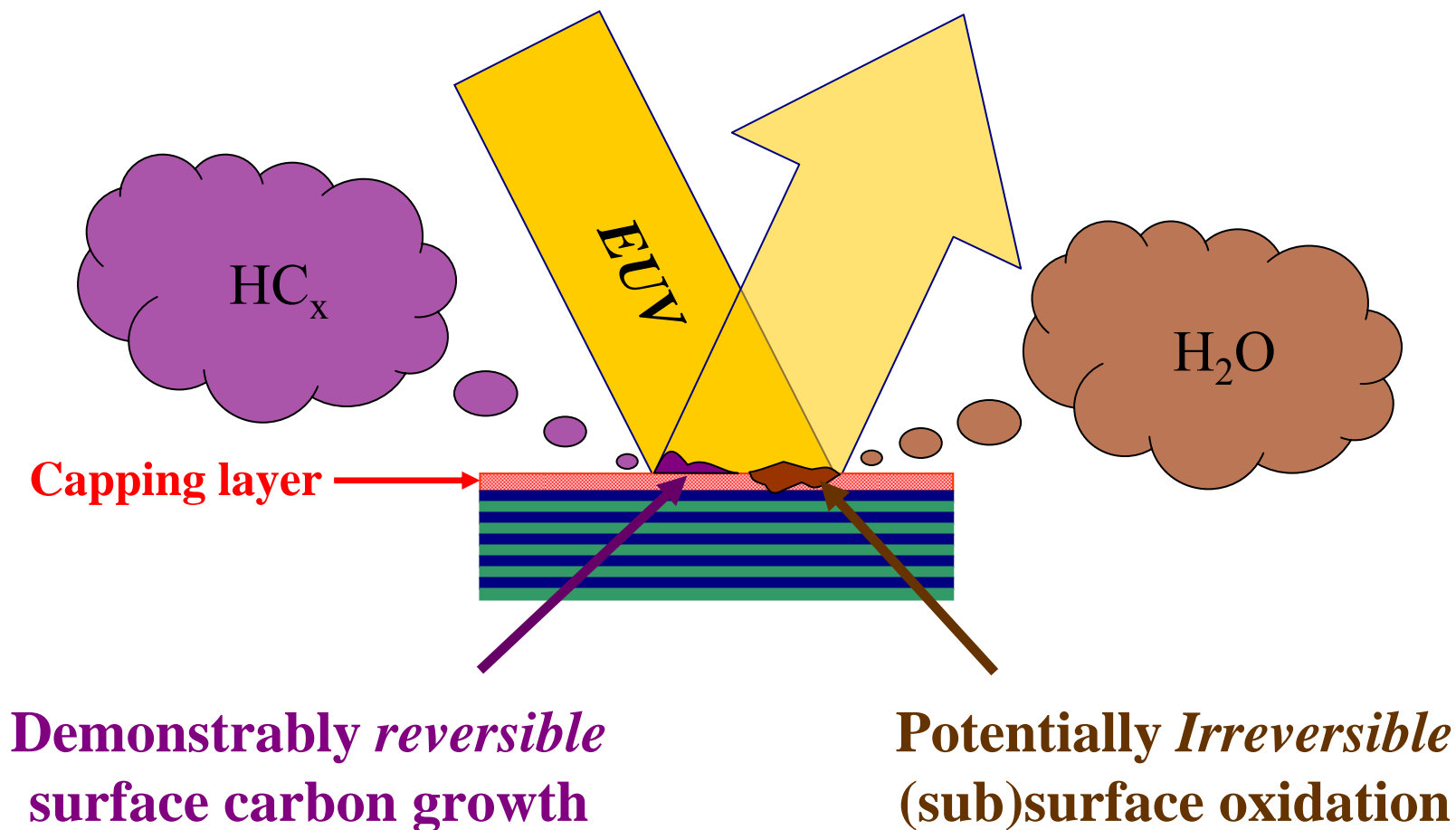
Conditions: EUV intensity, $I_{\text{EUV}} \leq 10 \text{ mW/mm}^2$

Unbaked vacuum, $P_{\text{H}_2\text{O}} \leq 10^{-7} \text{ Torr}$, $P_{\text{HC}_x} \sim 10^{-10} \text{ Torr}$

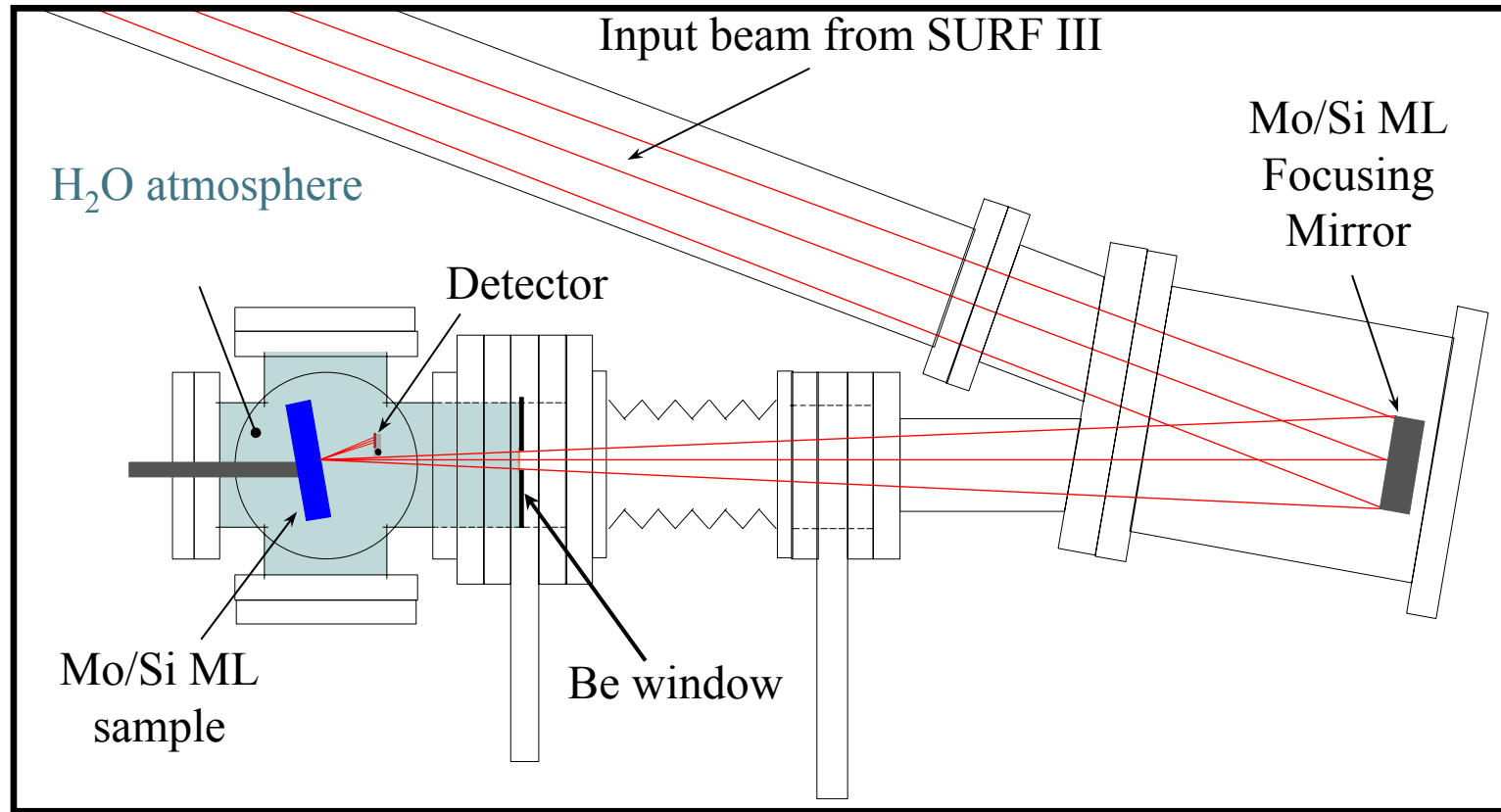
NIST Goals

- Provide rapid feedback to capping-layer-development community by establishing well characterized endurance testing facilities.
- Develop accelerated testing methods to predict optic lifetime in tool (~ 3.5 yrs) from $\sim 10^2$ hrs of exposure at aggressive I_{EUV} and $P_{\text{H}_2\text{O}, \text{HC}_x}$ conditions.

Present assumption: two competing mechanisms



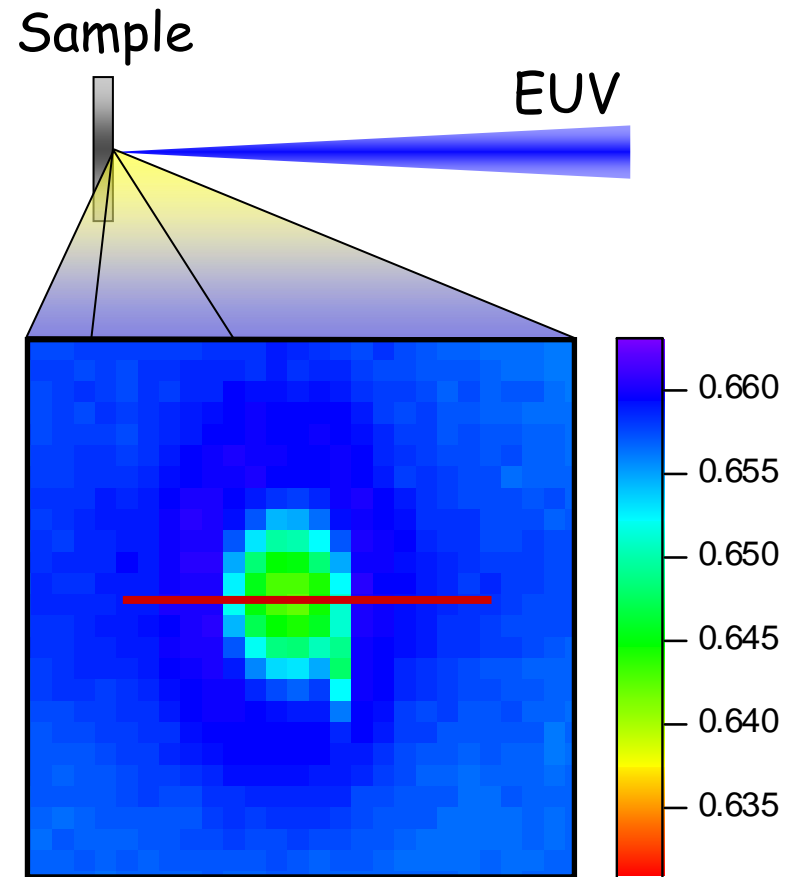
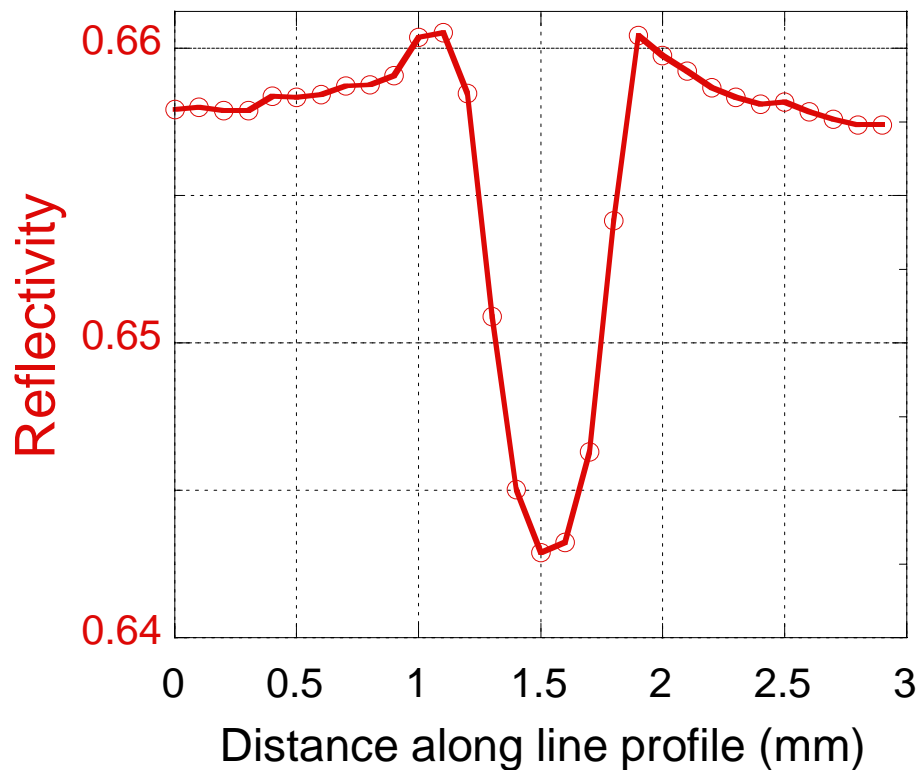
Existing EUV endurance testing facility at NIST



- Spot size $\sim 650 \mu\text{m} \times 650 \mu\text{m}$ (FWHM) at sample
- Average, in-band (13.1-13.6nm) intensity $\sim 5 \text{ mW}/\text{mm}^2$
- Be window permits high water vapor pressures: $P_{\text{H}_2\text{O}} \leq 10^{-5} \text{ Torr}$
- Automation upgrades increased exposure duty cycle: $\sim 15 \text{ hrs}/\text{day}$

Post exposure analysis

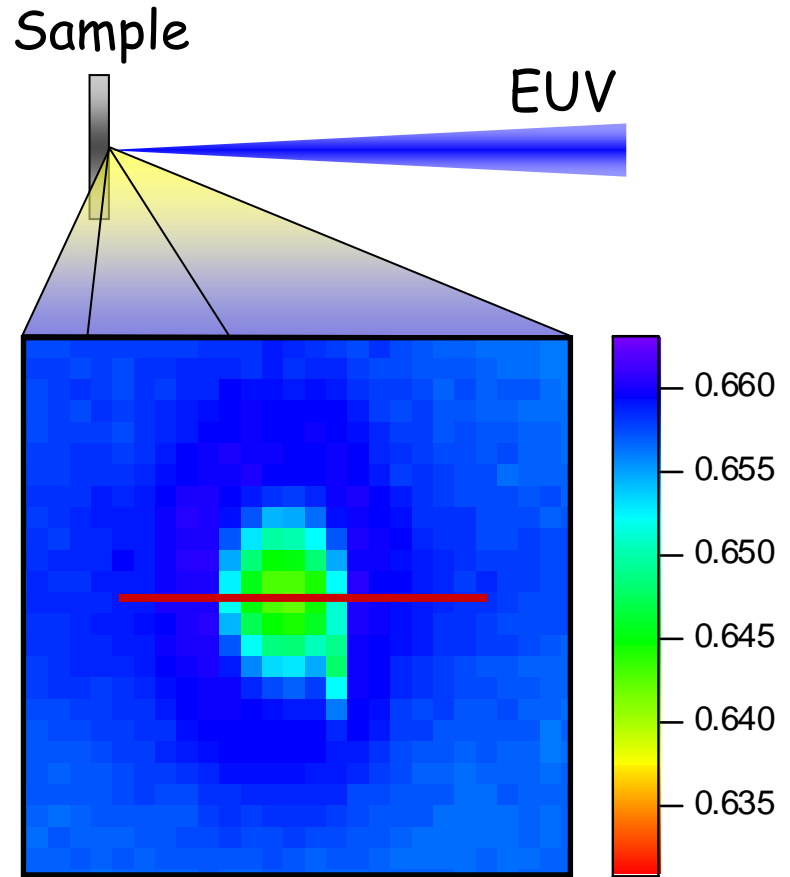
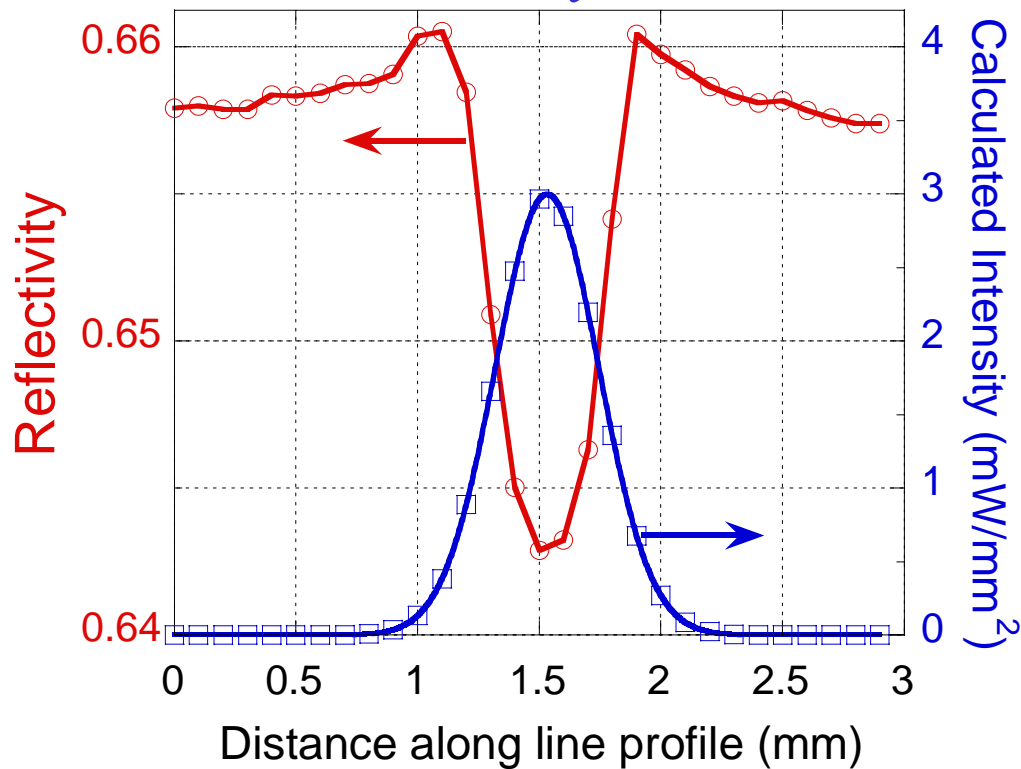
Line profile of reflectivity map



13.5nm reflectivity map (ALS)

Post exposure analysis

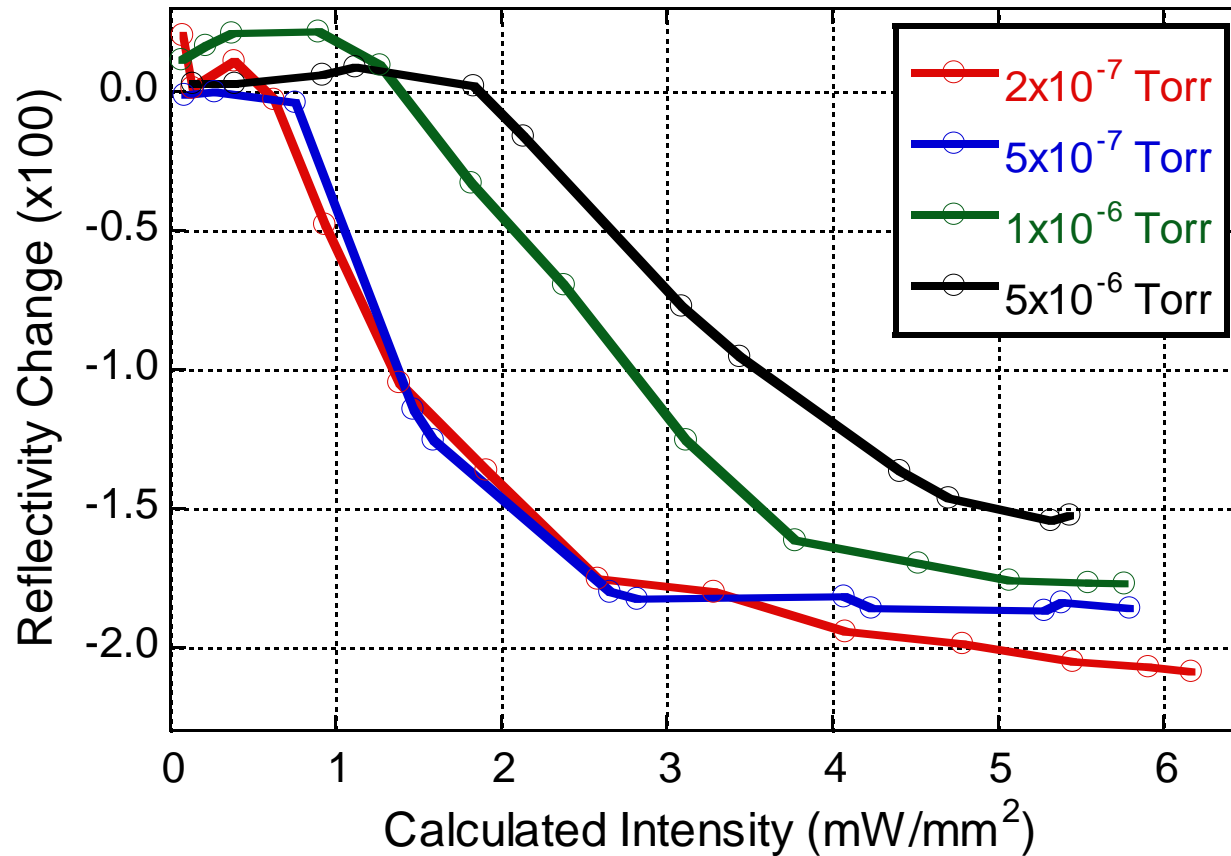
Line profile of reflectivity map
& EUV intensity distribution



13.5nm reflectivity map (ALS)

Intensity dependence of damage inferred from a **single** exposure!

Reflectivity loss as a function of incident intensity

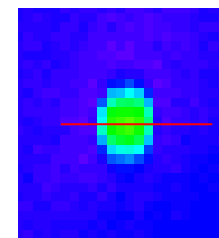
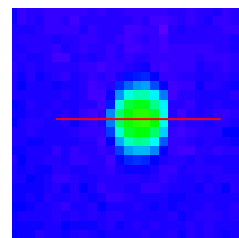
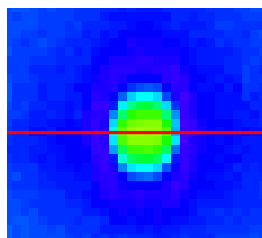
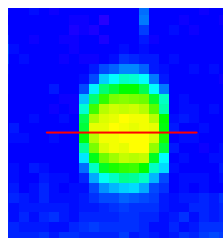
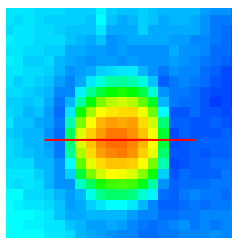
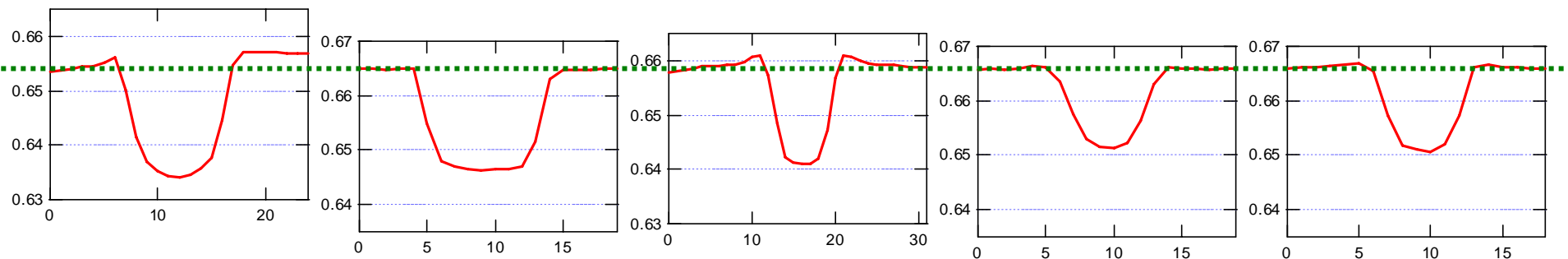


- Damage varies *inversely* with water partial pressure
- Pressure dependence decreases with intensity
- Suggests intensity saturation

Unexpected damage dependence on H₂O pressure

Reflectivity loss *decreases* with *increasing* water pressure

10hr Exposures at **Maximum Intensity** (~6 mW/mm²)



2×10^{-7} Torr H₂O

5×10^{-7} Torr H₂O

1×10^{-6} Torr H₂O

2×10^{-6} Torr H₂O

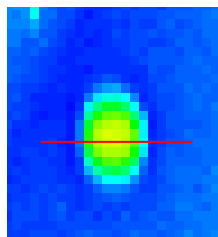
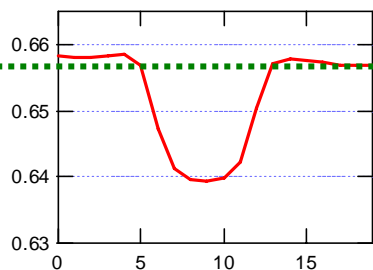
5×10^{-6} Torr H₂O

Increasing water vapor pressure

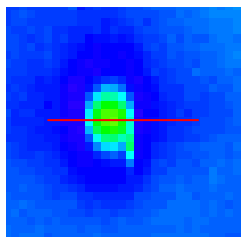
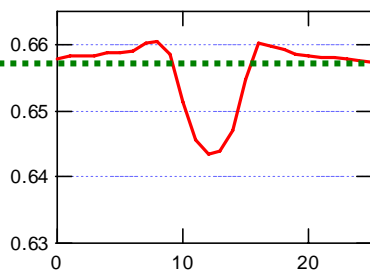
Unexpected damage dependence on H₂O pressure

Reflectivity loss *decreases* with *increasing* water pressure

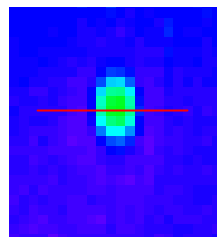
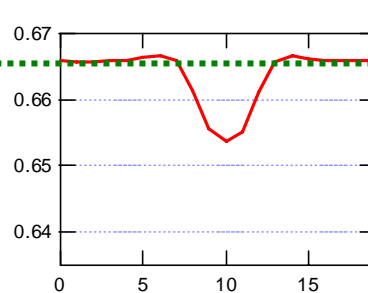
10hr Exposures at **Half Max Intensity** (~ 3 mW/mm²)



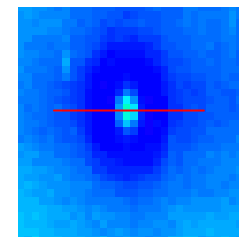
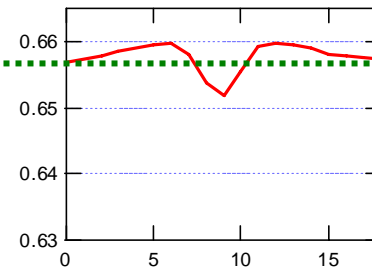
5×10^{-7} Torr H₂O



1×10^{-6} Torr H₂O



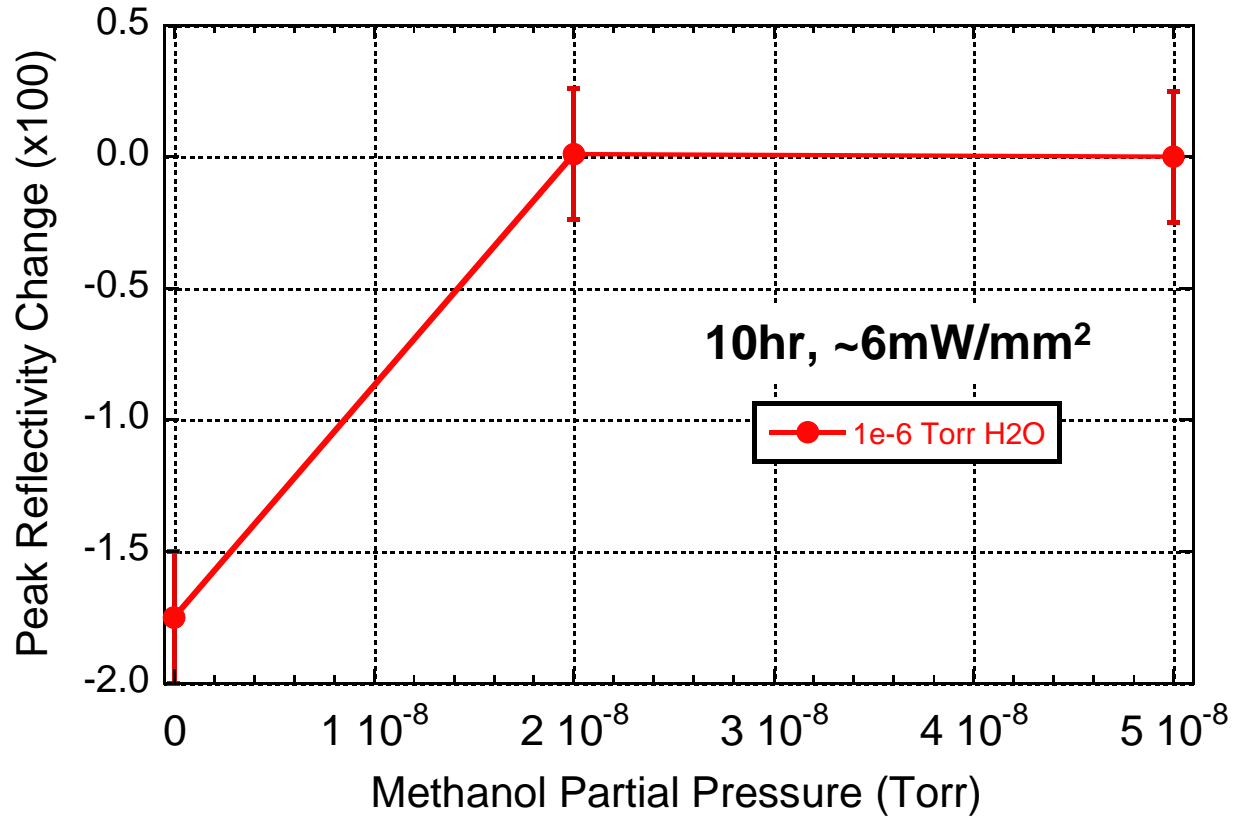
2×10^{-6} Torr H₂O



5×10^{-6} Torr H₂O

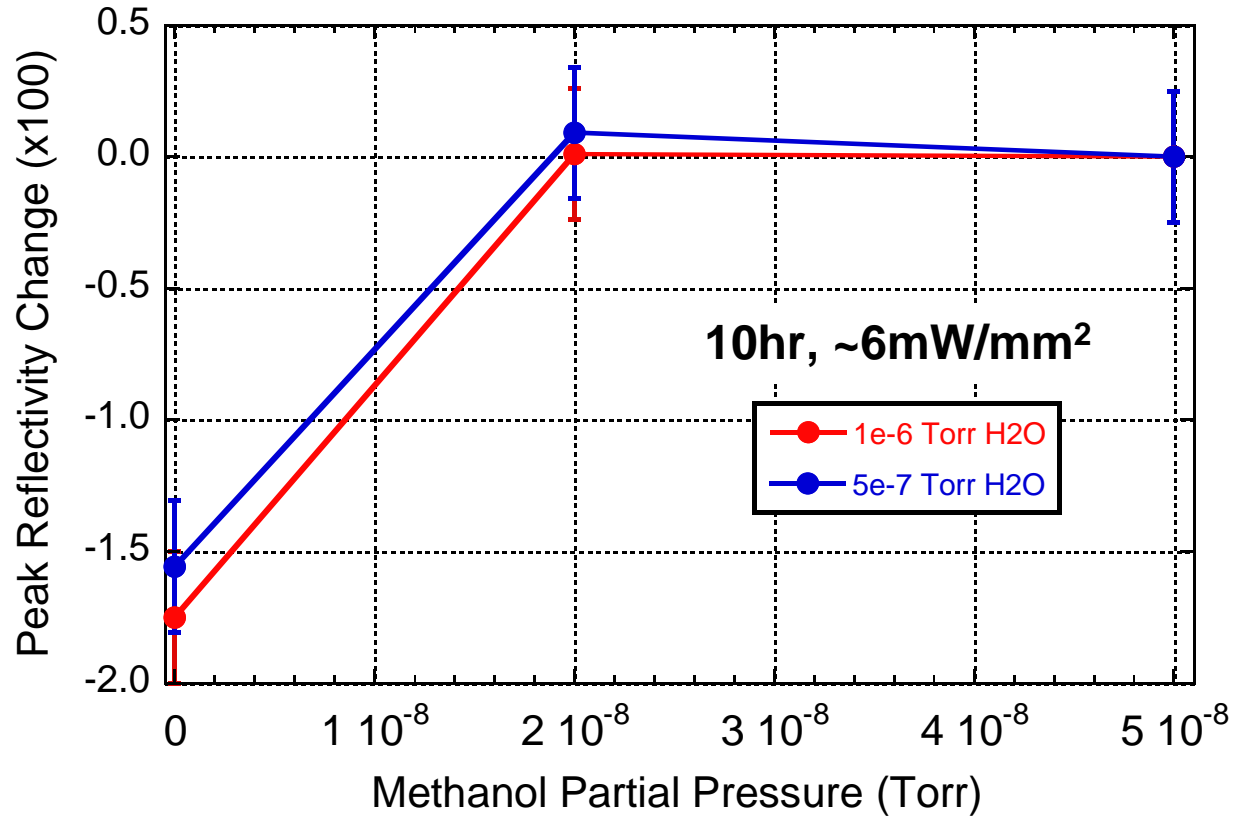
Increasing water vapor pressure

Methanol significantly reduces damage



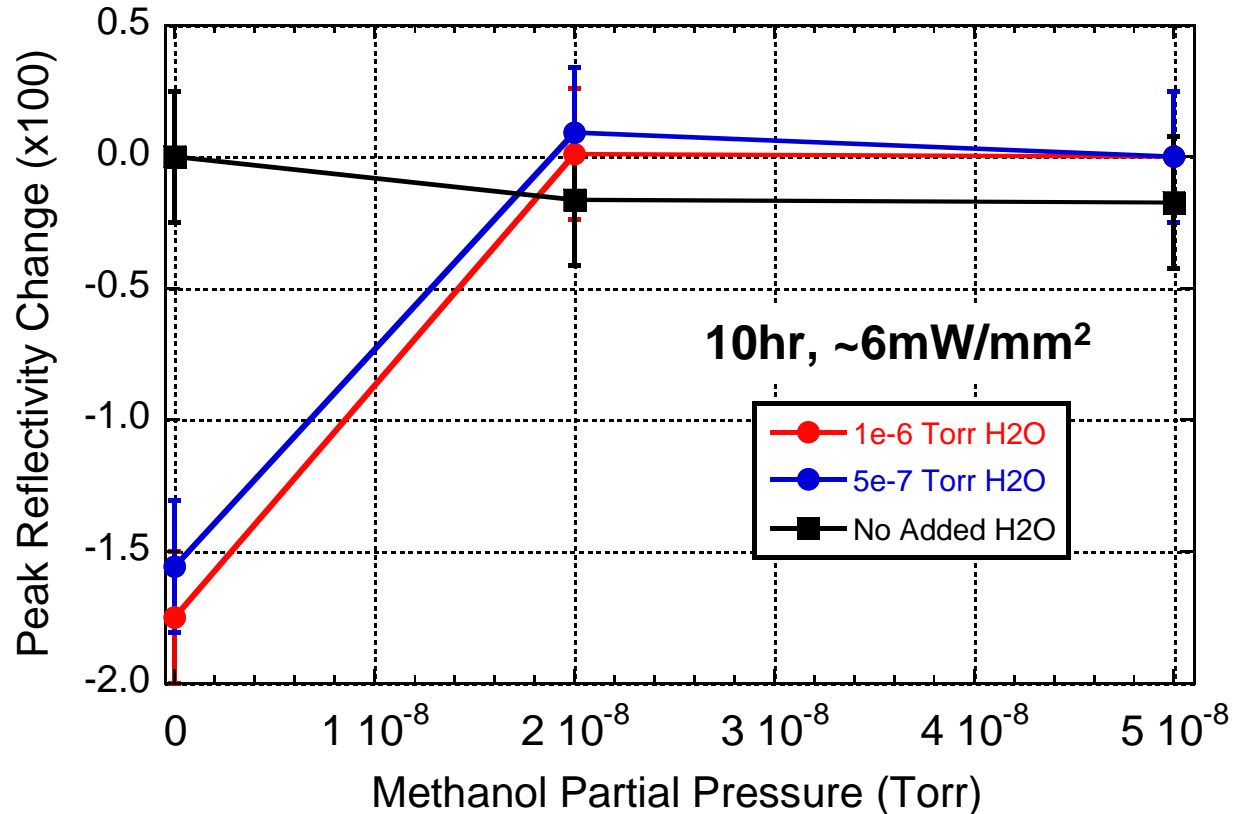
- Just 2×10^{-8} Torr methanol prevents measurable damage from water

Methanol significantly reduces damage



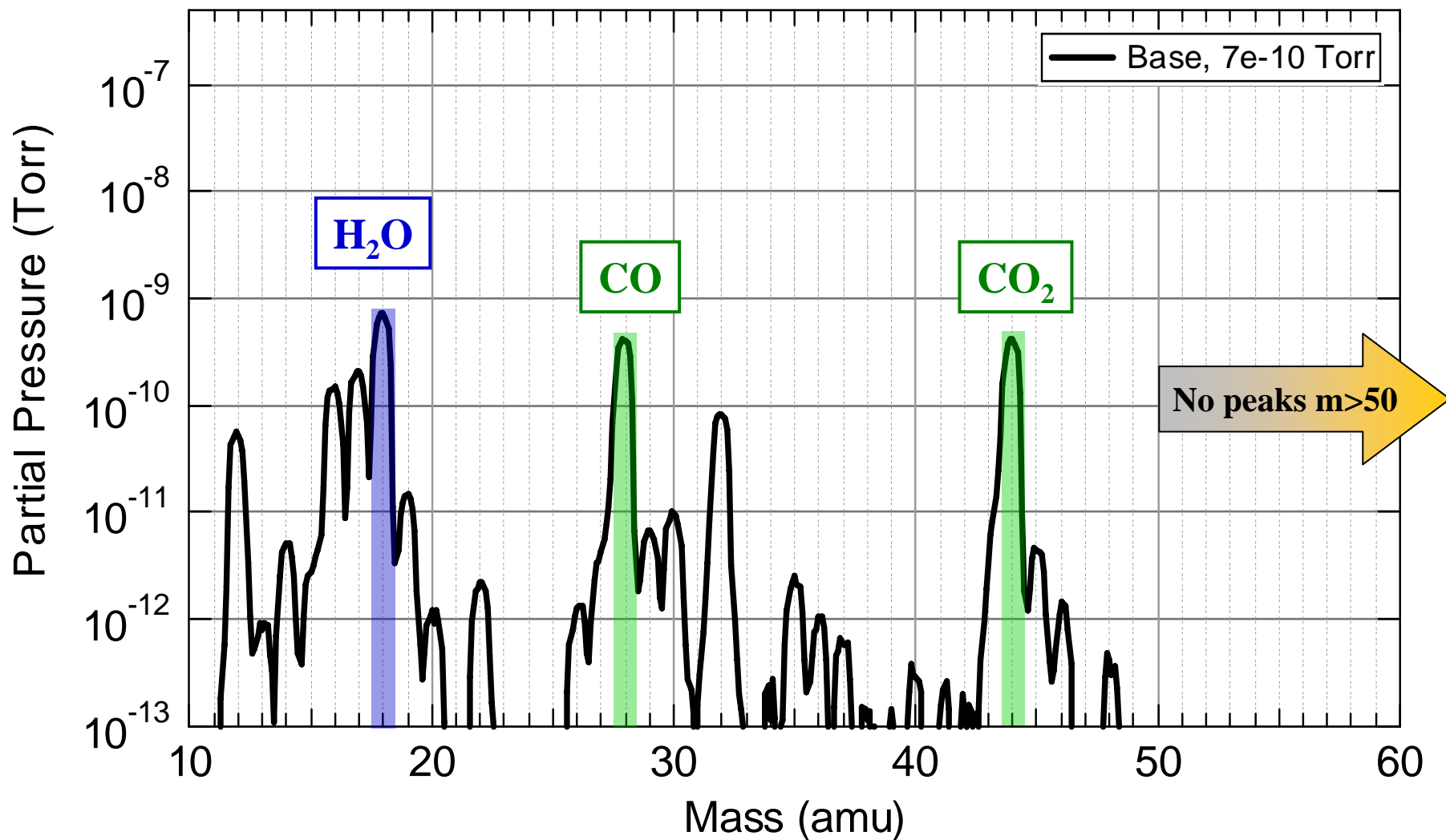
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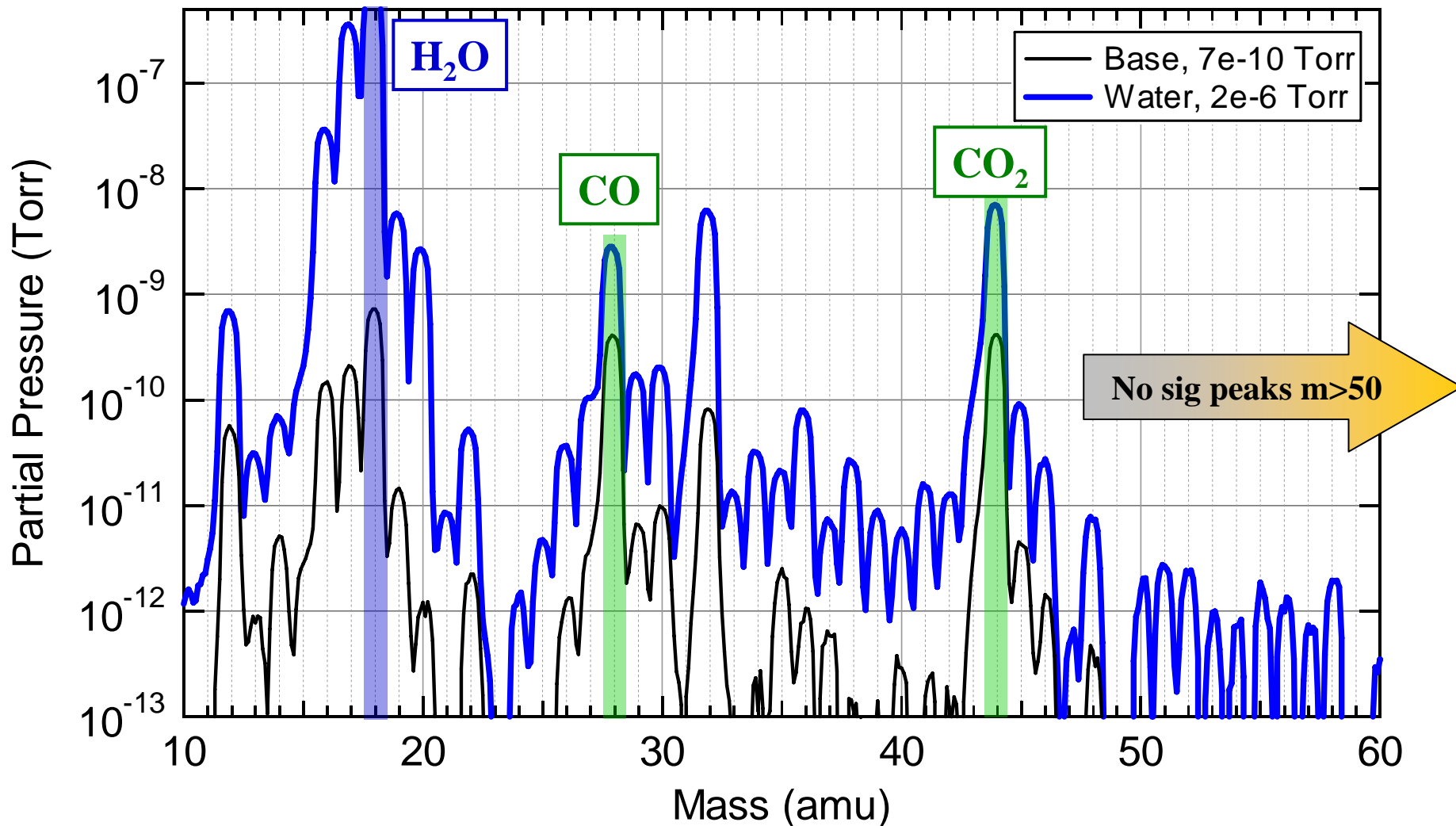
- Just 2×10^{-8} Torr methanol prevents measurable damage from water
- Very little damage from low levels of methanol alone
- Trace levels of carbon-containing compounds in ambient background may similarly mitigate damage by water

Identify potential mitigating species in vacuum



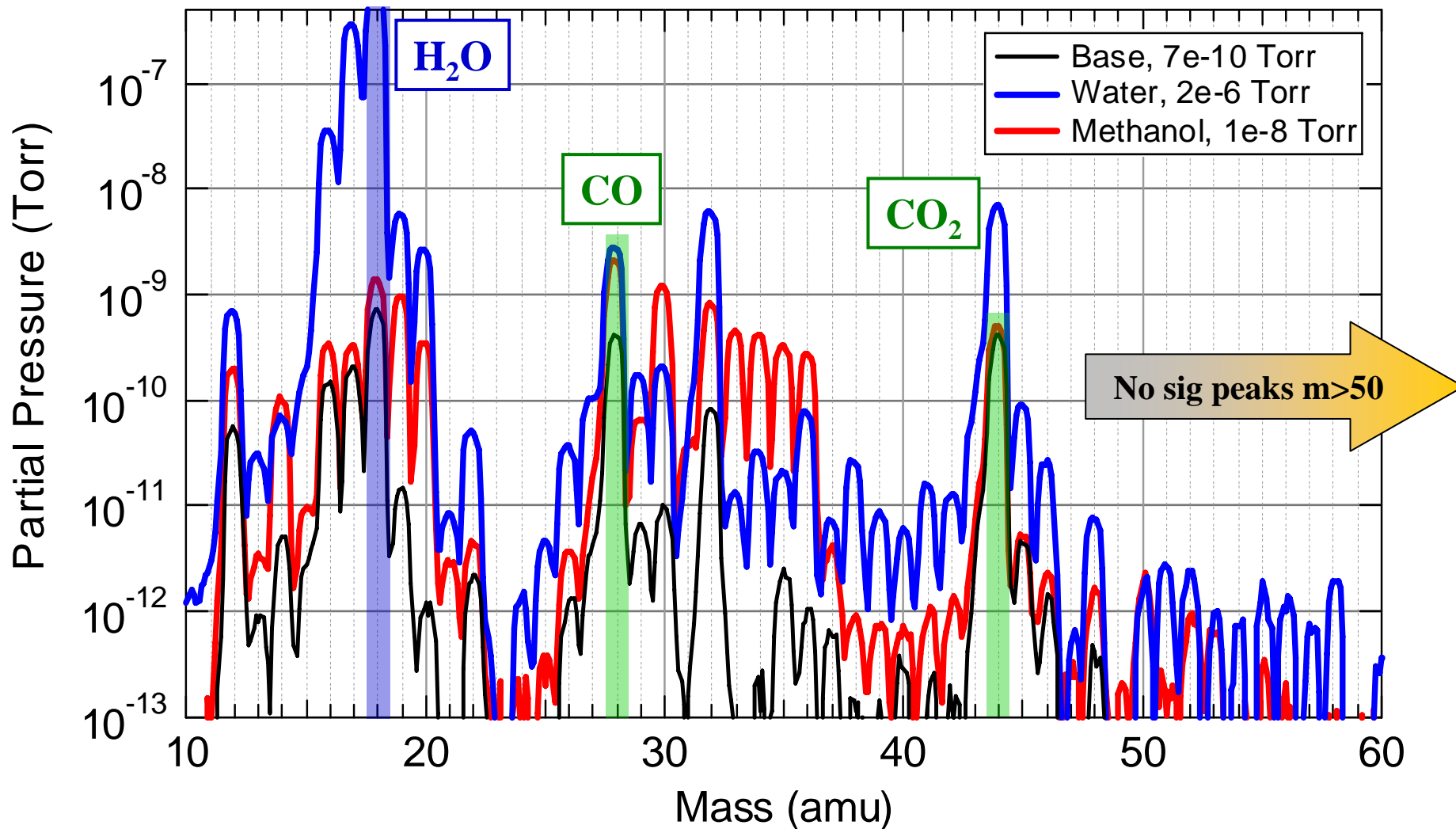
• No long-chain ($m > 50$) hydrocarbons present

Identify potential mitigating species in vacuum



• CO and CO₂ increase with water (no significant $m > 50$)

Identify potential mitigating species in vacuum



• CO and CO_2 contribution from *water* similar to *methanol*

Ancillary tests to find source of CO & CO₂

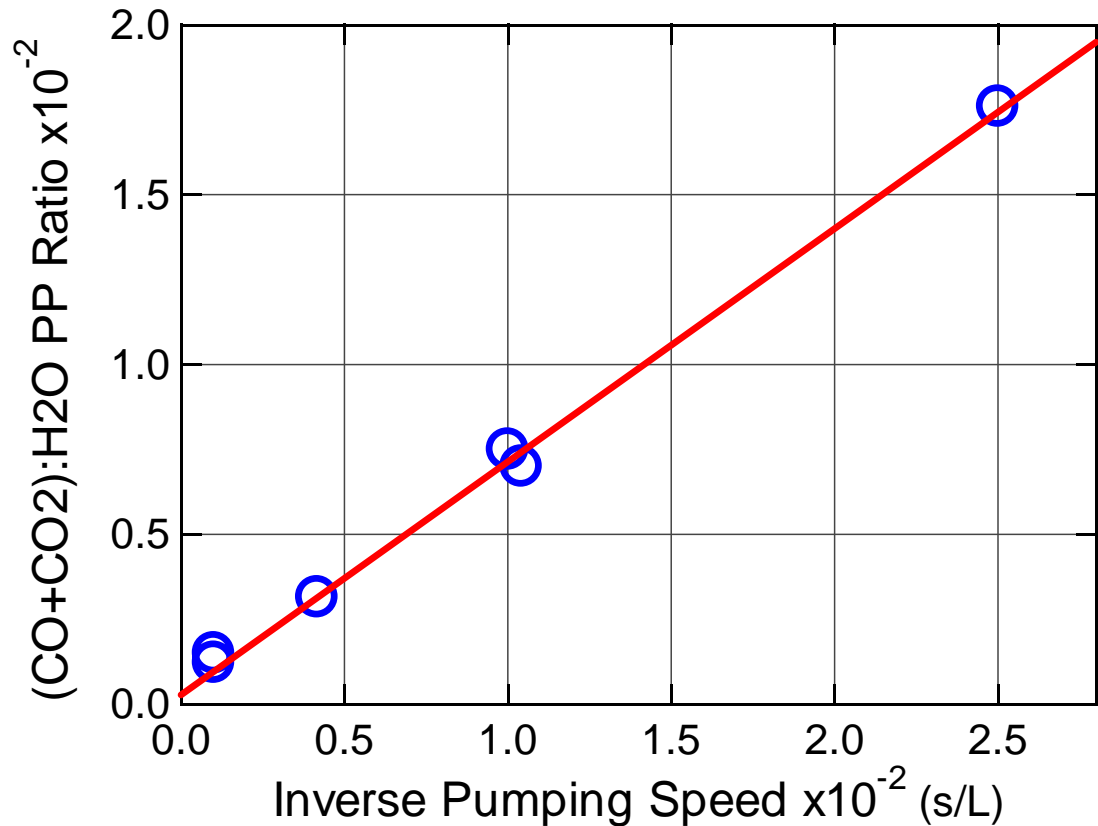
Is water contaminated?

Mass throughput equations

$$S_C P_C = \cancel{L_W} + \beta P_W$$

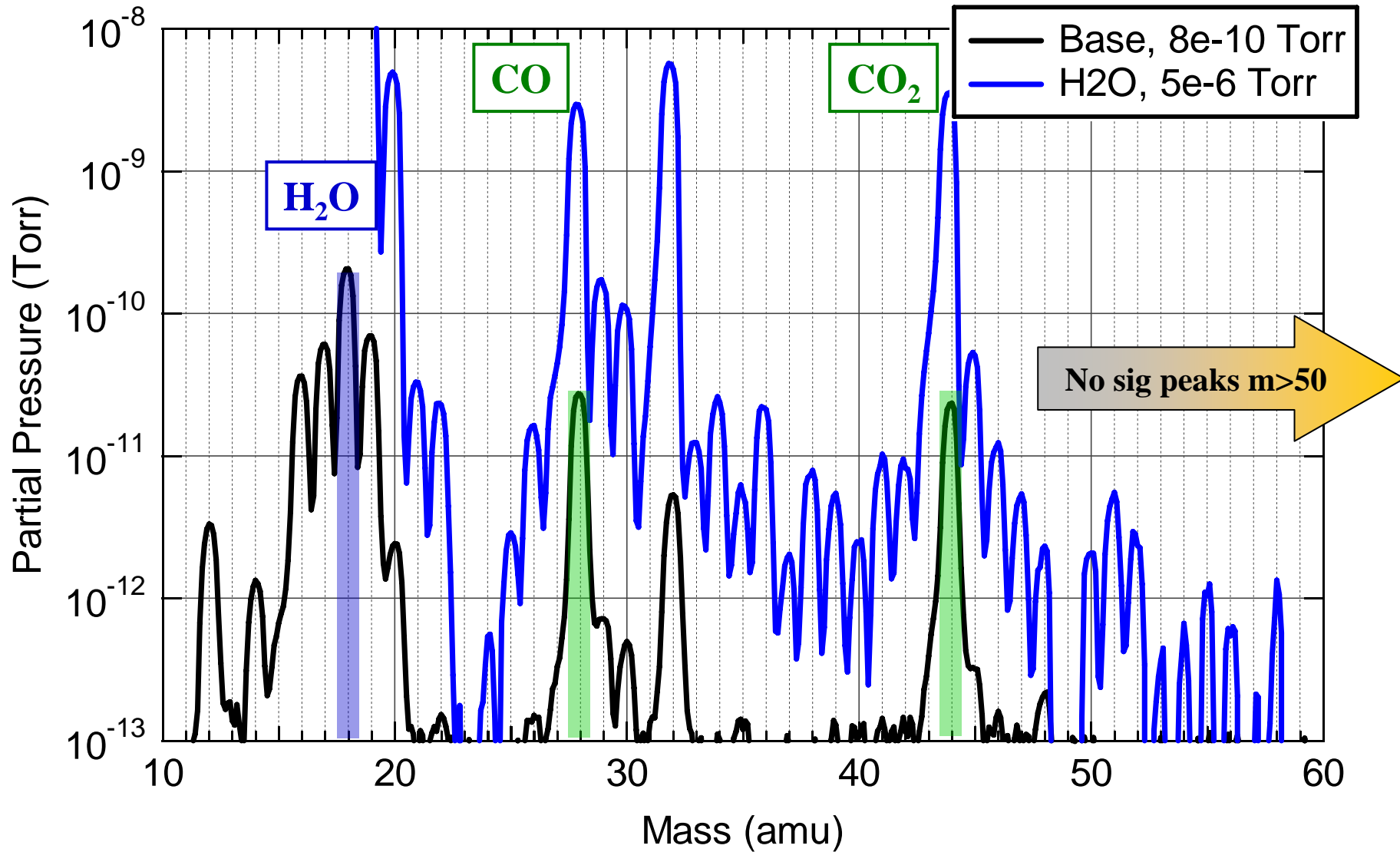
$$S_W P_W = L_W$$

$$\frac{P_C}{P_W} \propto \left(\cancel{L} + \frac{\beta}{S_W} \right)$$



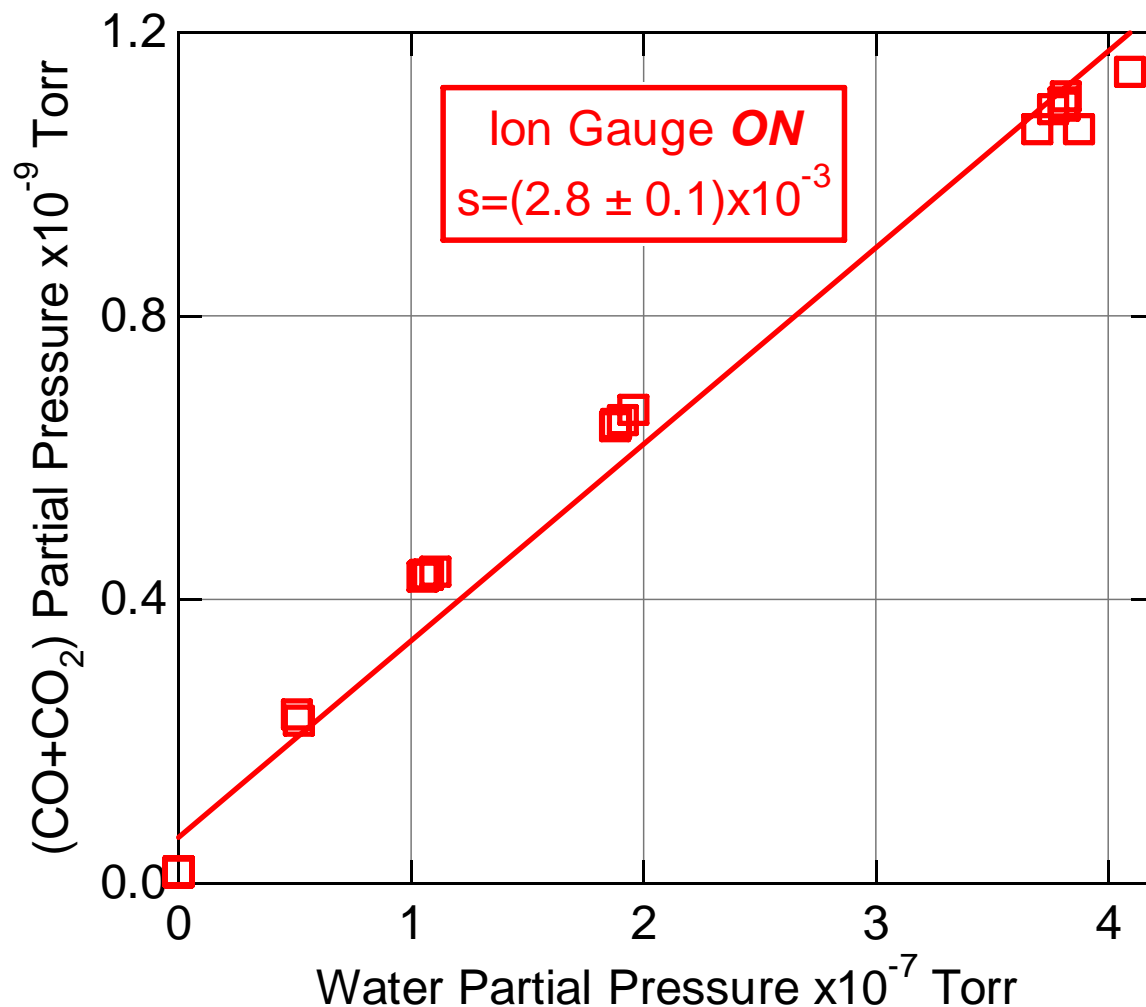
- CO & CO₂ **NOT** from contaminated water supply
- Produced by water interaction with chamber
 - C-species displaced from unbaked chamber walls by water
 - Reaction of water with C in hot tungsten/iridium filaments

Improved mass spectrum after bake & cleaning



Ancillary tests to find source(s) of CO & CO₂

- C-species generated at rate proportional to water partial pressure
- Chamber contains two filaments: IG, RGA
- Is rate of C-species production different with only RGA on?

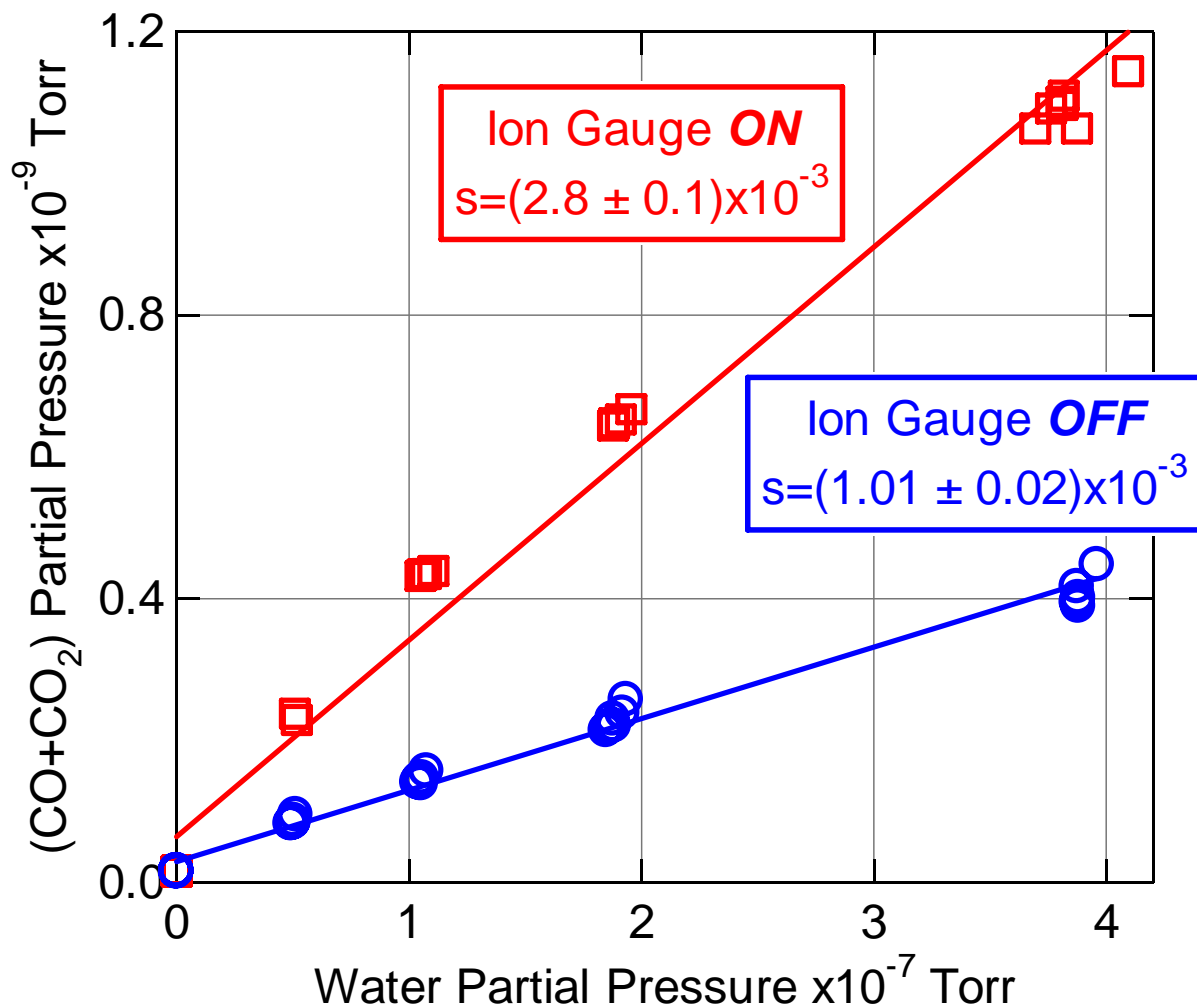


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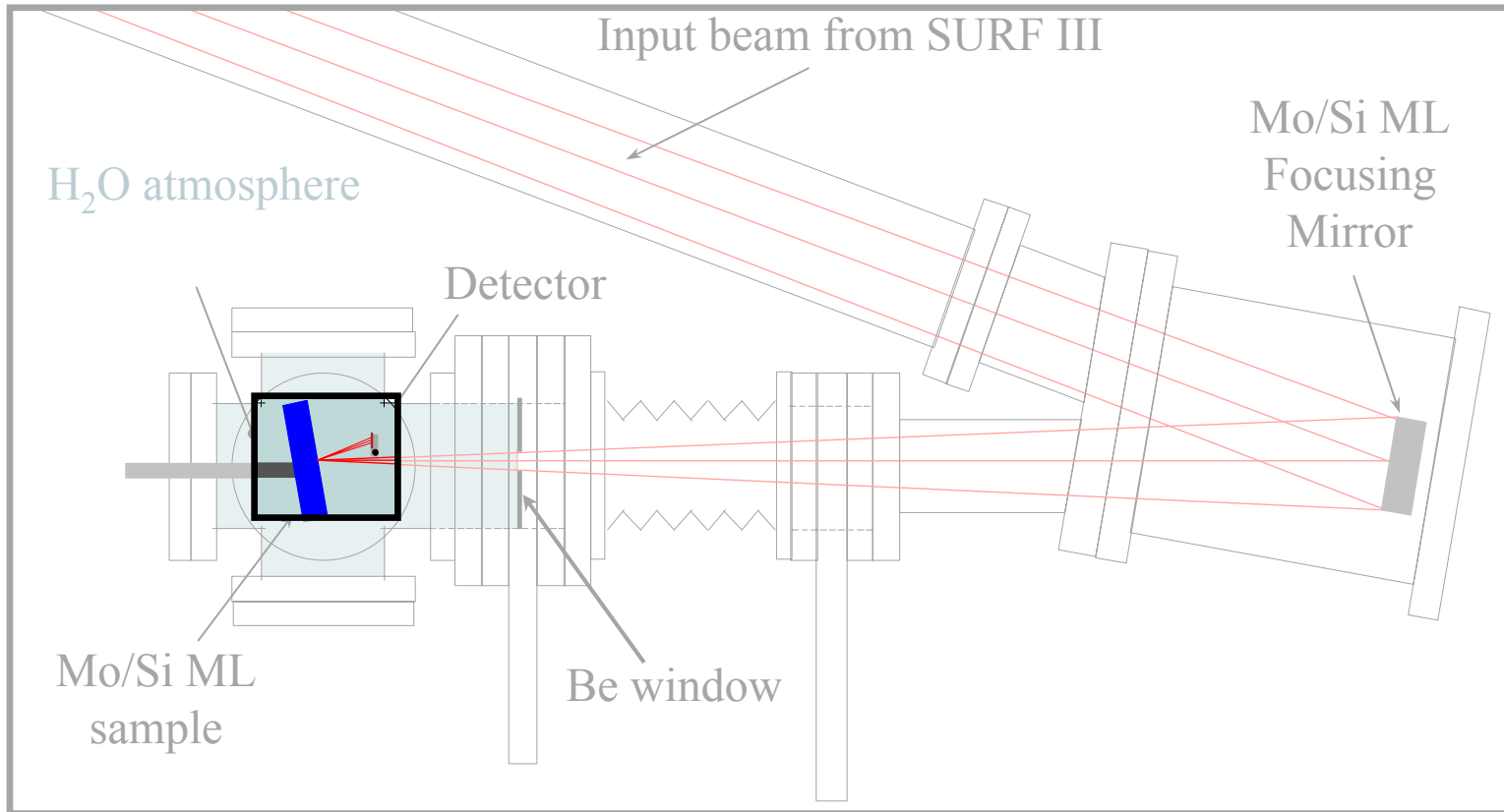
YES!

- CO & CO₂ 3x smaller with IG off
- Likely reduced further if RGA also off



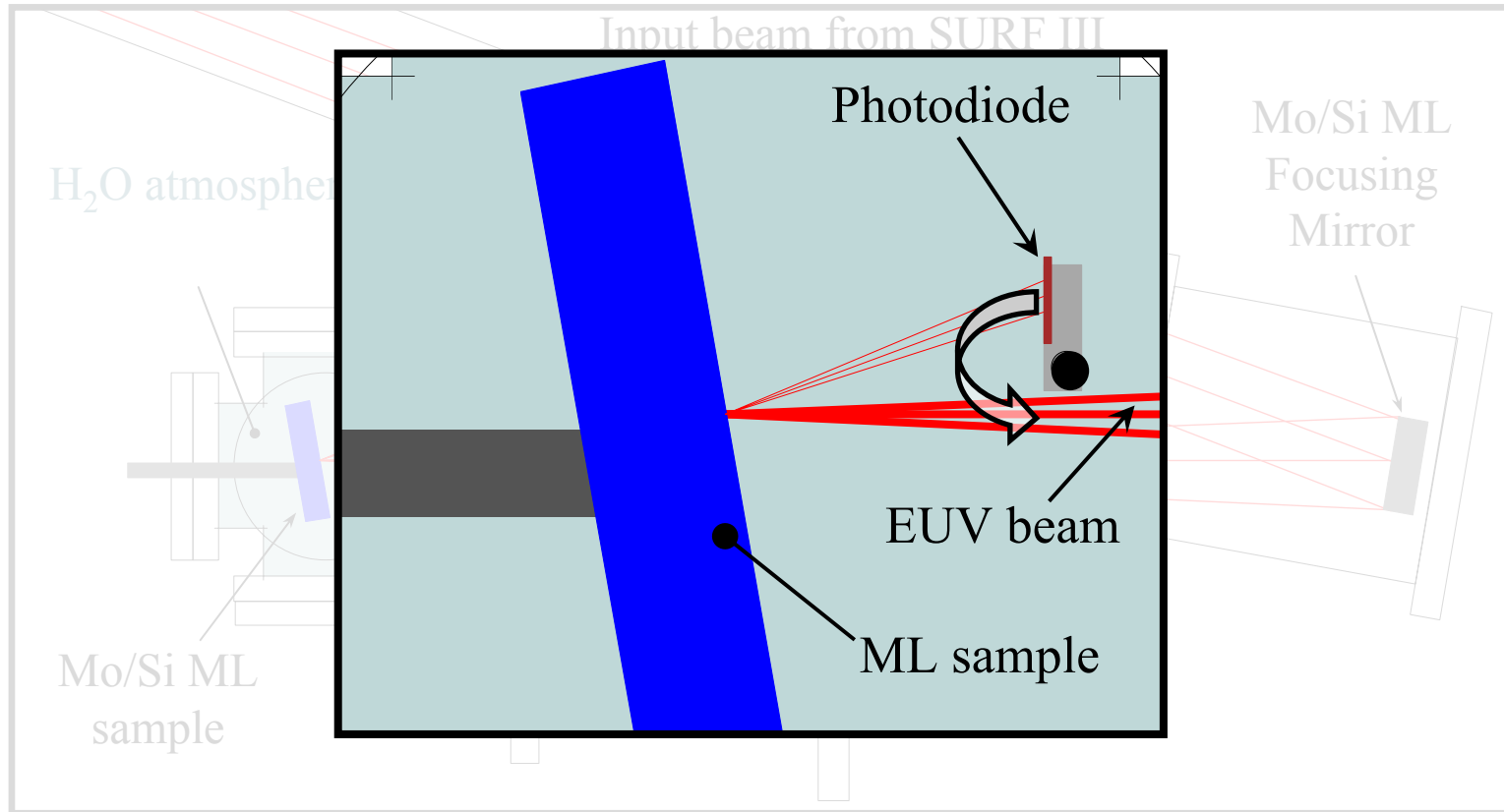
How will this affect EUV damage to ML optics?

Use *in situ* reflectivity monitor for initial tests



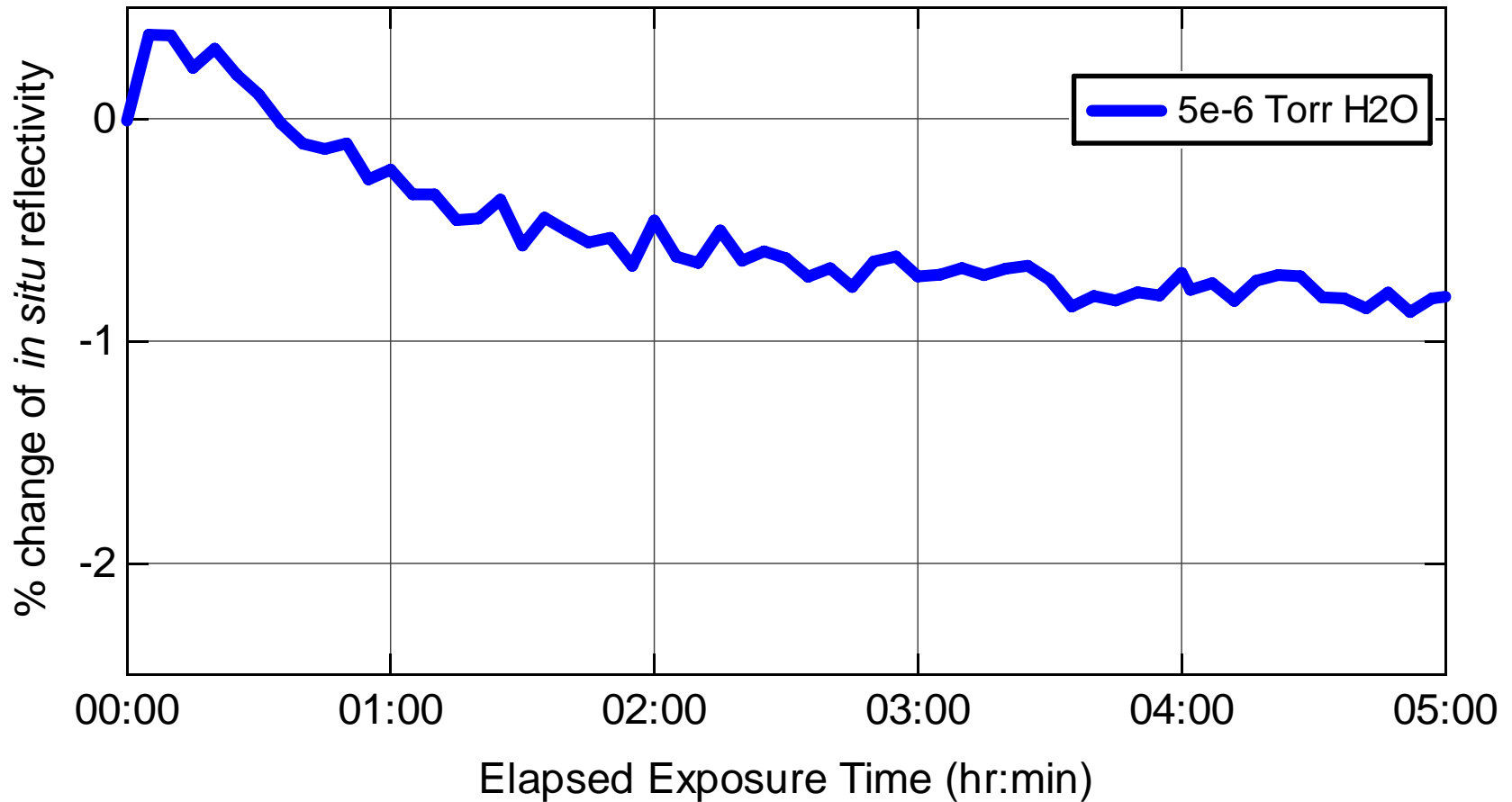
- Only need relative measurement of real-time decay

Use *in situ* reflectivity monitor for initial tests

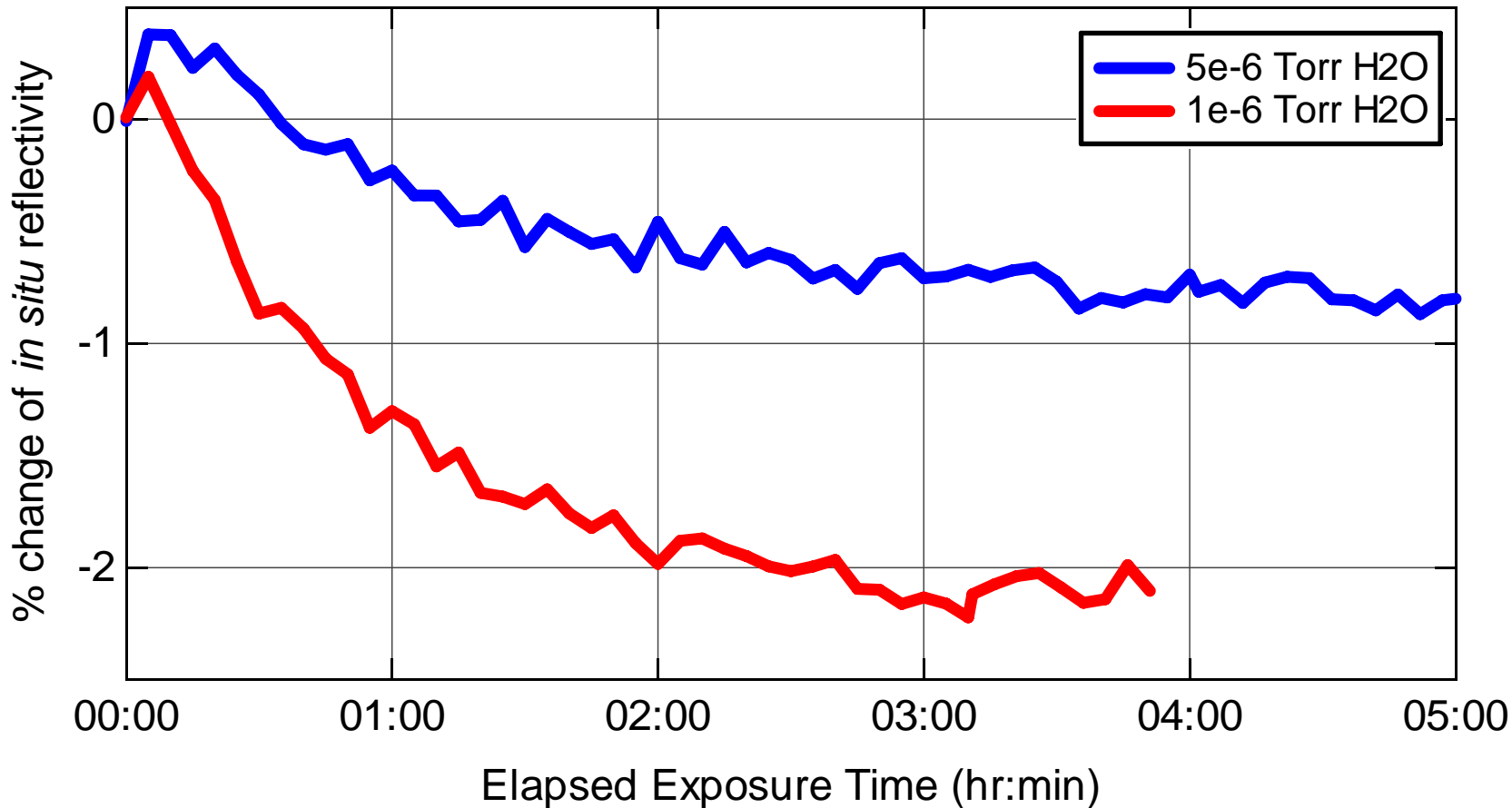


- Only need relative measurement of real-time decay
- Suitable for monitoring initial decay and changes $>0.5\%$ (abs)
- Not reliable for absolute measurements over long exposures due to highly non-uniform spatial distribution of damage.

in situ measurement of reflectivity decay

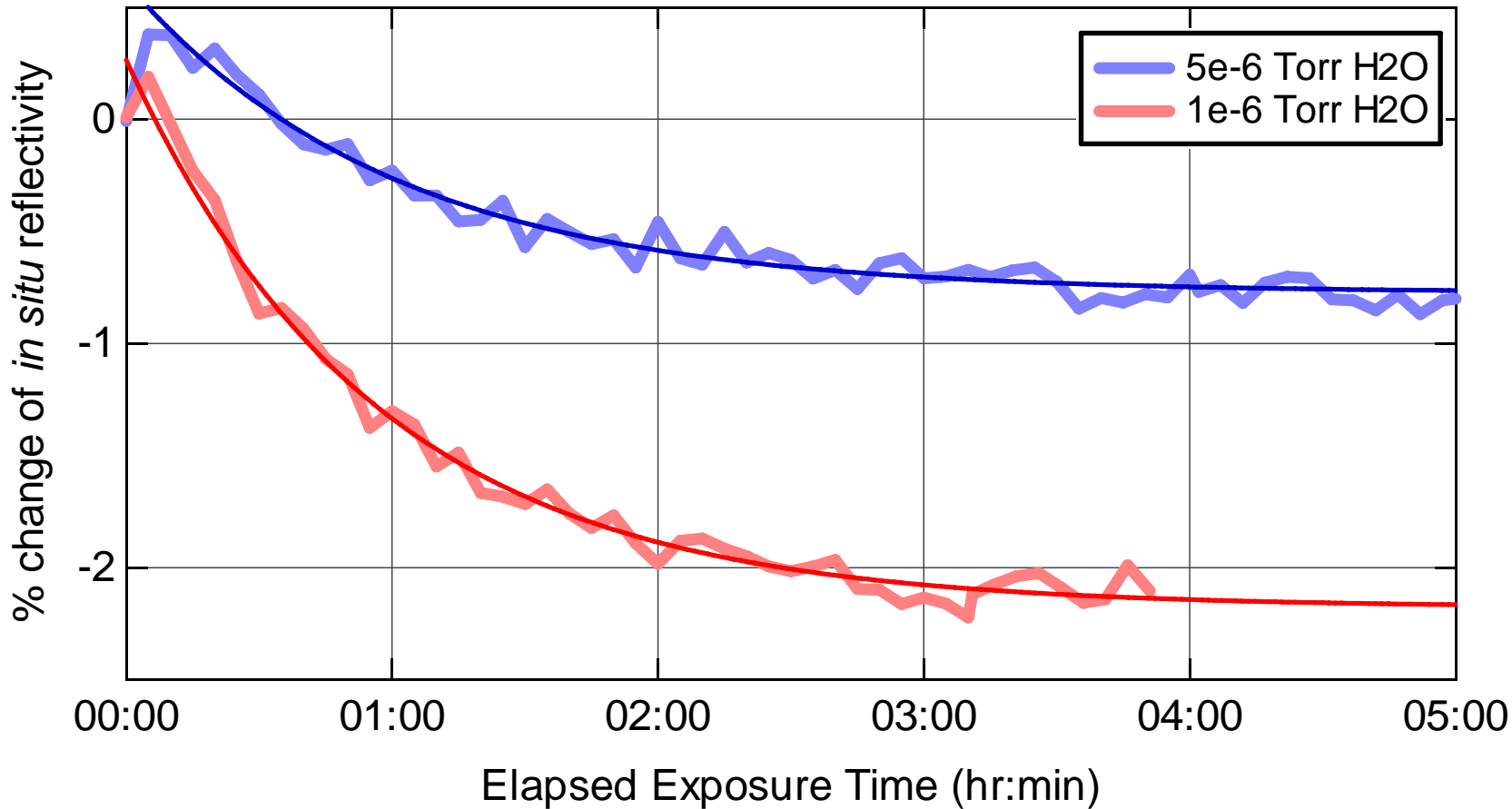


in situ measurement of reflectivity decay



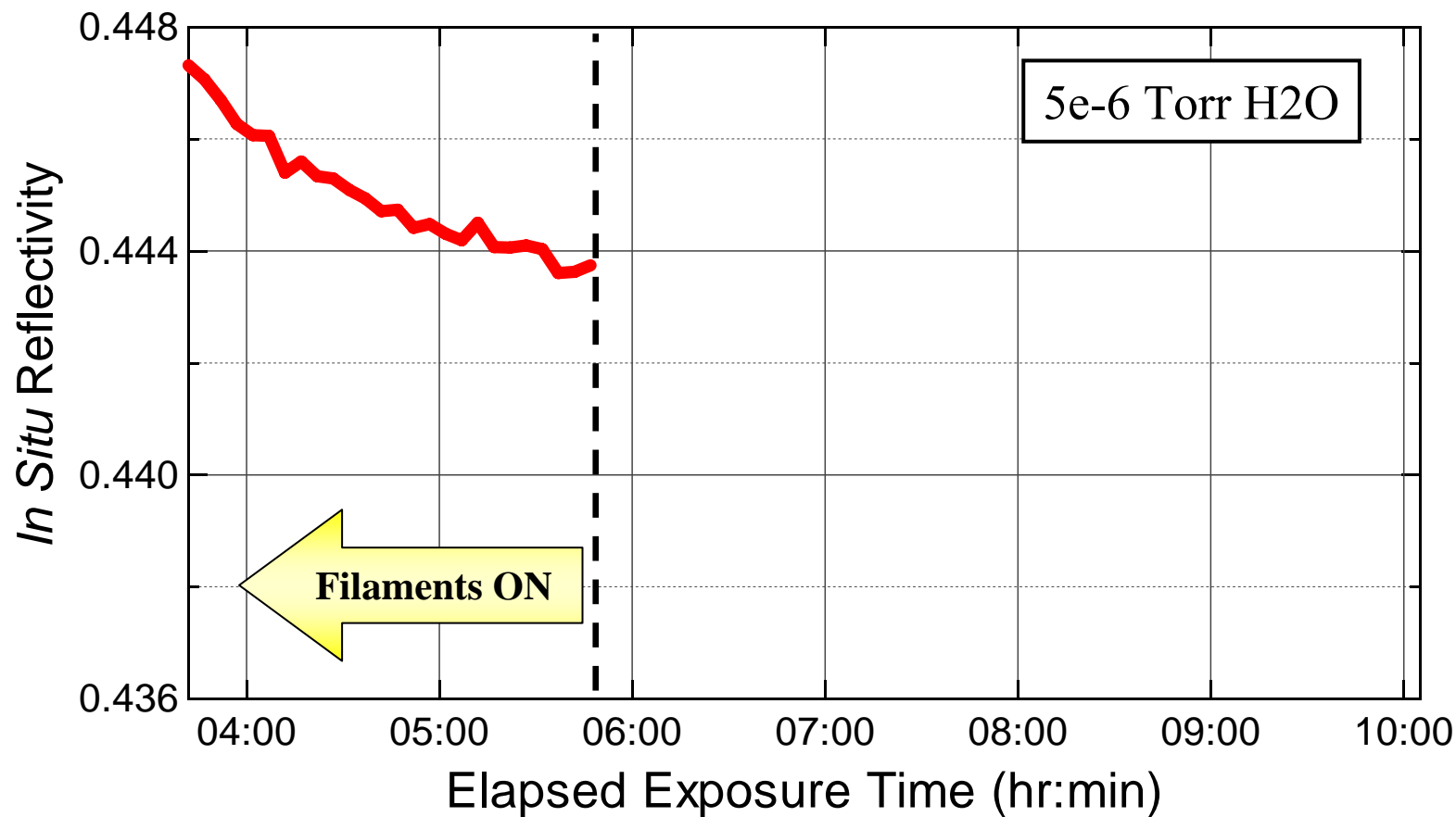
- Observe *increased* damage at *lower* H₂O pressures

in situ measurement of reflectivity decay

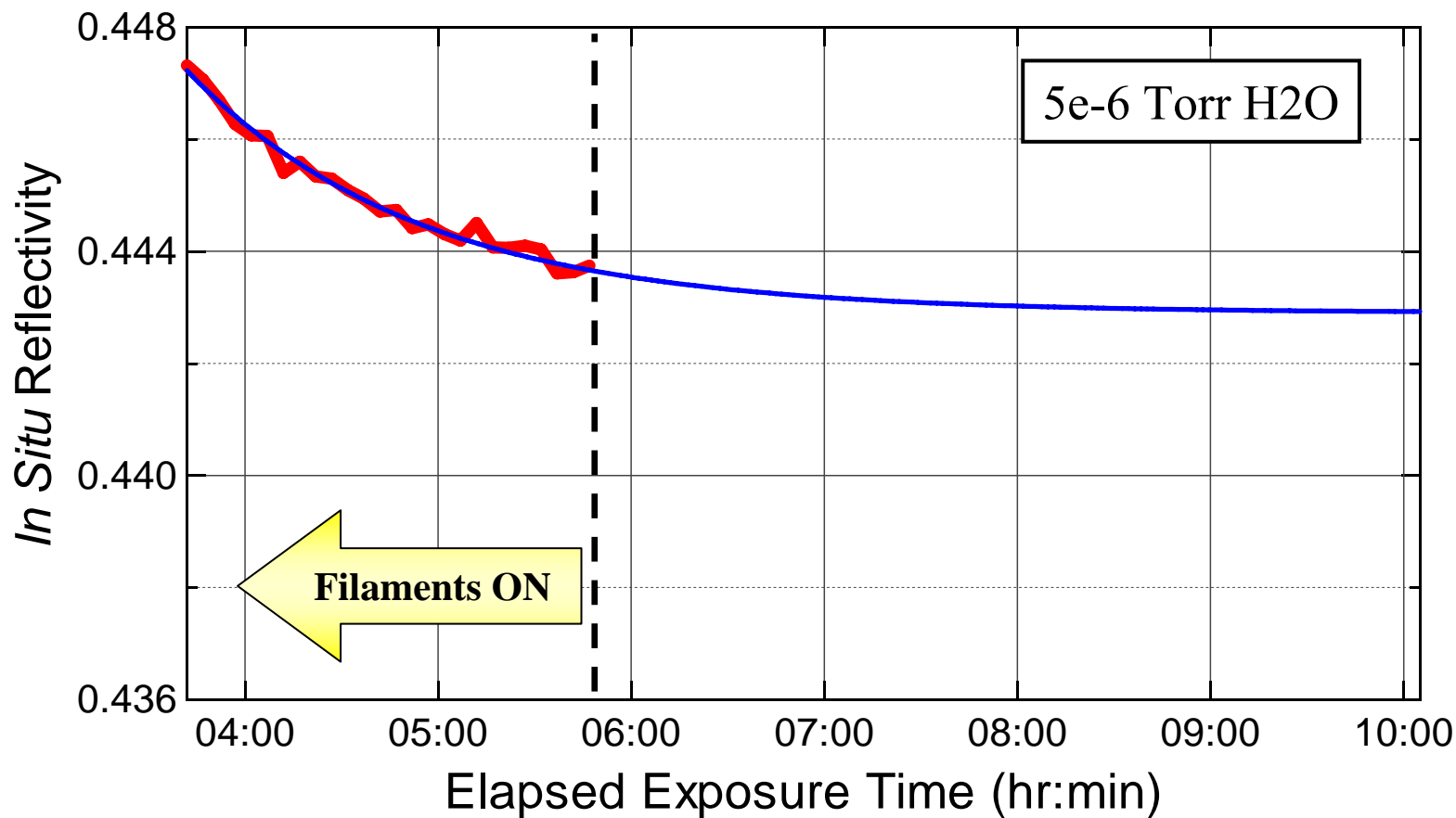


- Observe *increased* damage at *lower* H₂O pressures
- Initial decay empirically described by exponential

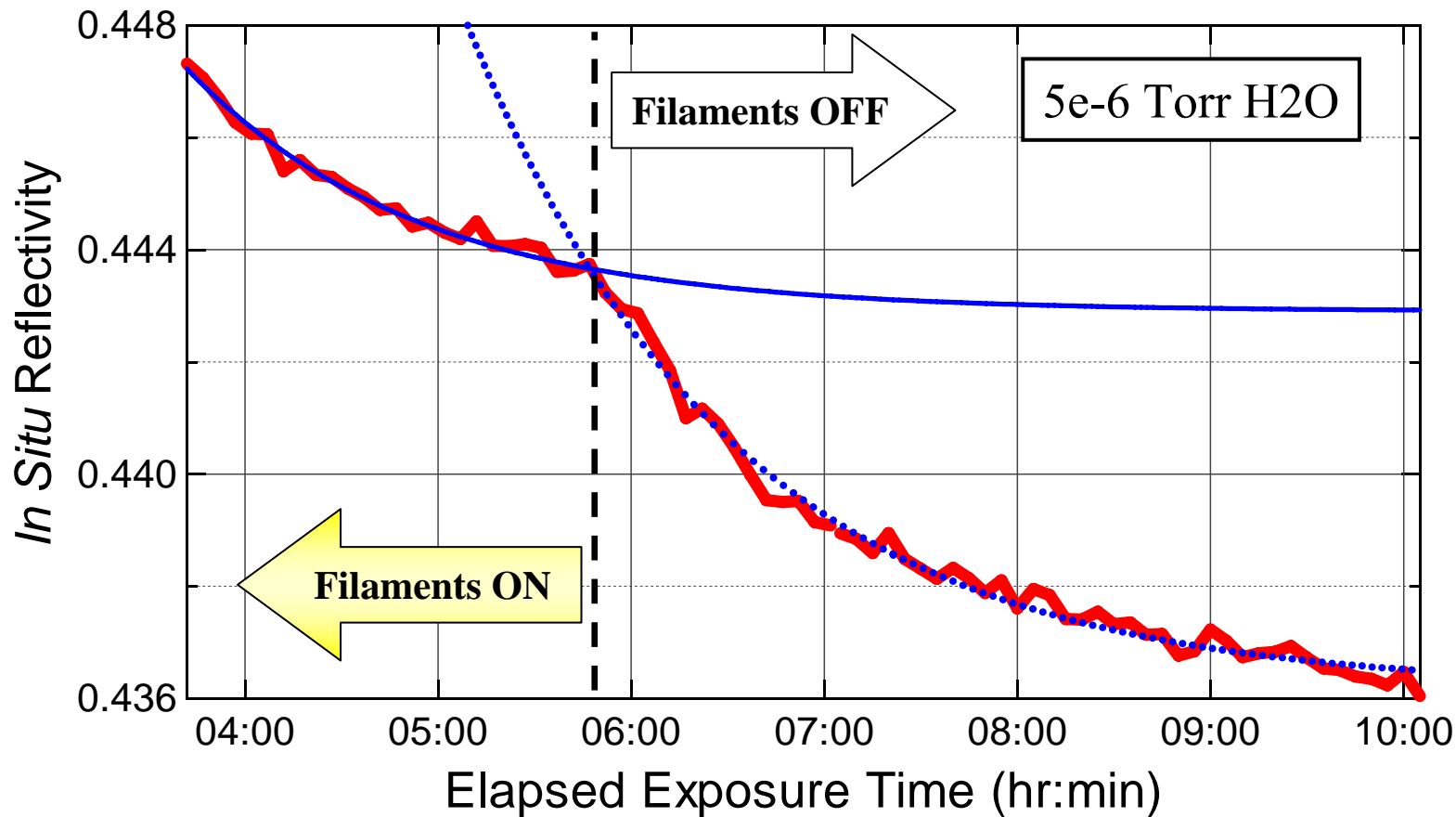
Effect of filaments on reflectivity decay



Effect of filaments on reflectivity decay

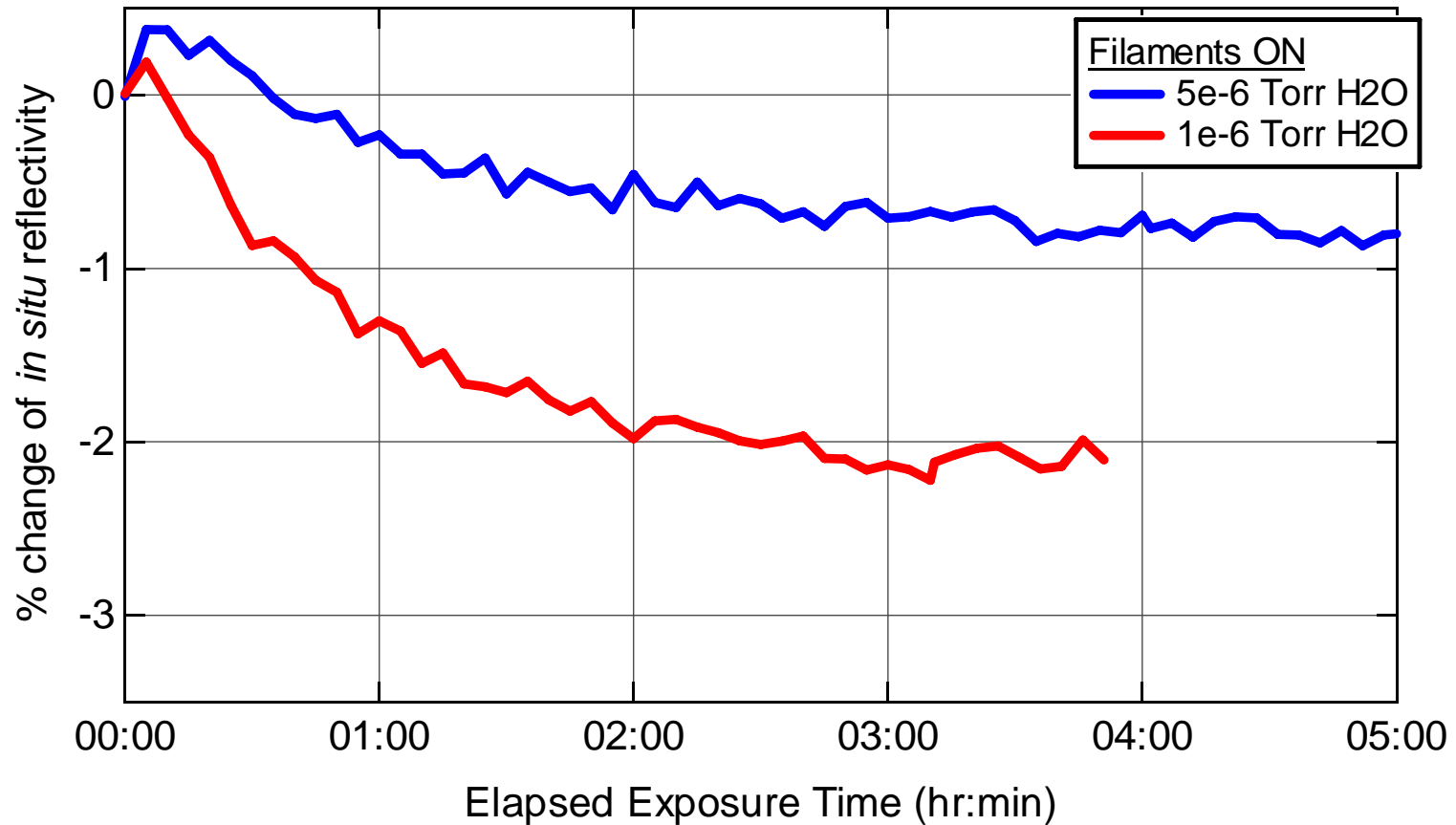


Effect of filaments on reflectivity decay

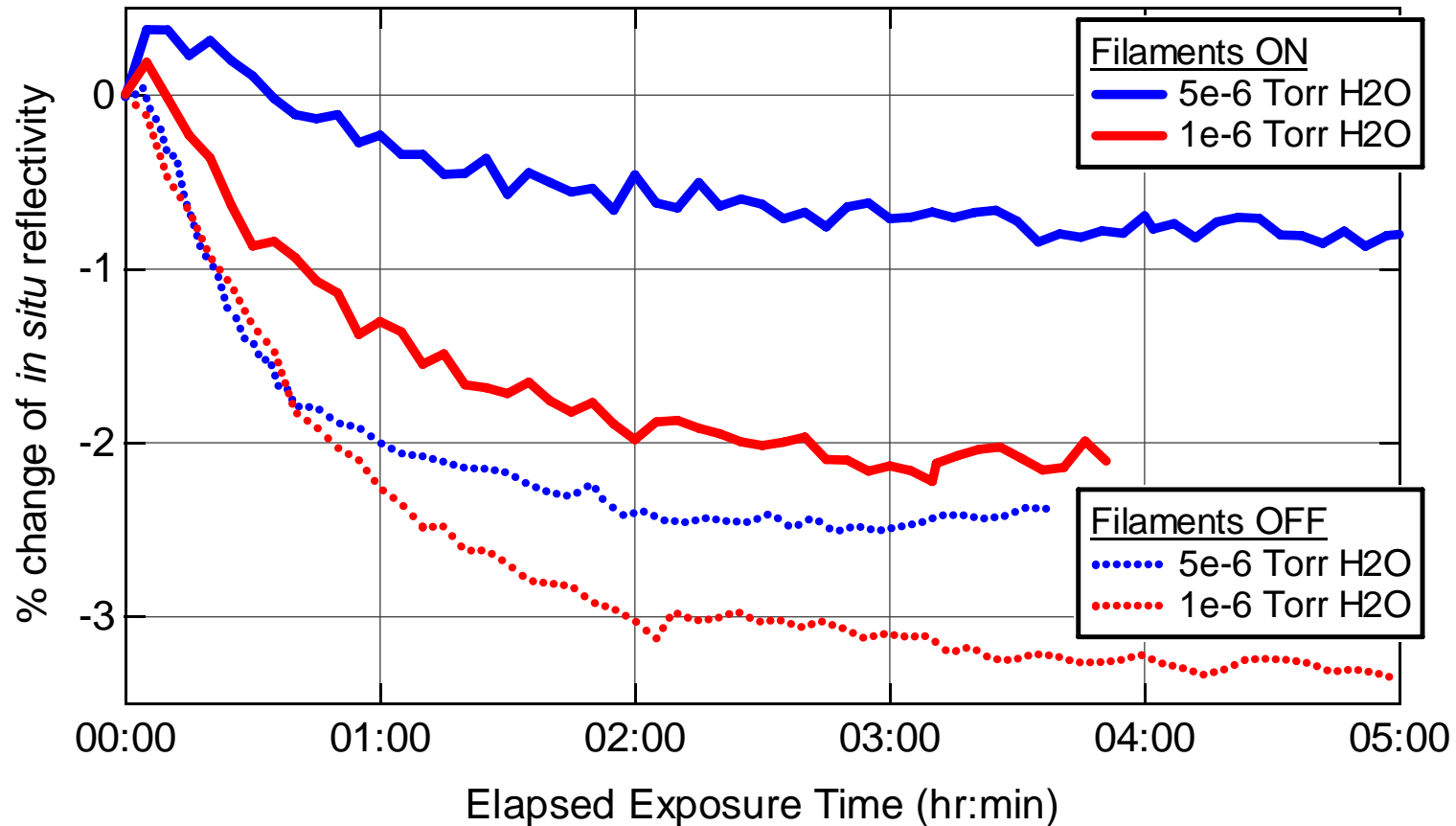


- Damage is measurably accelerated when filaments are switched off
- Hot filaments play critical role in damage processes
- Production of mitigating species: CO, CO₂ and/or perhaps H

Effect of filaments at different pressures



Effect of filaments at different pressures

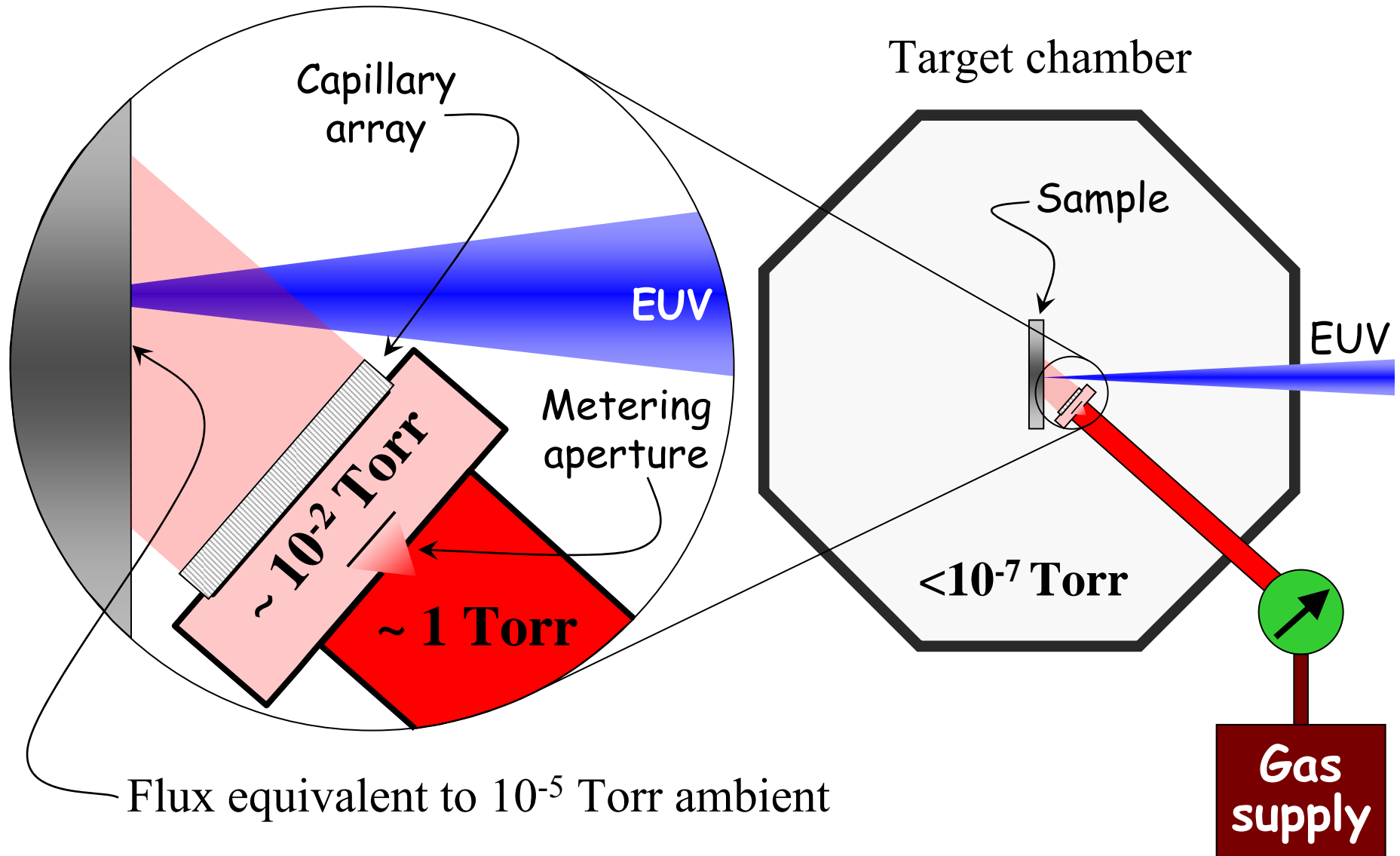


- Damage still greater for lower H₂O partial pressure, though less pronounced without filaments
- Suggests trace levels of mitigating species still present and active

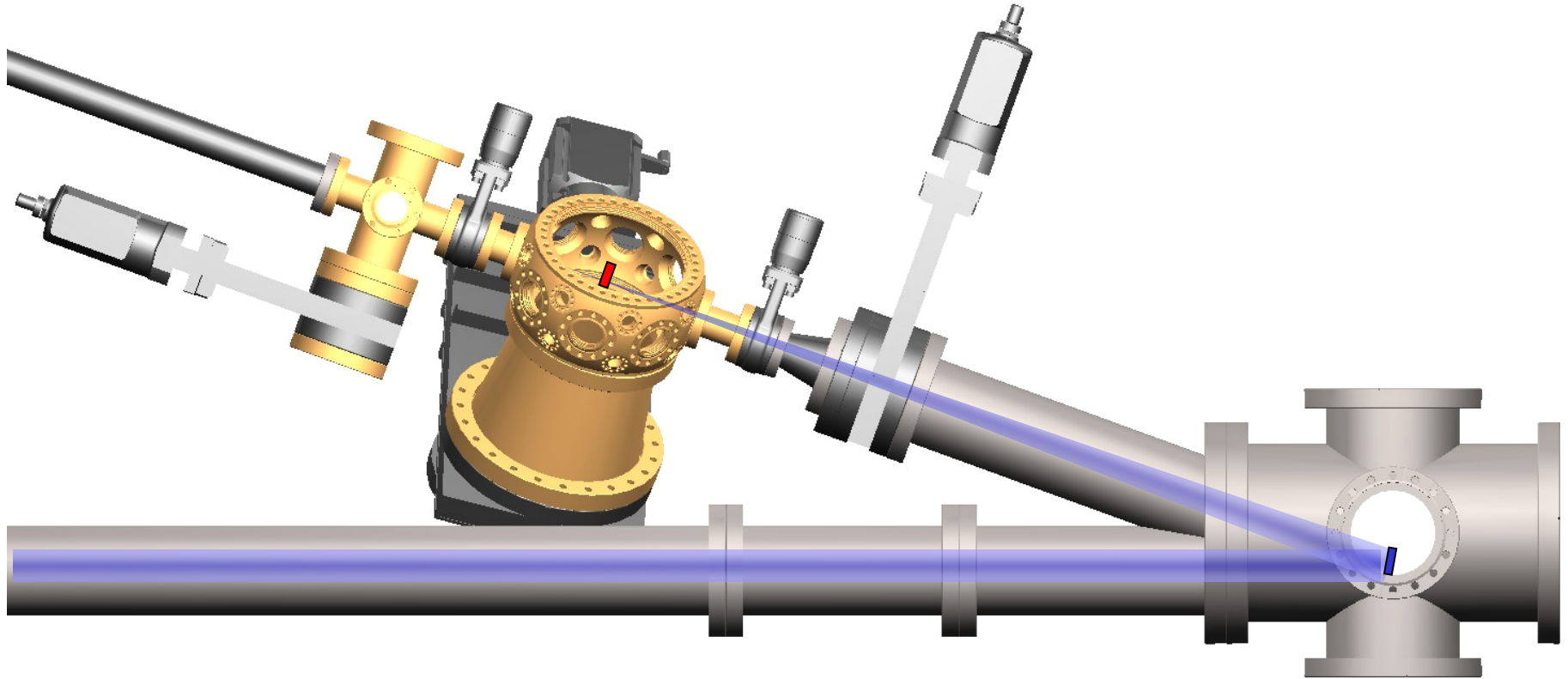
Preliminary indications and next steps

- *In situ* reflectivity can monitor initial evolution of damage
 - Verify with accurate reflectometry (next weeks)
- Observed mitigation attributed to low-mass species like CO, CO₂. **NOT** due to $m > 45$ amu hydrocarbons (e.g., $m = 55$)
 - Direct admission of CO and/or CO₂
- CO, CO₂ & possibly H produced by H₂O reacting with hot filaments significantly slows damage of Ru-cap MLs
 - Reflectometry of long exposure with and without filaments
- Mitigating C-species may result from water-induced desorption/displacement of C-compounds on chamber walls.
Common concern in surface science
 - Designing new, UHV bakable chamber
 - Use doser to reduce ambient pressure

Planned use of doser



New UHV exposure facility under construction



- Load lock: *cleanliness* and increased *throughput*
- Bake to 150-200 C
- Gold plate majority of chamber surface area
- Can accommodate two independent dosers
- Potential to heat and cool samples during exposure ($\sim 0-50$ C)

Future directions

- Continue to identify critical factors to establish well characterized exposure environment for benchmarking and capping layer development
- Investigate differences between pulsed and quasi-cw synchrotron exposures
- Commission third high intensity exposure facility
 - ~ 150 mW/mm² broadband
 - Also UHV design
 - Investigate intensity dependence for accelerated testing
- Collaborate to identify useful surface analysis techniques: e.g., IR, elastic ion backscatter, XPS, TOF-SIMS,...