Essential procedures for endurance testing of multi-layer mirrors

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questions

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Outline

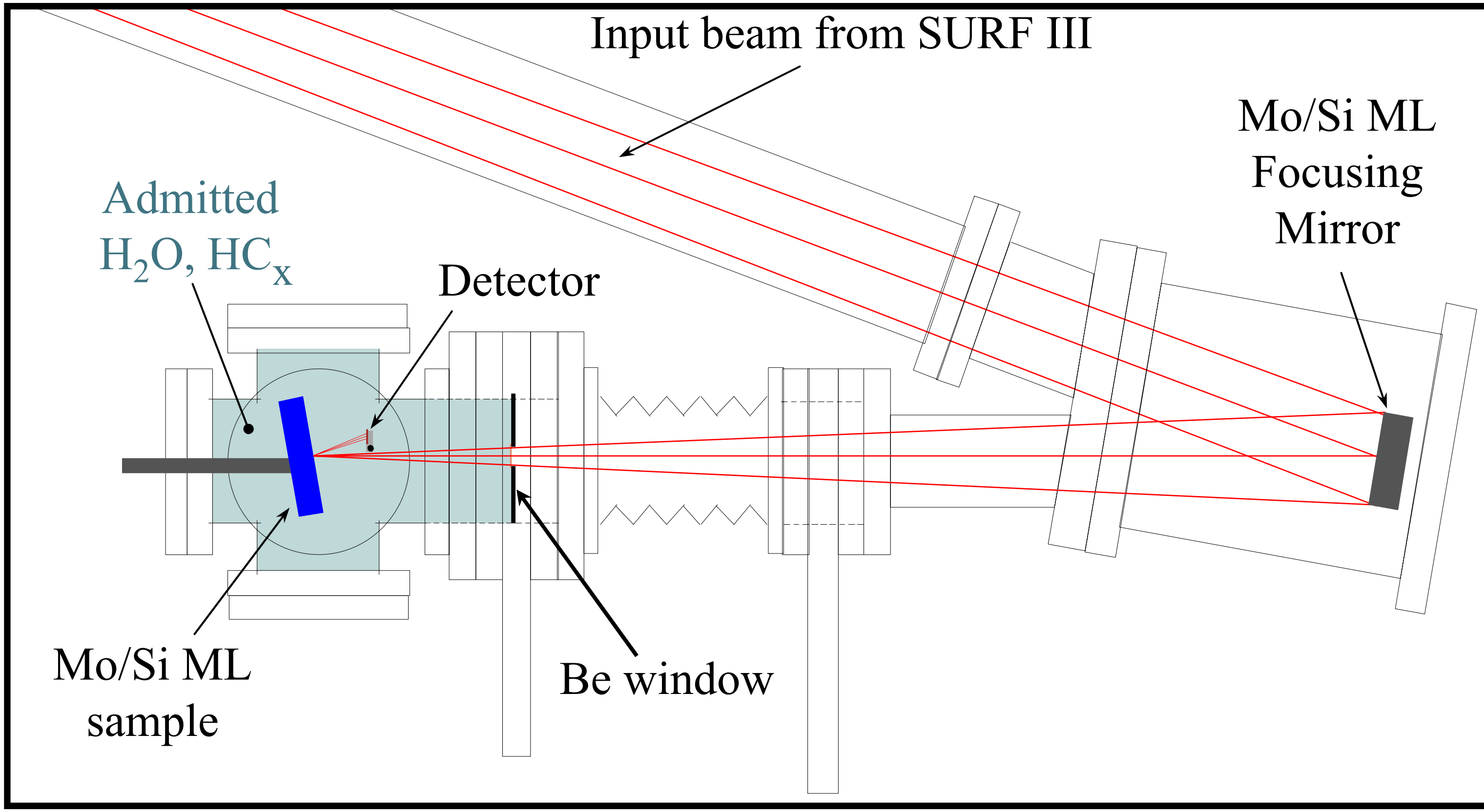
- Describe original and new NIST endurance testing facilities
- Review previous results and hypotheses for degradation of Ru-capped multilayers. (Fabricated by Saša Bajt, LLNL)†
- Discuss impact of recent exposures
- Outline remaining and new questions
- Discuss future work and direction of endurance testing of MLMs.

† This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48

NIST Objective

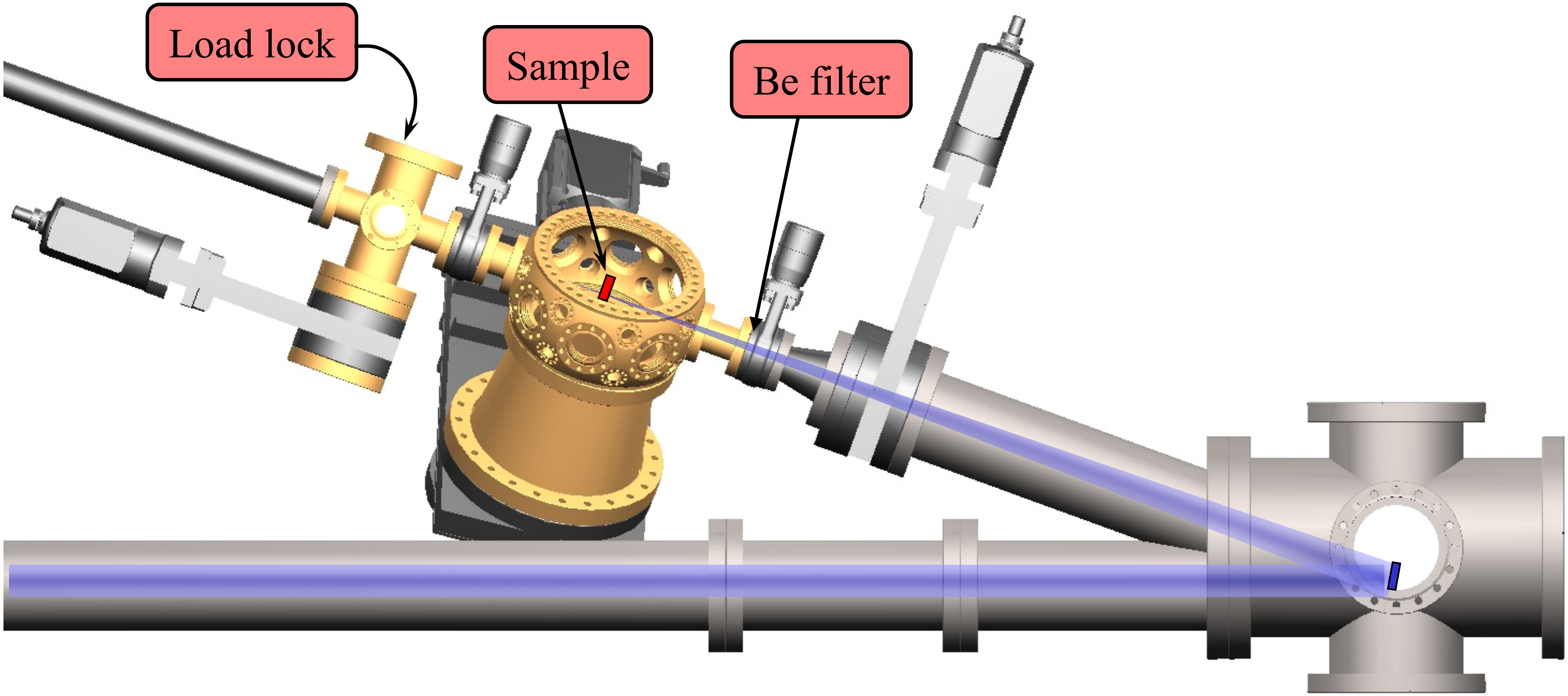
Establish *well characterized* endurance-testing facilities for rapid feedback to capping-layer-development community, with goal of establishing standardized accelerated lifetime testing.

First EUV endurance testing facility at NIST



- Gaussian focal spot ~ 650μm × 650μm (FWHM) at sample
- Average, in-band (13.1-13.6nm) intensity 5-6 mW/mm^2
- Be window permits high water vapor pressures: $P_{H_2O} \leq 10^{-5}$ Torr
- Automation upgrades increased exposure duty cycle ~24 hrs/day

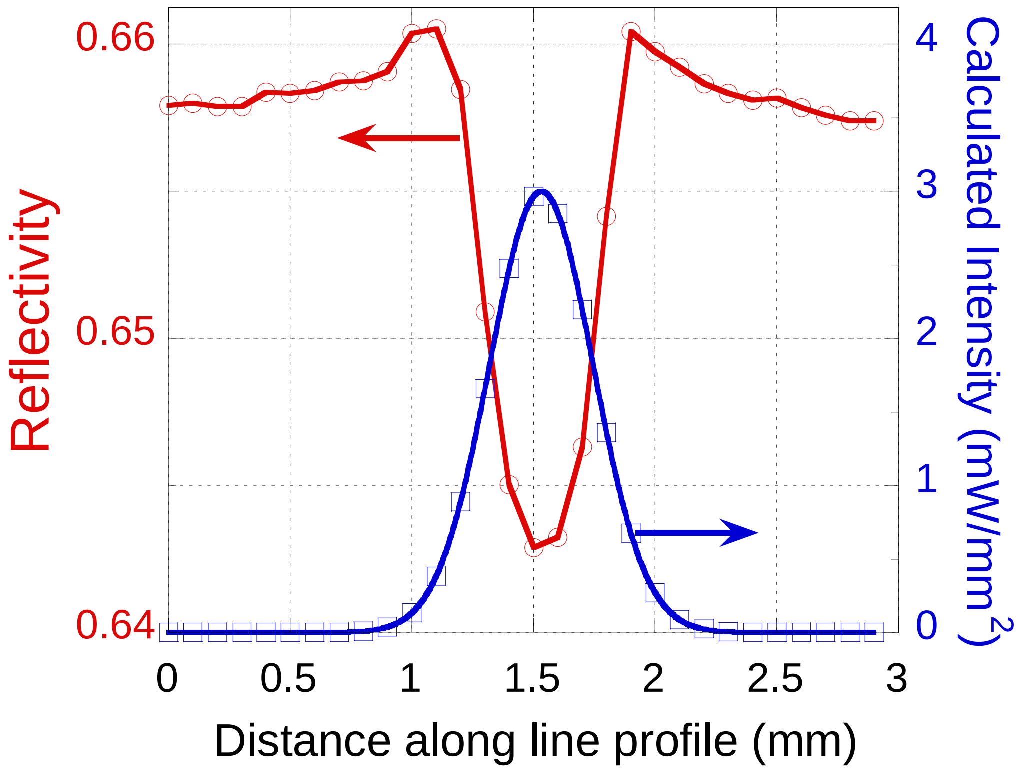
New UHV exposure facility

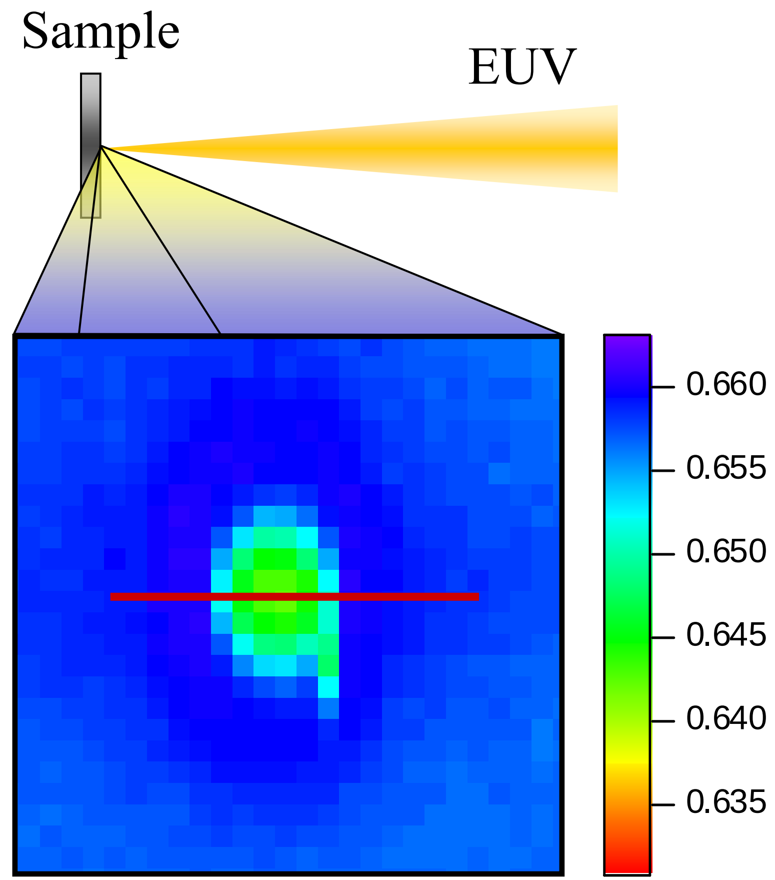


- Gaussian focal spot ~ 915µm × 717µm (FWHM) at sample
- Average, in-band (13.1-13.6nm) intensity 5-6 mW/mm^2
- Load lock increases throughput and cleanliness
- Bake to 150-200º C
- Potential to heat and cool samples during exposure (0-50º C)

Post exposure analysis

Line profile of reflectivity map
& EUV intensity distribution





13.5nm reflectivity map

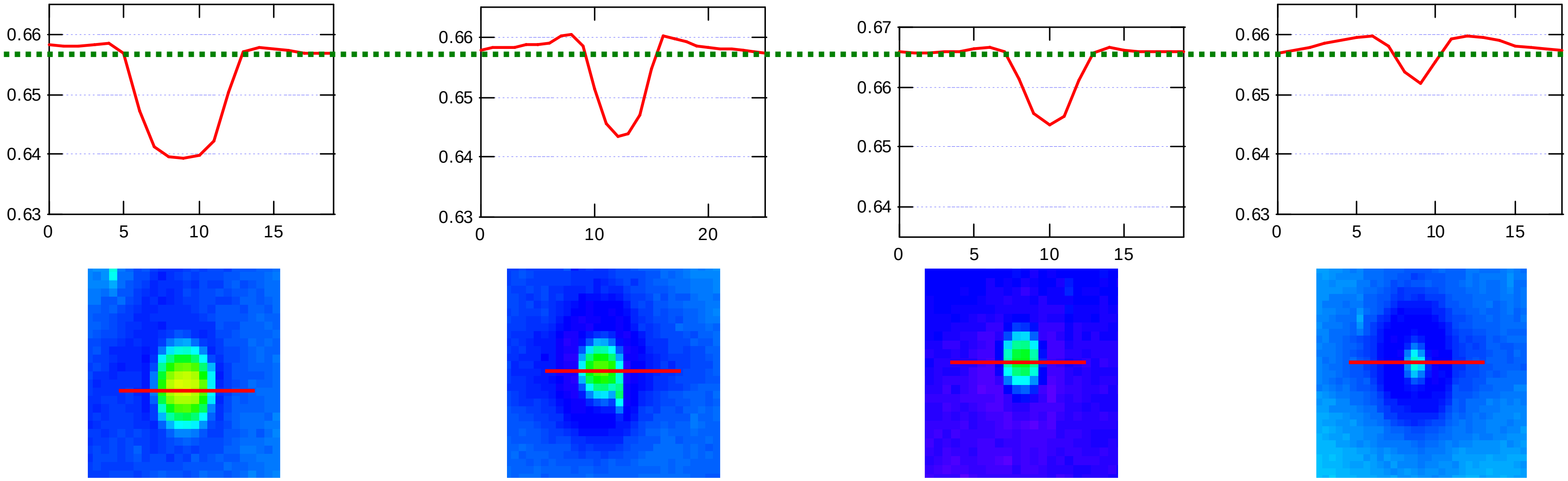
Reflectometry performed by Eric Gullikson at ALS, Berkeley, CA

Unexpected damage dependence on H_2O pressure

(Early 2005)

Reflectivity loss *decreases* with *increasing* water pressure

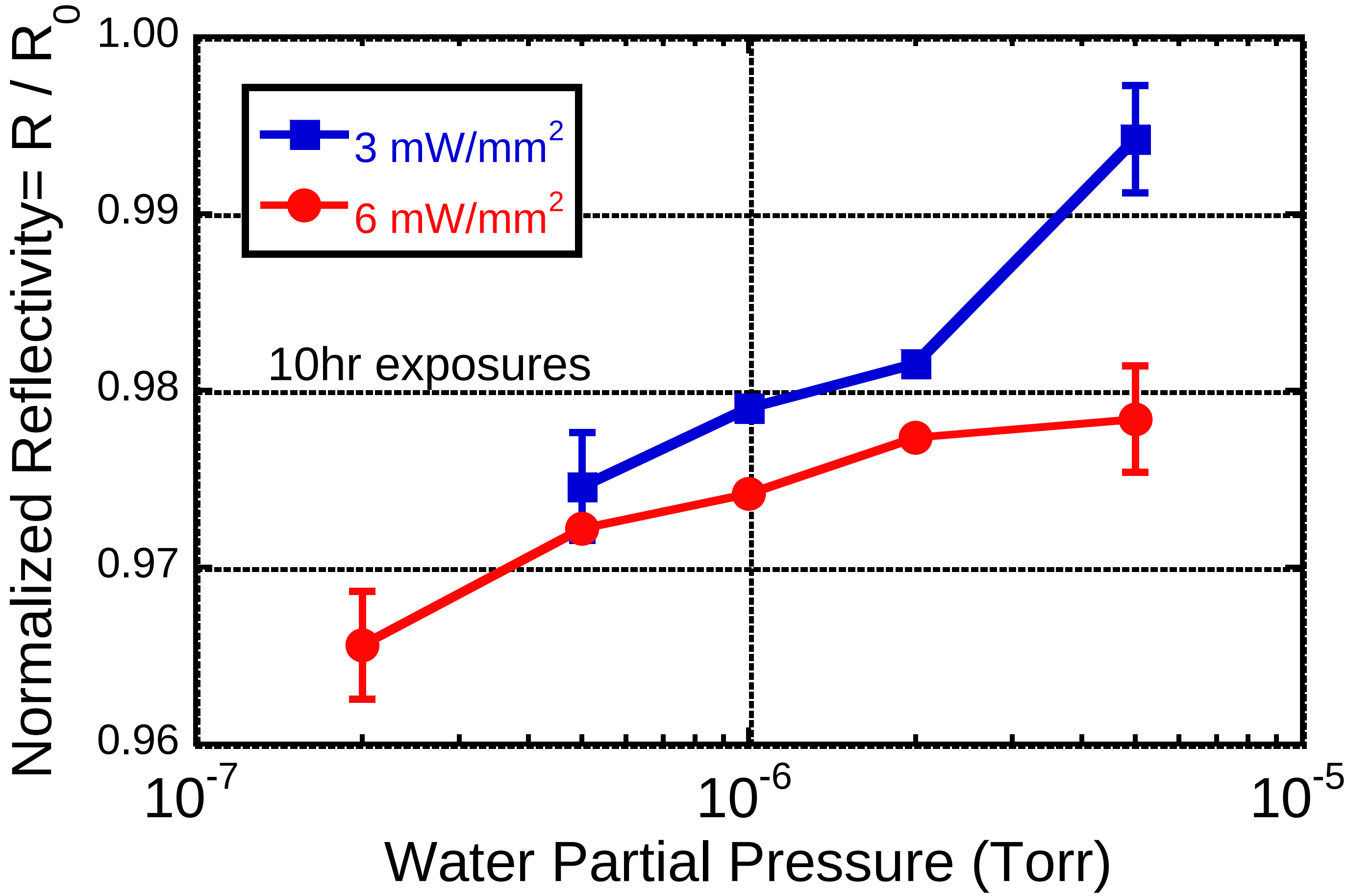
10hr Exposures at **Half Max Intensity** (~3 mW/mm^2)



5×10^{-7} Torr H_2O | **1×10^{-6} Torr H_2O** | **2×10^{-6} Torr H_2O** | **5×10^{-6} Torr H_2O**

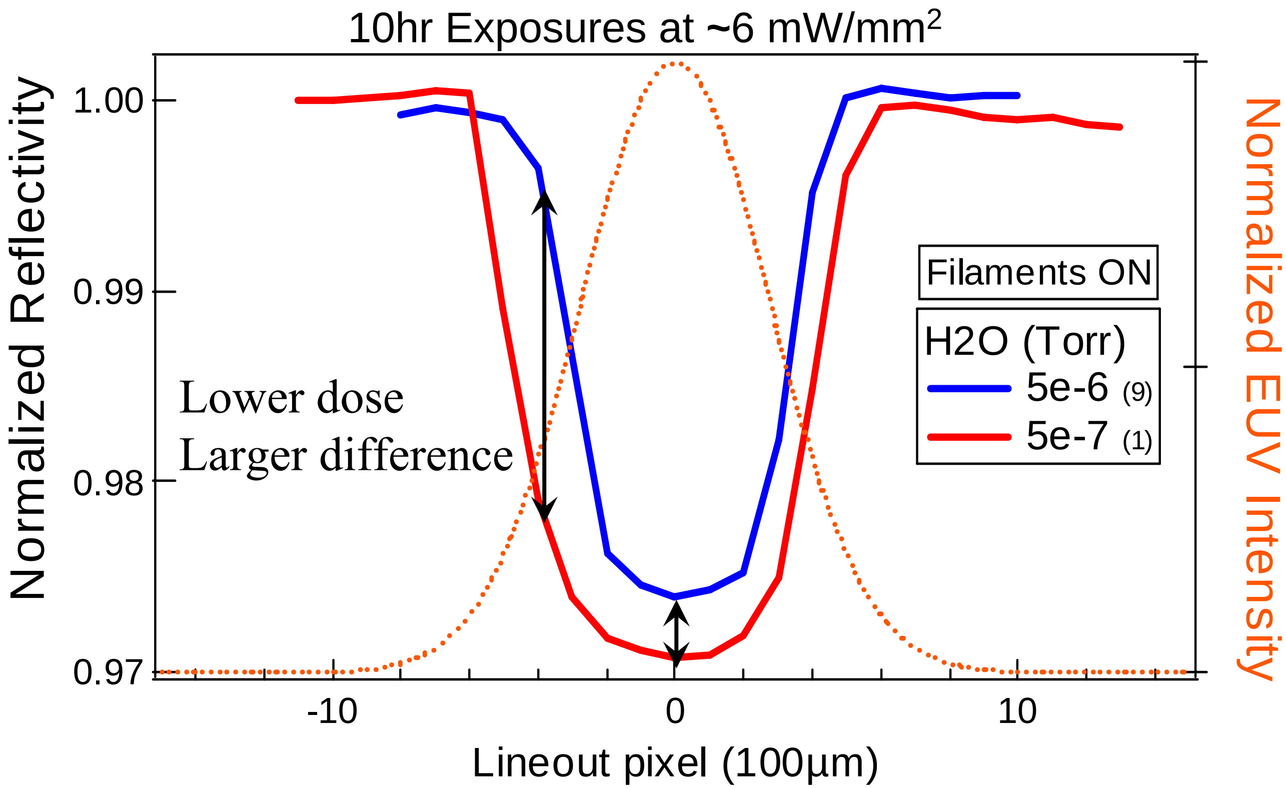
Increasing **water vapor pressure**

Peak reflectivity loss decreases with H_2O level
(Early 2005)



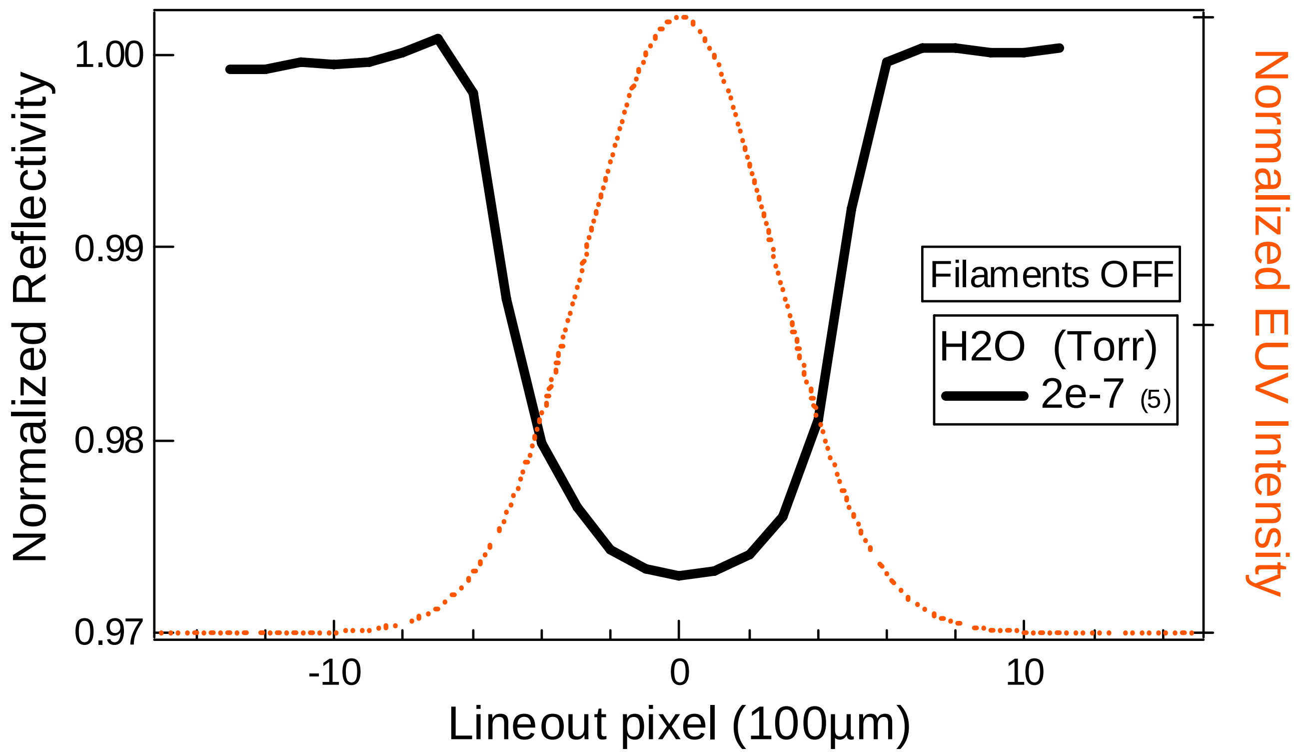
- Inverse damage dependence on H_2O pressure more pronounced at lower doses

Confirm increasing damage with decreasing H_2O pressure *(Mid 2006)*



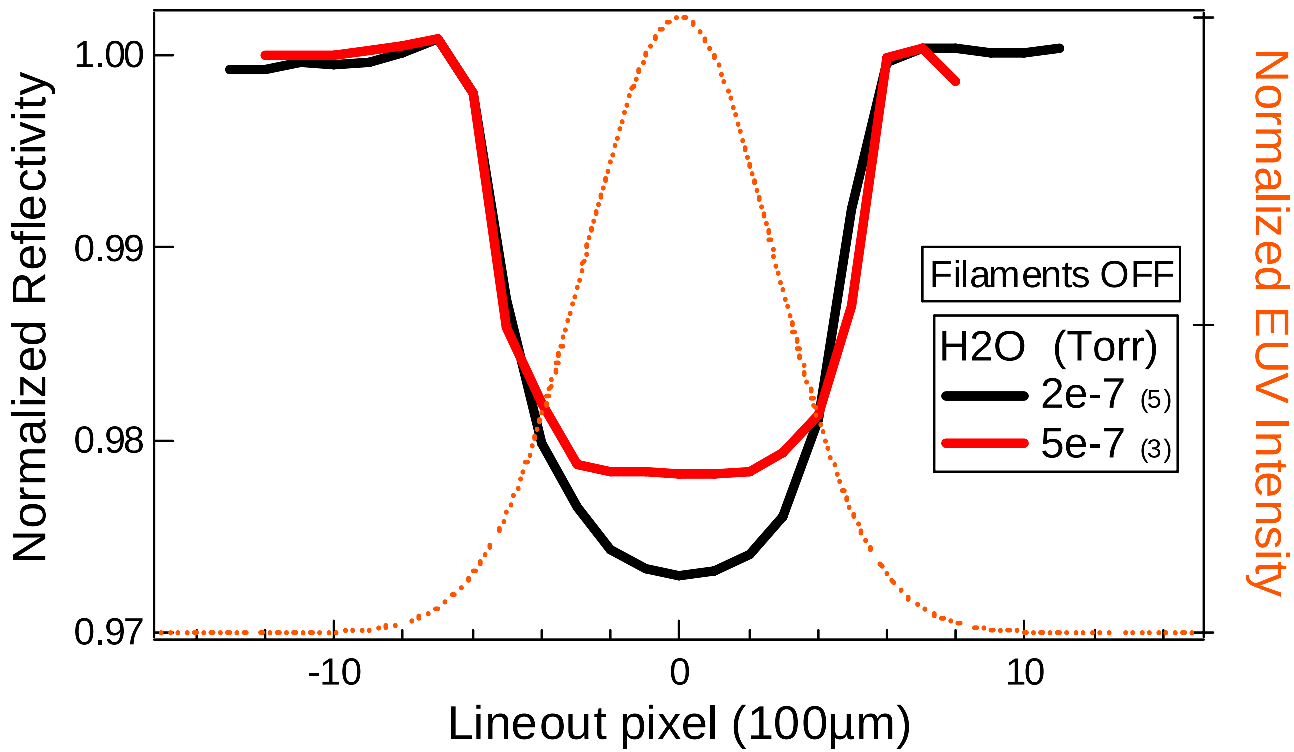
- Exposures in new chamber exhibit similar inverse H_2O dependence
- All previous exposures conducted with ion gauge and RGA filaments on
- Try turning filaments off since they may be affecting damage process

Damage profiles with filaments OFF



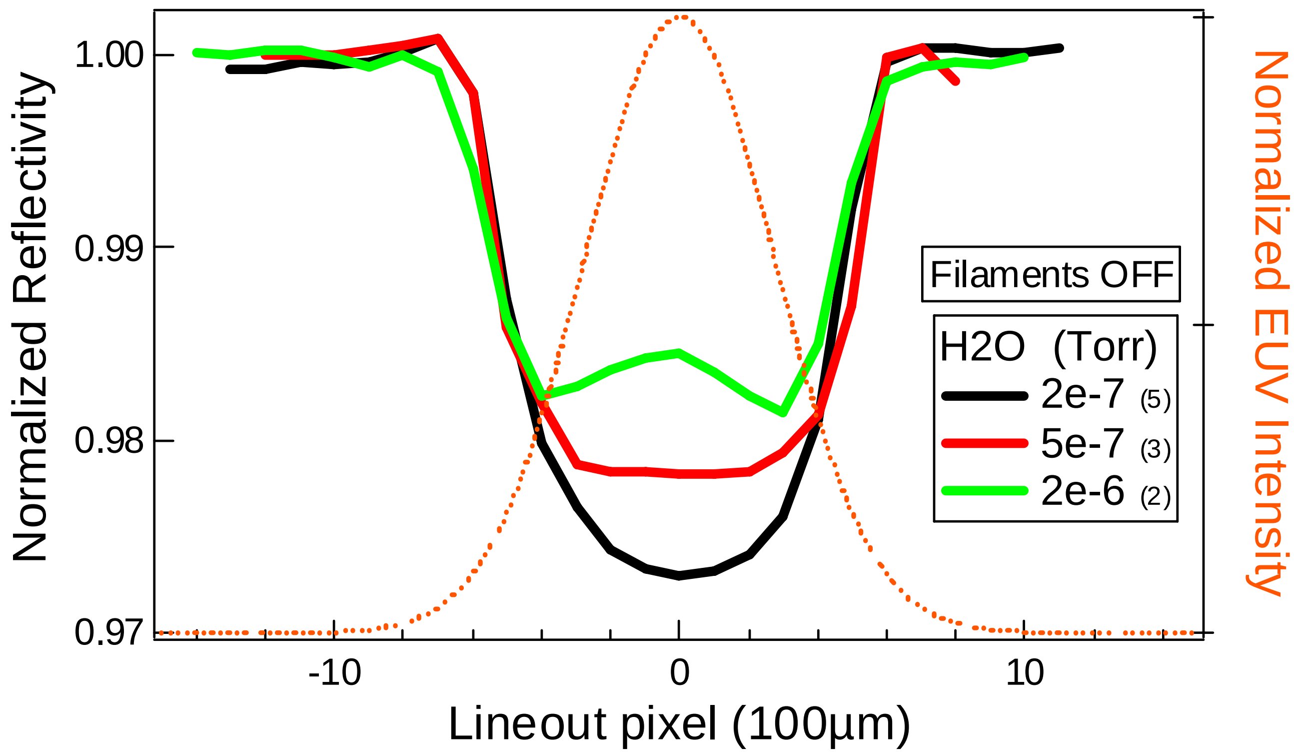
- All 10hr, ~6mW/mm² (170-190 J/mm²) exposures on same sample of Ru-capped ML

Damage profiles with filaments OFF



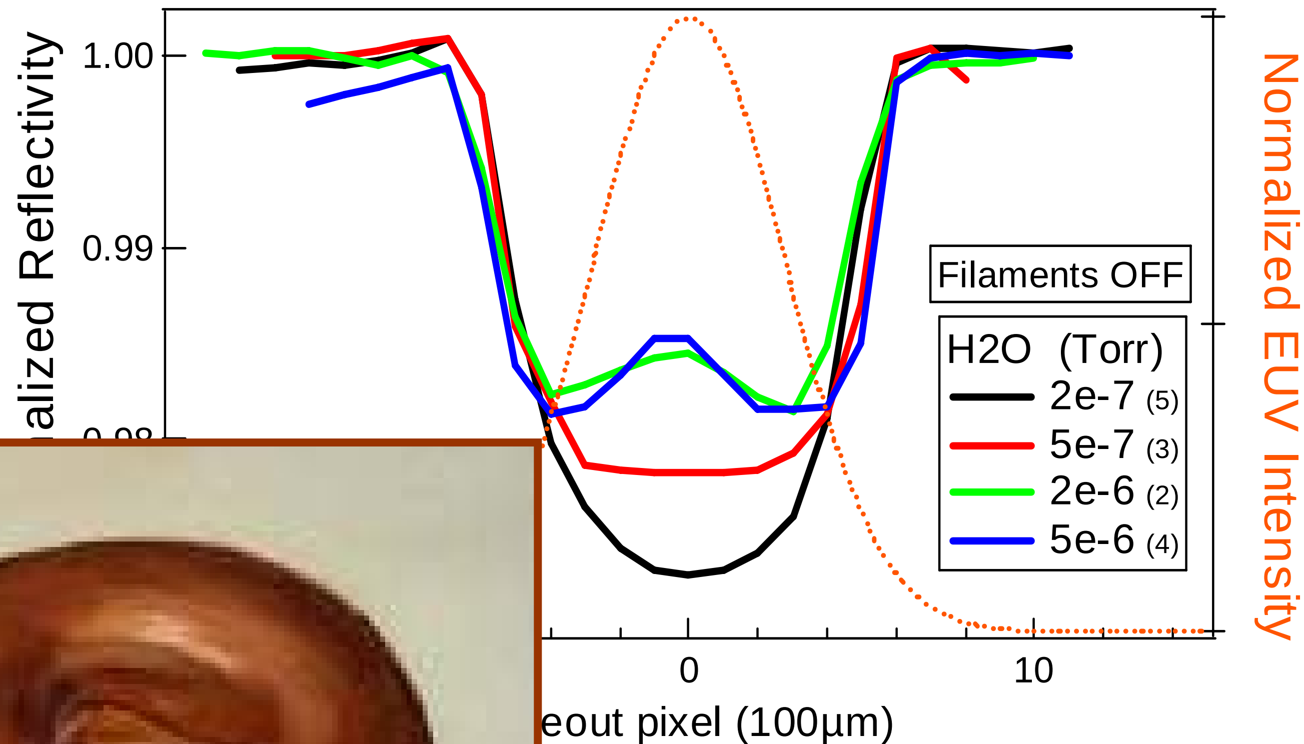
- All 10hr, ~6mW/mm² (170-190 J/mm²) exposures on same sample of Ru-capped ML

Damage profiles with filaments OFF



- All 10hr, ~6mW/mm² (170-190 J/mm²) exposures on same sample of Ru-capped ML

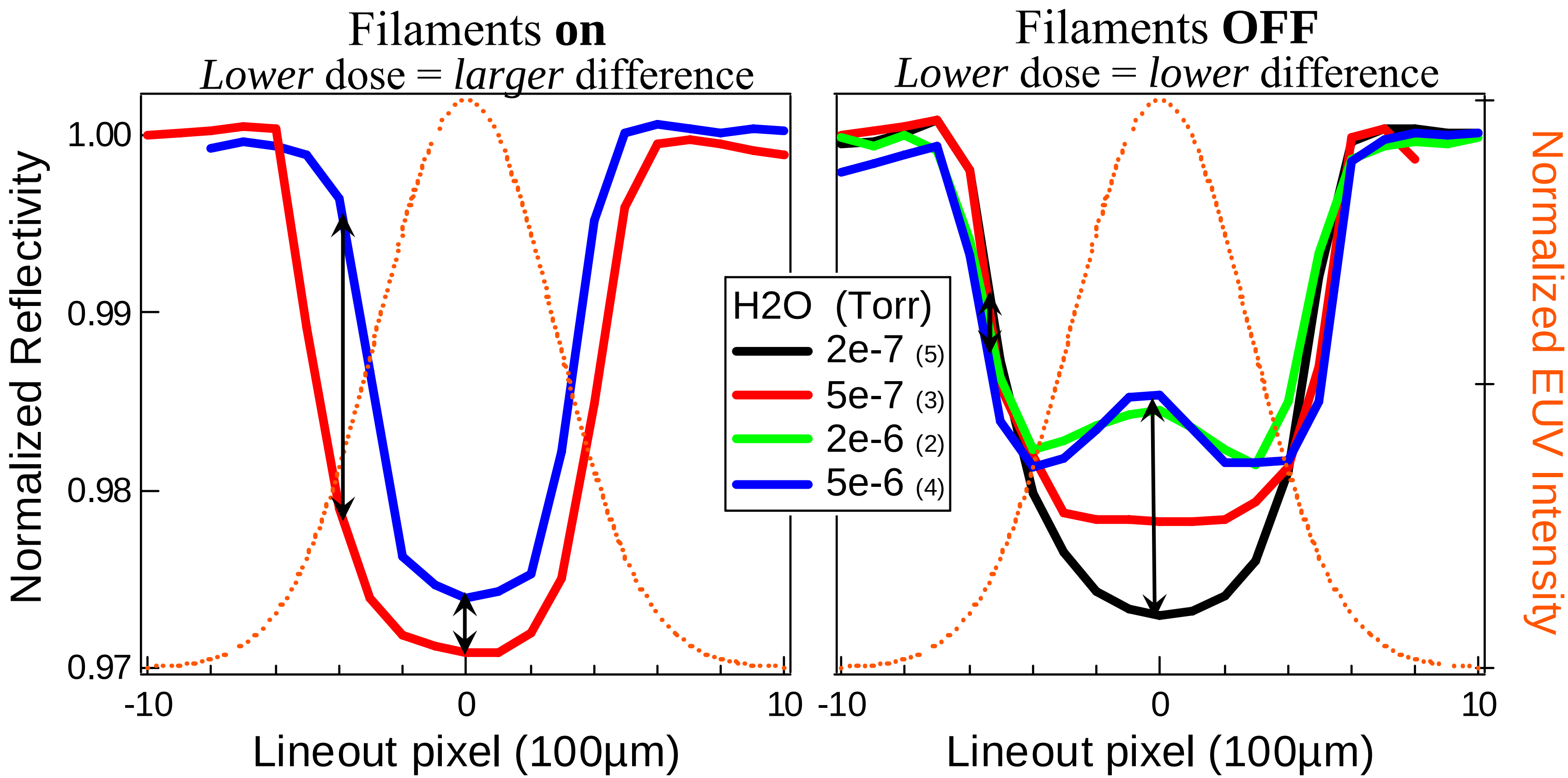
Damage profiles with filaments OFF



m²) exposures on same sample of Ru-capped ML

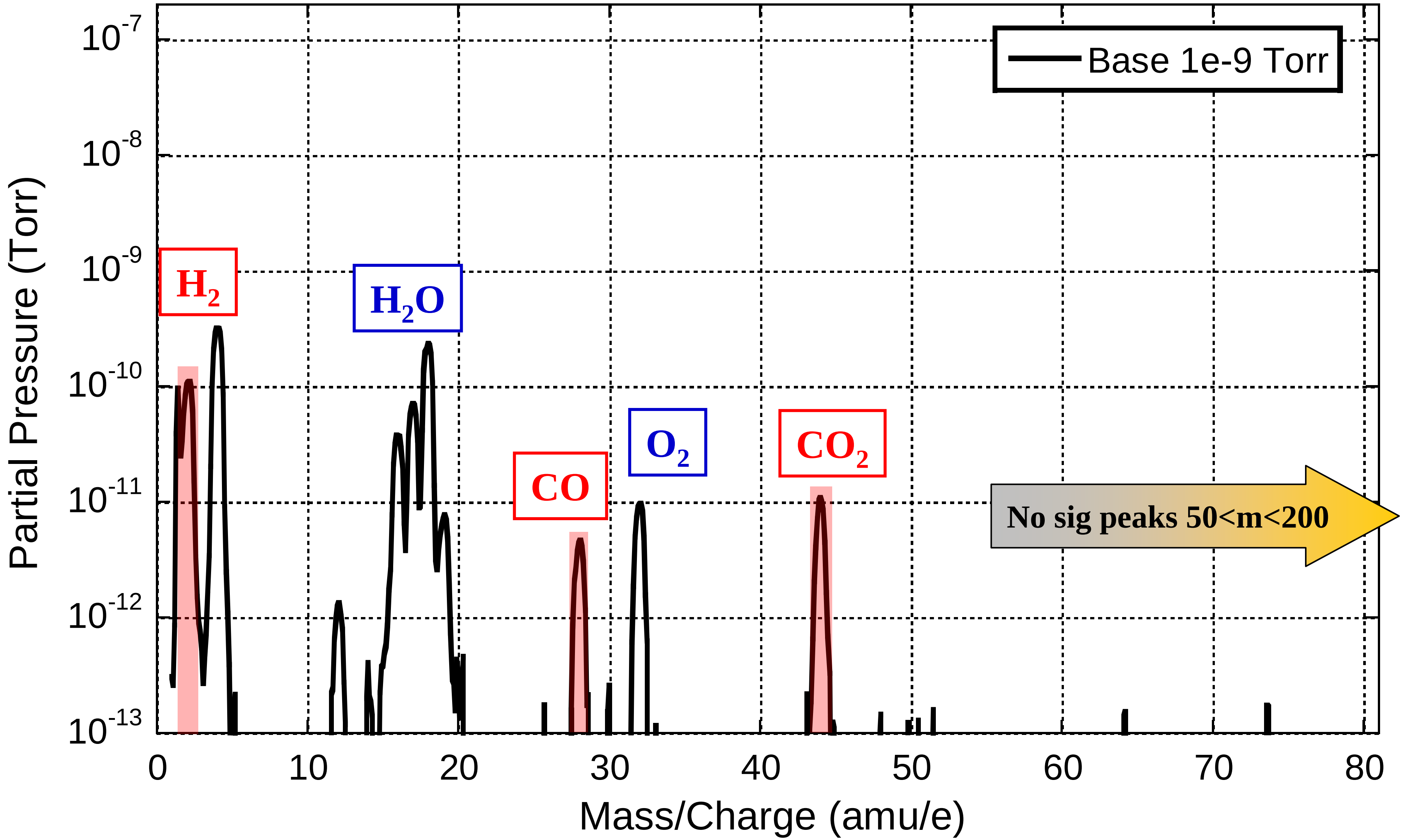
ibution at high H_2O pressures

Effect of filaments on damage rates

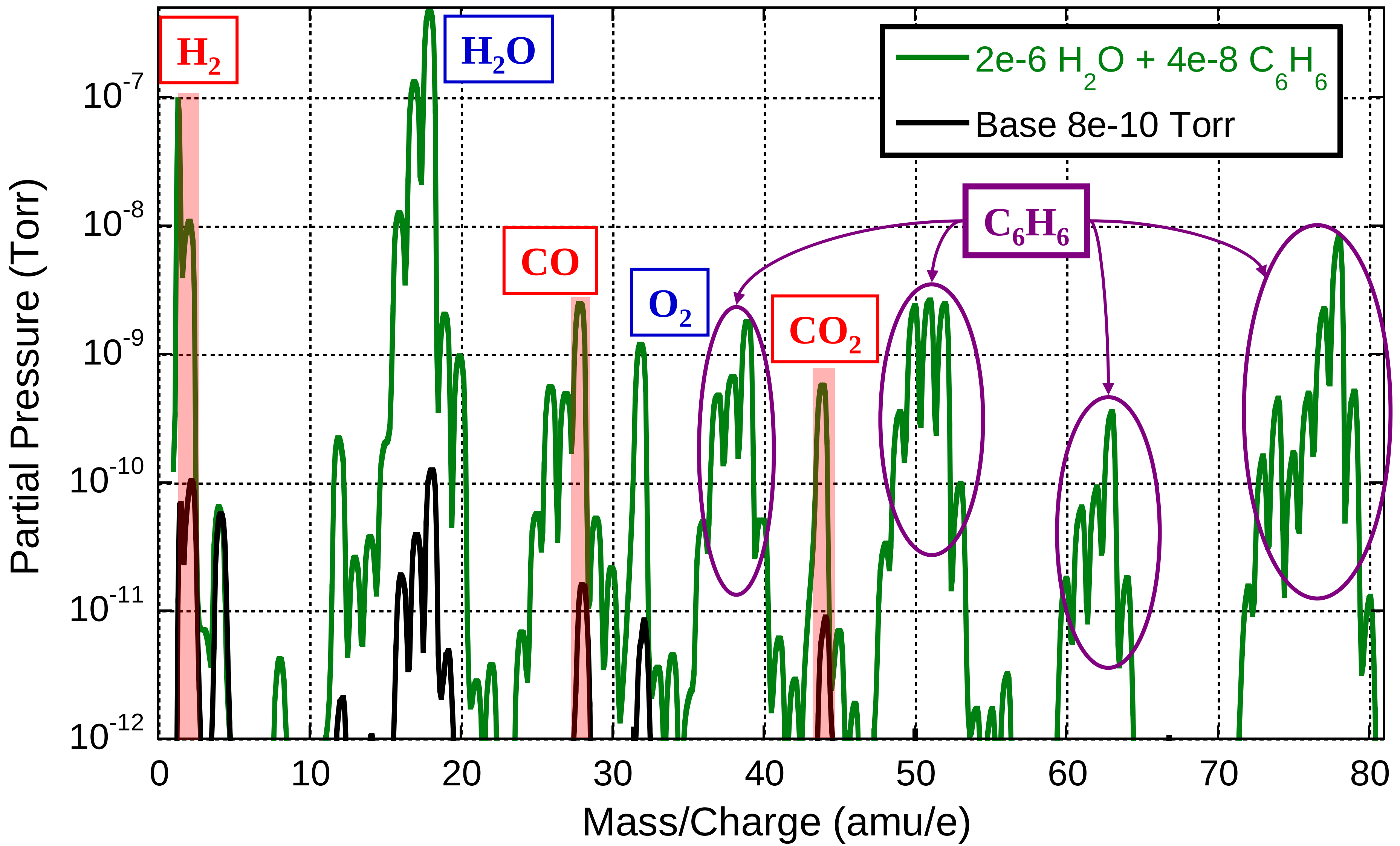


- All 10hr (170-190 J/mm²) exposures on same sample of Ru-capped ML
- Similar "donut" effect observed in new chamber with different filament placement
- Interaction of H_2O and hot filaments increase CO and CO_2 pressures in both chambers. (T. E. Madey, J. Vac. Sci. Technol. A5 (1987) 3249)

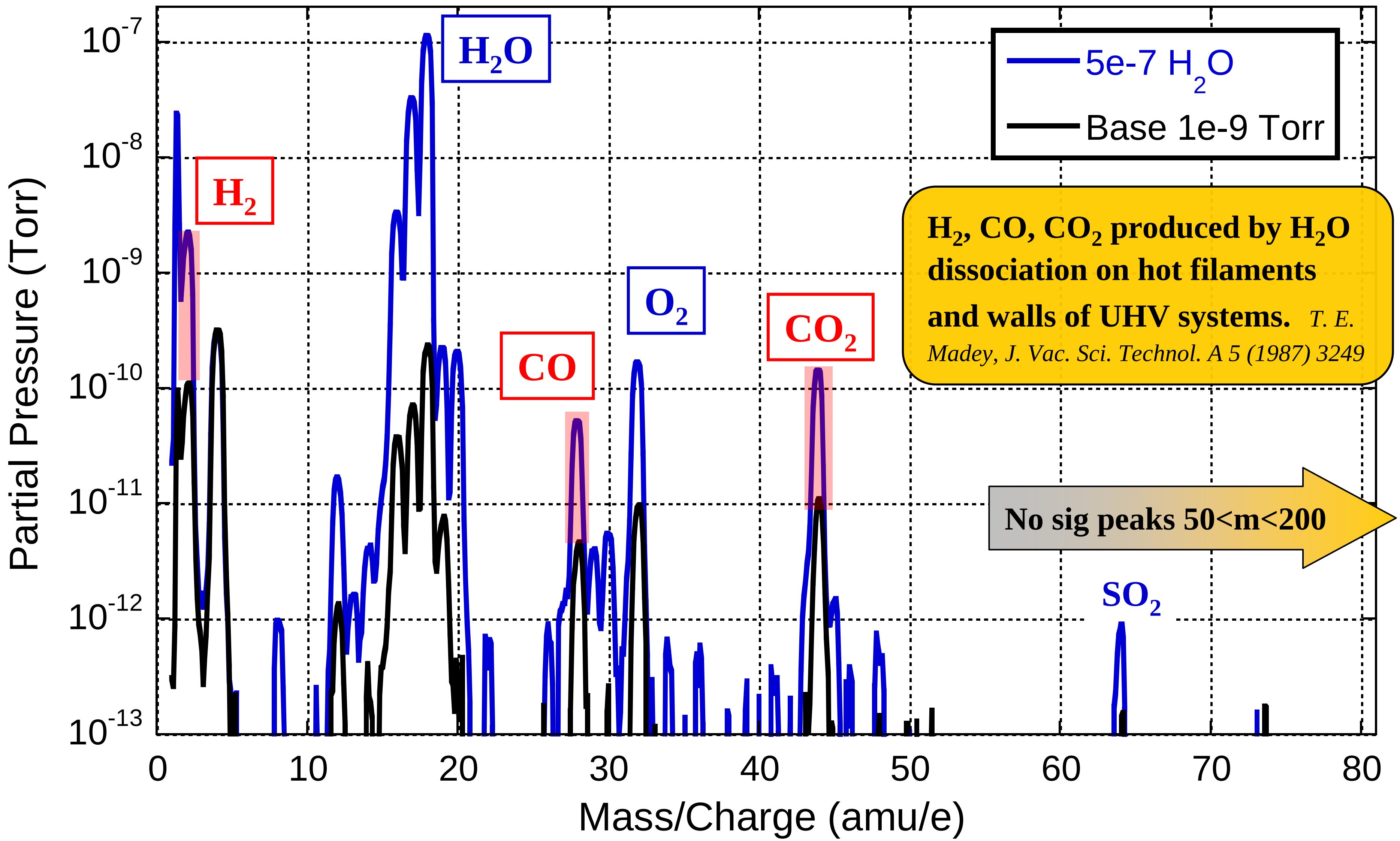
Other than H_2O, near-UHV vacuum conditions



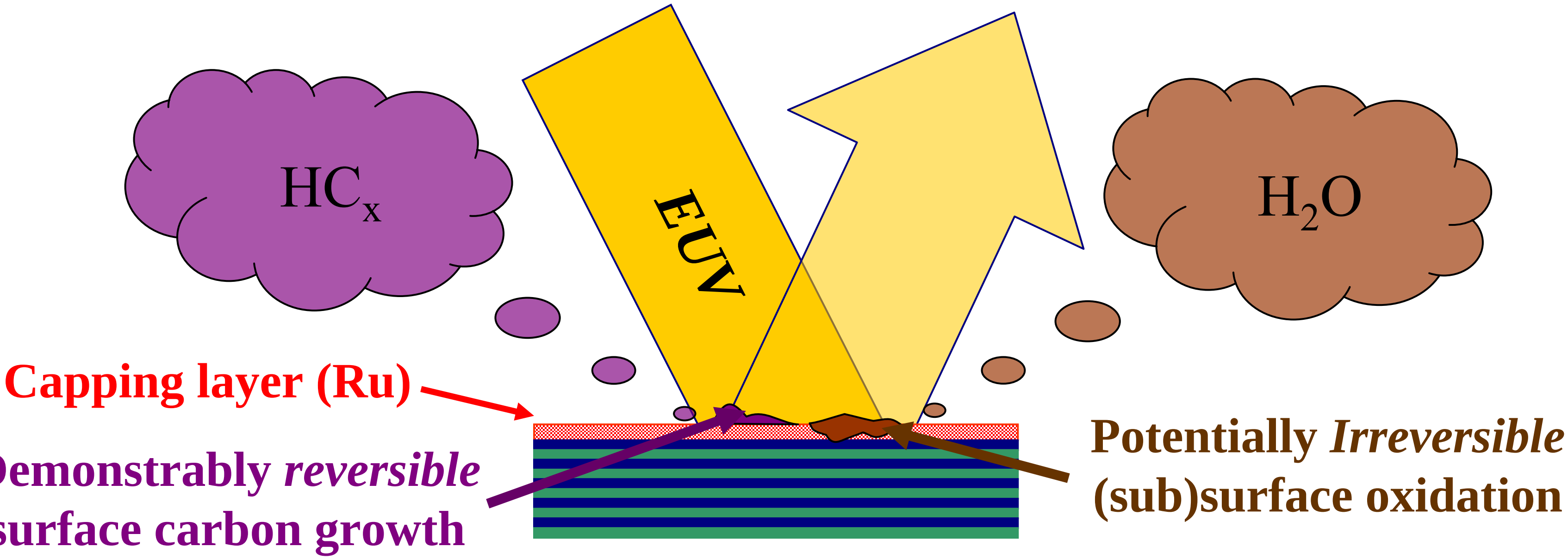
Confirm high-mass sensitivity of QMS



Other than H_2O, near-UHV vacuum conditions

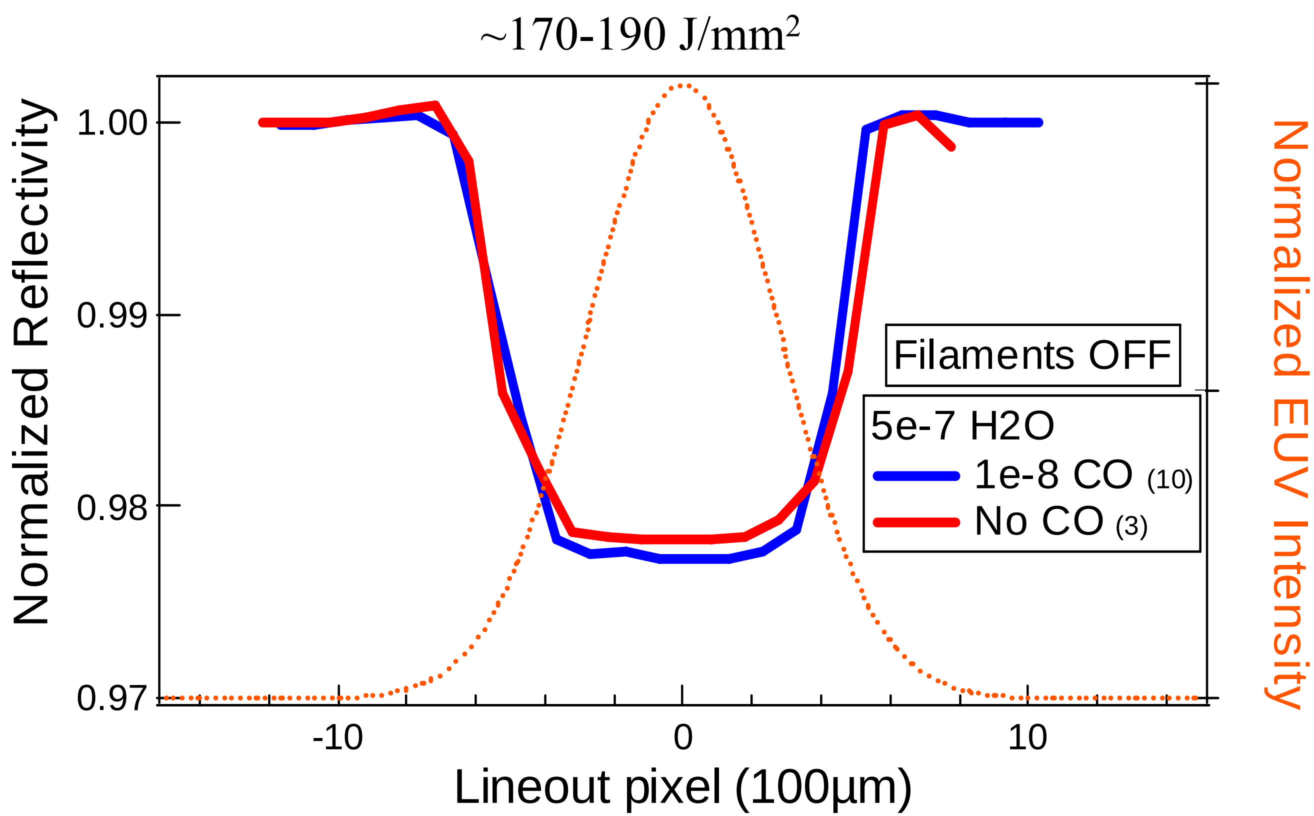


Original hypothesis:
Damage caused by two competing processes



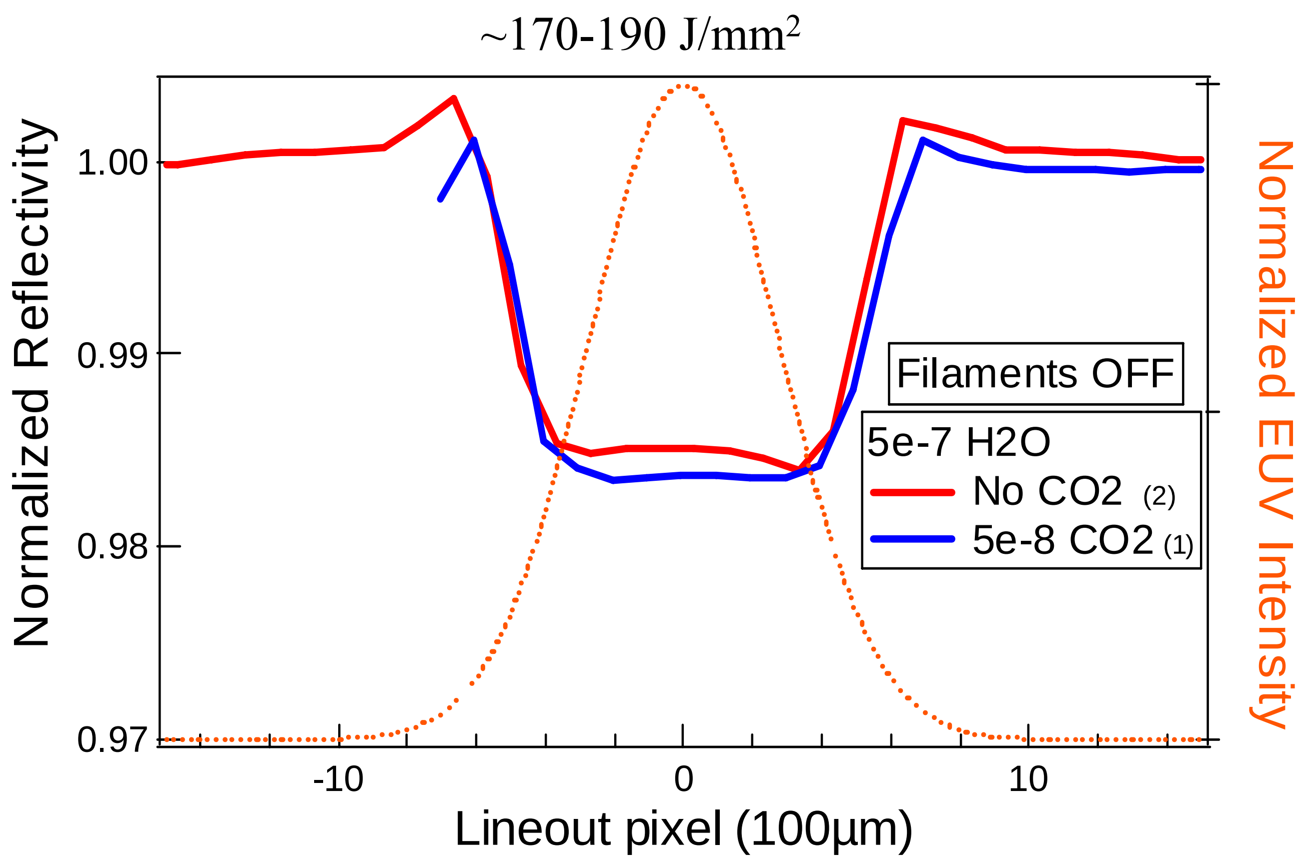
- *Hypothesis*: Competing oxidation and carbon-growth processes evolve differently with EUV dose and depend differently on pressure of carbonaceous species.
- 2×10^{-8} Torr methanol prevents measurable damage for 10hr exposure in 10^{-6} H_2O
- Ethanol also mitigates H_2O + EUV damage
  - L.E. Klebanoff, *et al*, J. Vac. Sci. Technol. **A22(2),** 425 (2004)
  - Masahito Niibe, poster 02-CC-13
- Can CO and CO_2 have similar mitigating effects?

10hr exposures in admitted $CO+H_2O$



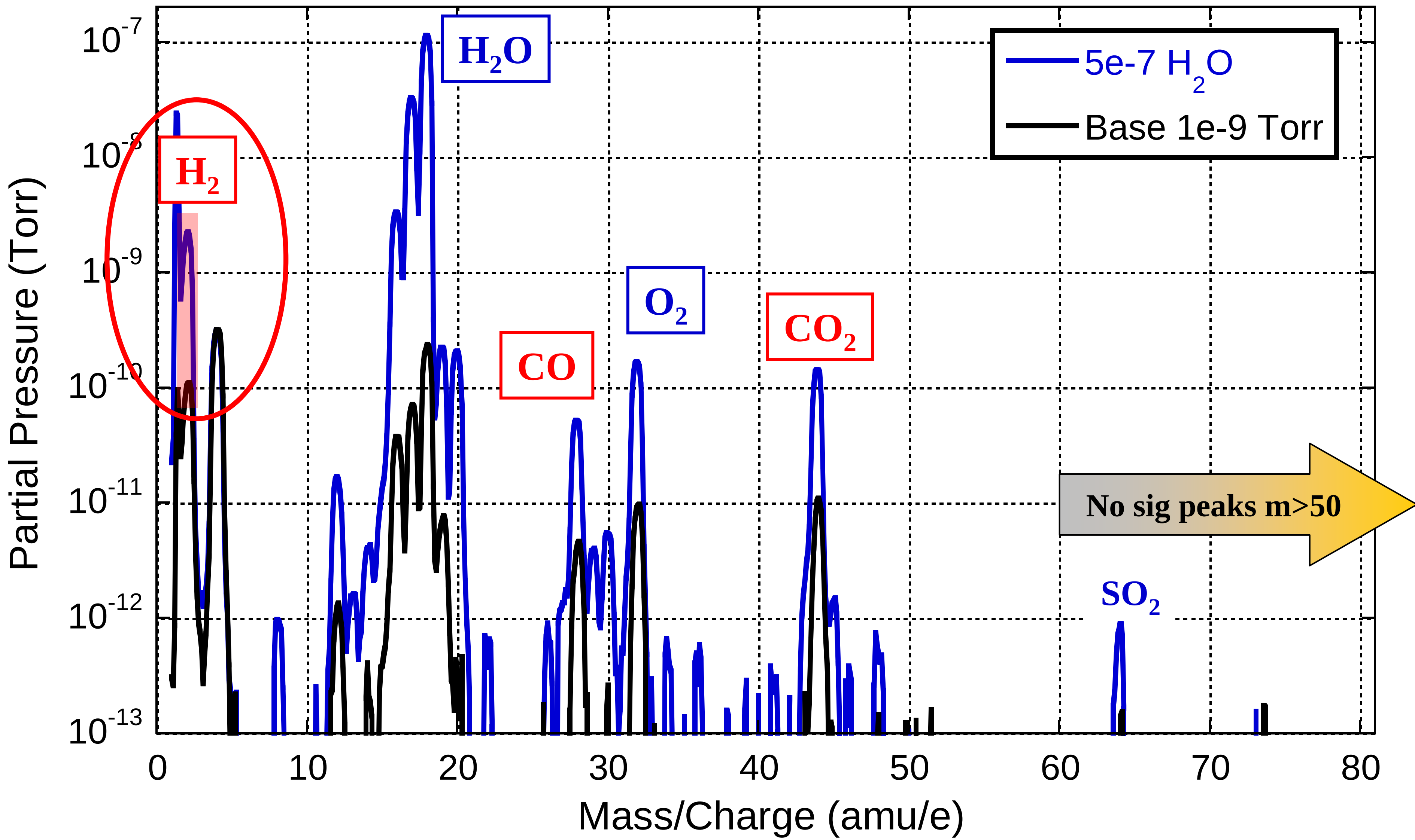
- CO partial pressure >10 times residual level produced by H_2O-chamber interactions.
- CO admixture does not affect EUV damage rate in $5\times(10^{-7}-10^{-6})$ Torr H_2O

10hr exposures in admitted CO_2+H_2O

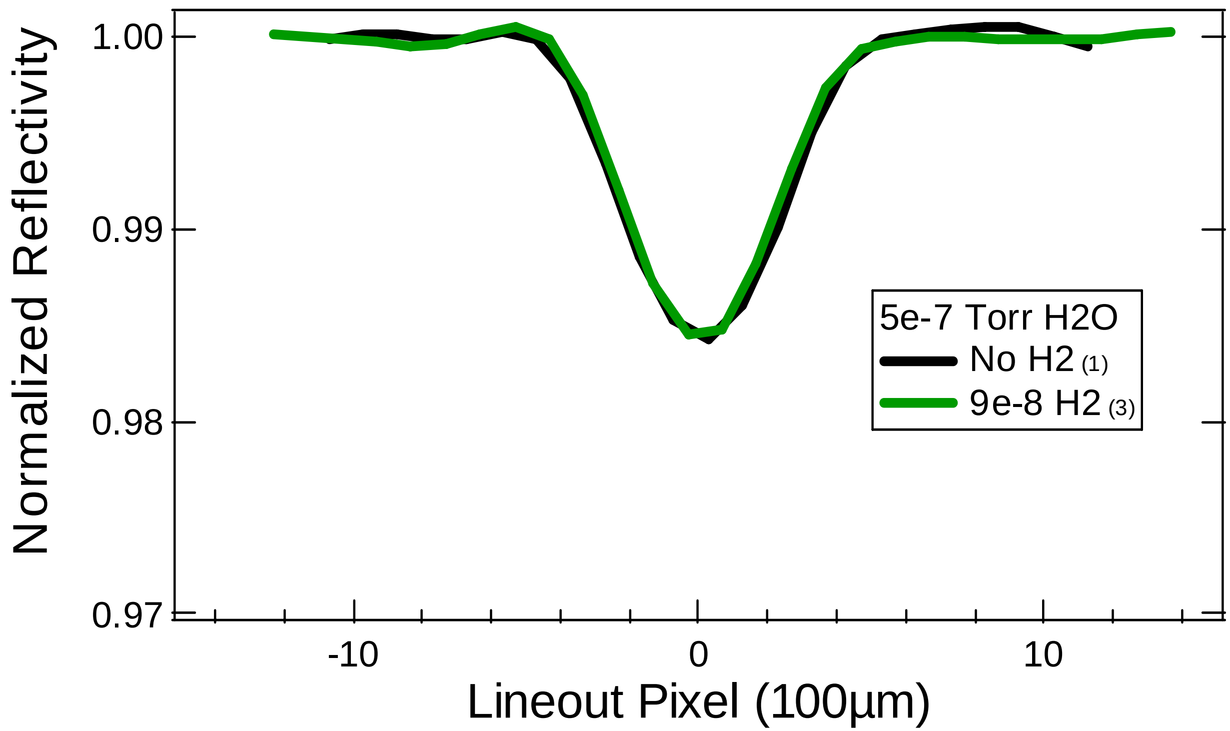


- CO_2 partial pressure ~50 times residual level produced by H_2O-chamber interactions.
- CO_2 admixture does not affect EUV damage rate in $5\times(10^{-7}\text{-}10^{-6})$ Torr H_2O

Other than H_2O, near-UHV vacuum conditions

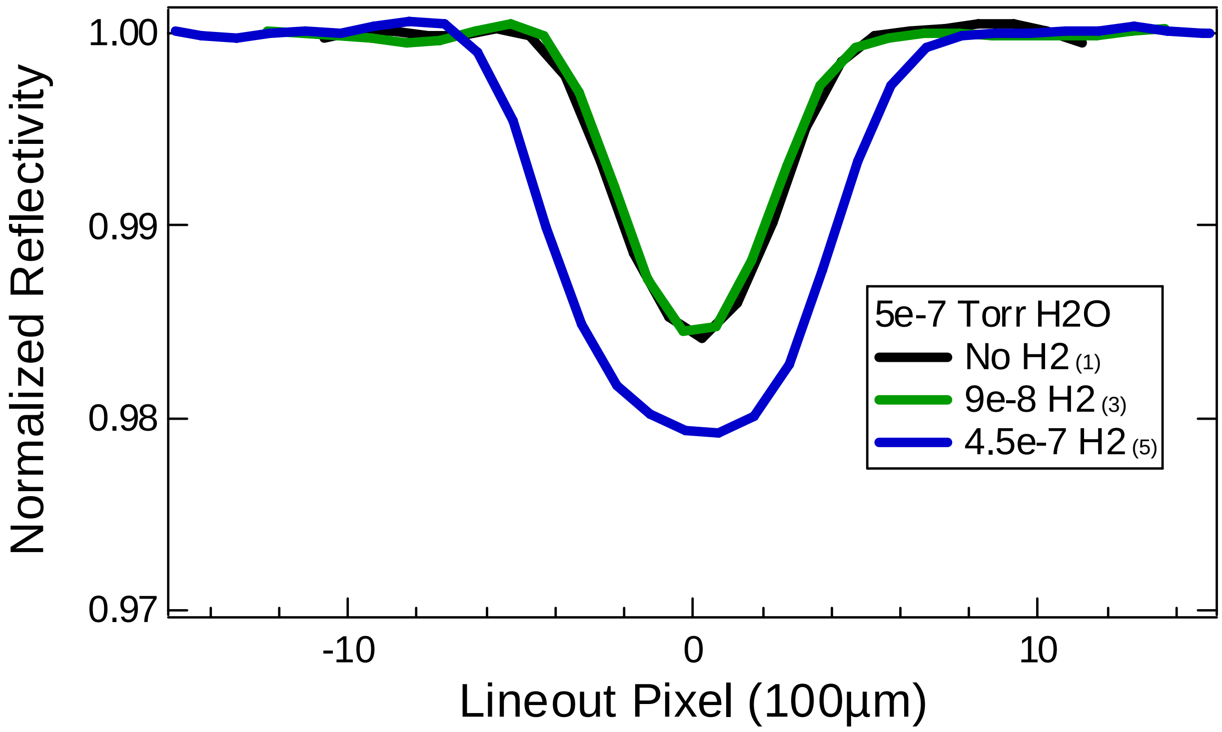


10hr exposures in admitted H_2+H_2O



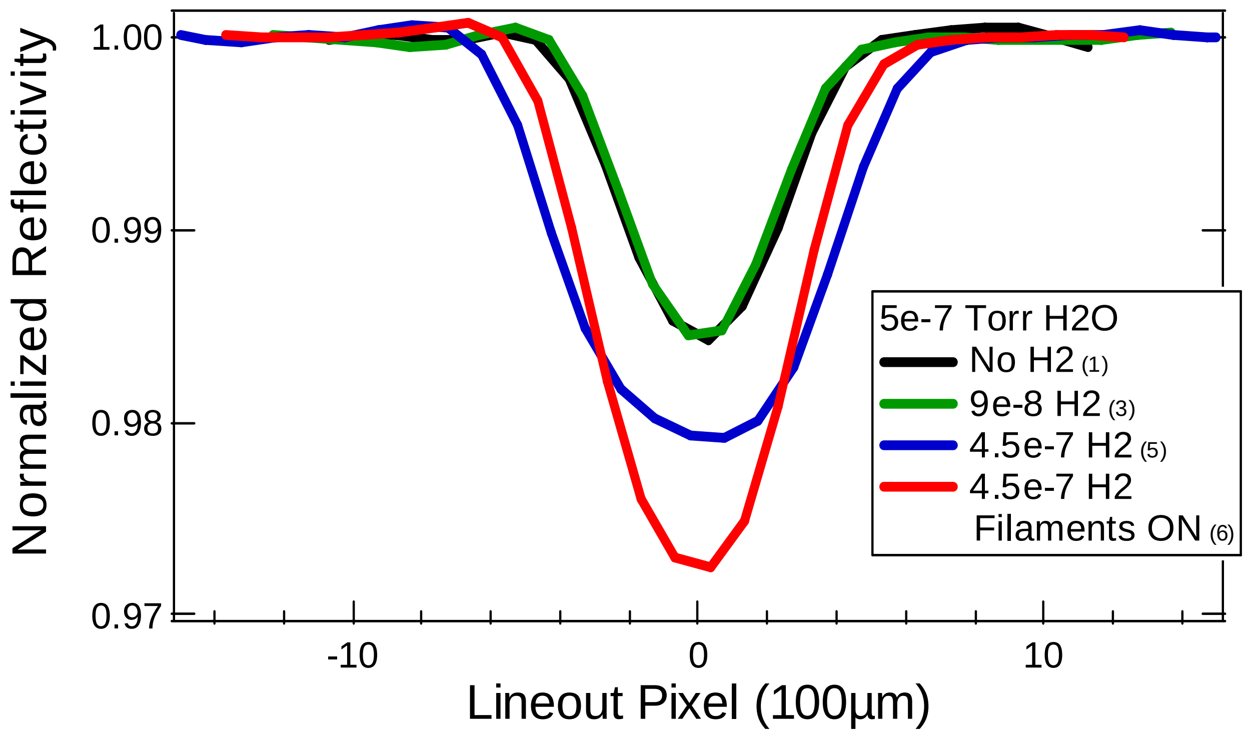
- H_2 partial pressure ~50 times residual level produced by H_2O-chamber interactions.
- For PP(H_2) < PP(H_2O) and filaments off, no effect on EUV damage rate

10hr exposures in admitted H_2+H_2O



- H_2 partial pressure ~50 times residual level produced by H_2O-chamber interactions.
- For PP(H_2) < PP(H_2O) and filaments off, no effect on EUV damage rate
- For PP(H_2) ~ PP(H_2O) and filaments off, EUV damage rate *increases*

10hr exposures in admitted H_2+H_2O

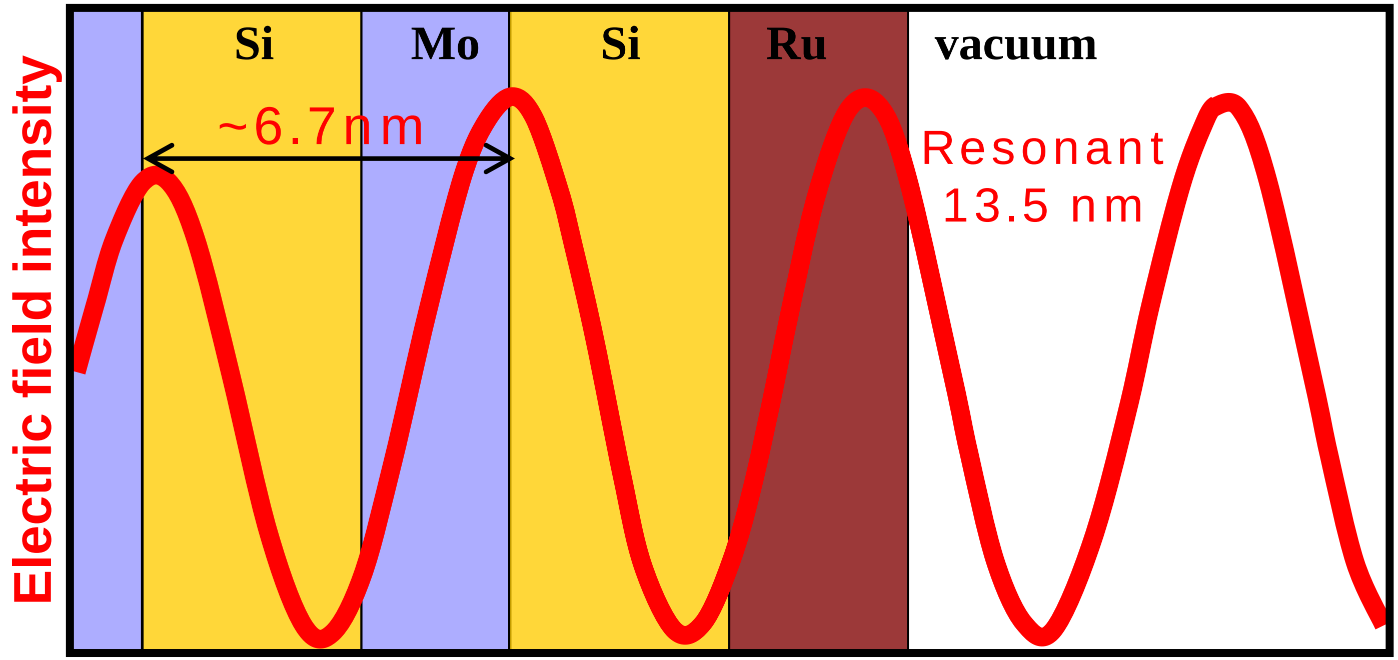


- H_2 partial pressure ~50 times residual level produced by H_2O-chamber interactions.
- For PP(H_2) < PP(H_2O) and filaments off, no effect on EUV damage rate
- For PP(H_2) ~ PP(H_2O) and filaments off, EUV damage rate *increases*
- For PP(H_2) ~ PP(H_2O) and filaments **on**, EUV damage rate ***increases more***

Summary of LLNL Ru-capped MLs exposed in HC-free NIST chambers

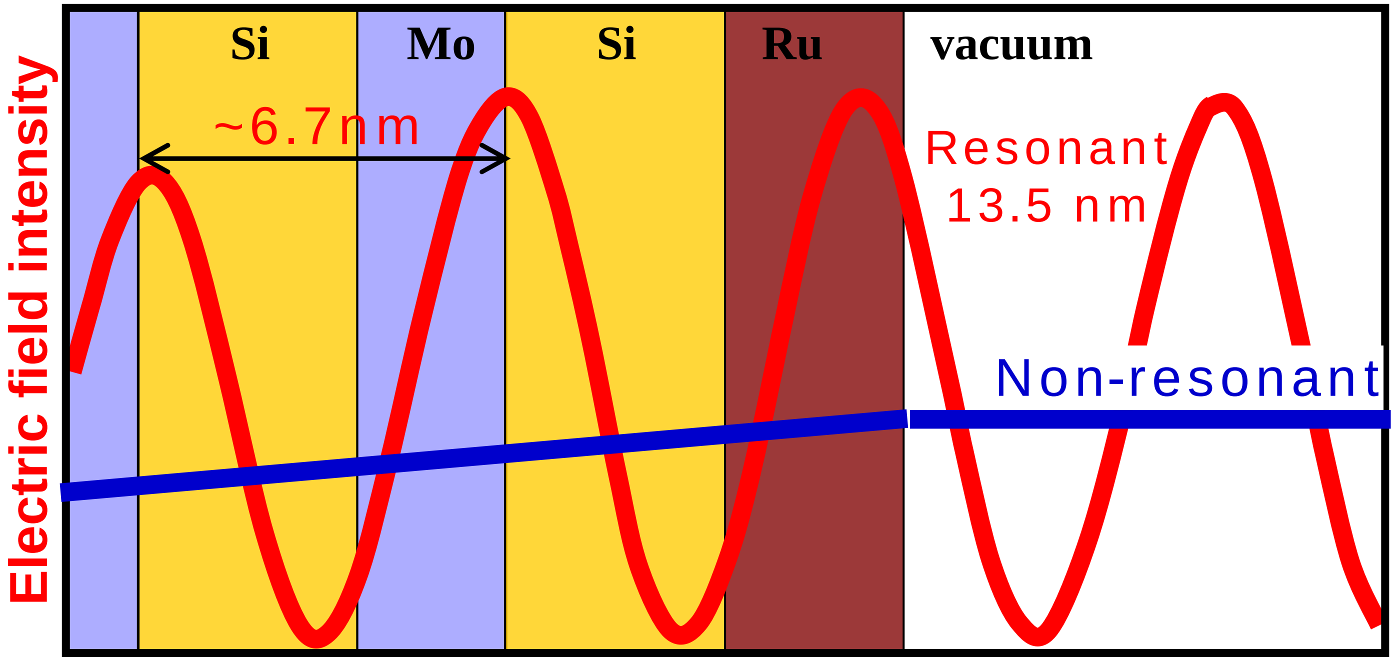
- Damage likely caused by oxidation alone
- At $P(HC_x)=10^{-11}-10^{-10}$ Torr, monolayer coverage in 30-300 hrs
- $P(CO, CO_2)$ much higher, but test exposures show no effect
- Low C coverage undetectable by XPS due to Ru-C peak overlap
- Inverse $P(H_2O)$ dependence of damage and role of filaments not explained by competing reactions from water-filament products
- Sub-monolayer O, C, H coverage *can* alter surface kinetics of H_2O
- Behavior likely depends on cap-layer micro-structure: results from tests performed on different Ru-cap MLs are different.

Surface interaction with resonant standing wave



- Reflectivity significantly affected by location of mirror surface in standing-wave field
- Reflectivity can *increase* if expansion due to damage moves surface through node
- Possible reason for inverse P(H_2O) dependence and related influence of dose.
- Vary exposure time to investigate *evolution* of damage profiles

Potential effect of bandwidth on damage rate



- Damage rate depends on location of surface in standing wave
- Field strength at surface for resonant light can be larger than or much smaller than equal intensity non-resonant light
- Evolution of damage for equal doses of broad-band and 13.5nm radiation could be quite different.
- Must use same bandwidth when comparing exposures (e.g., pulsed and CW exposures)

NIST Summary

- Carbon-growth is not likely source of degradation since HC partial pressures are too low for significant accumulation

- Exposures in admitted CO, CO_2, H_2 demonstrate that residual levels of these gases do not affect damage process.

- Adding H_2 at pressures comparable to water pressure can *accelerate* damage, especially if hot filaments are present.

- Observed in both vacuum chambers:
  - Inverse dependence of damage with water pressure
  - Non-Gaussian damage profiles with less damage in high-intensity center of beam only when filaments OFF.

- Time evolution of damage will be studied to investigate role of standing-wave in damage process and hence the importance of bandwidth in endurance testing.

Executive Summary

- Initial plan to understand and establish baseline lifetime-testing parameters in clean vacuum environment revealed non-intuitive and likely system- and sample-specific damage dependencies.
- These effects may be overshadowed by other processes in less-clean tool environments.
- Establishment of standardized accelerated testing protocols requires better characterization of actual production vacuum conditions, including resist outgassing.

Acknowledgments

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ALS, Lawrence Berkeley National Laboratory

Saša Bajt
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Thank You!

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Thank you!

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Backup / discussion slides follow

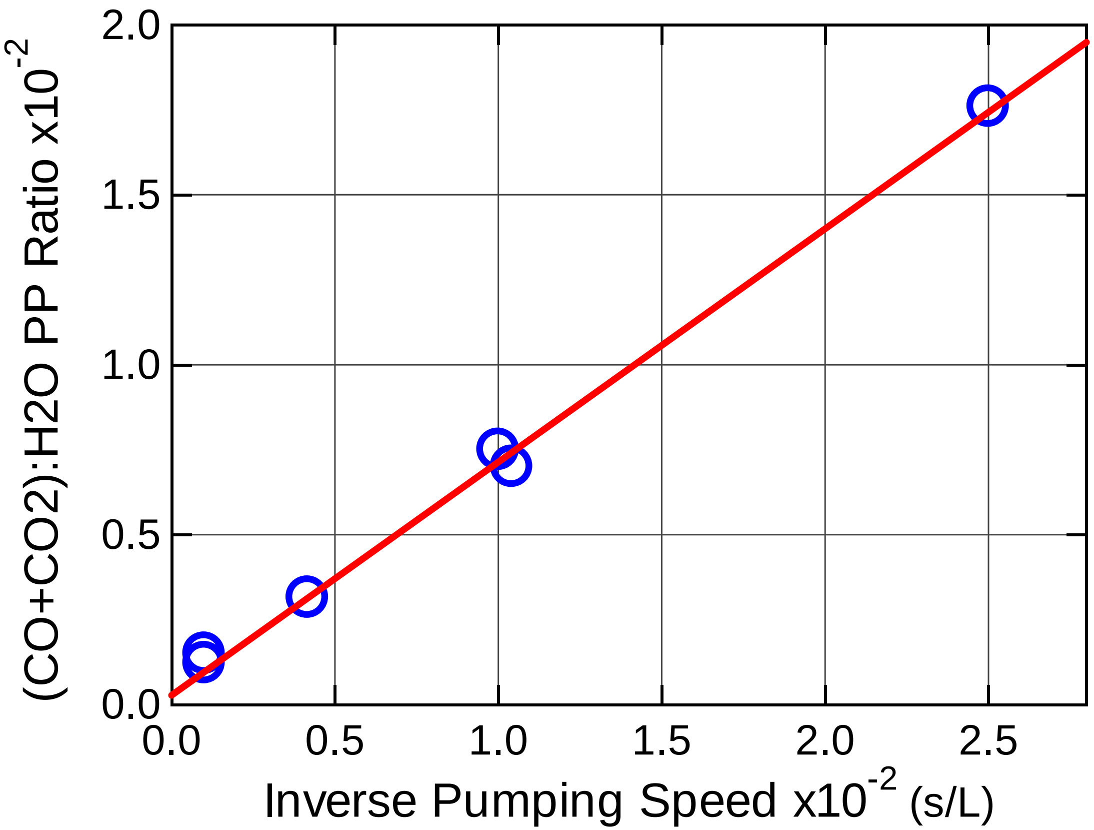
Ancillary tests to find source of CO & CO_2

Is water contaminated?

Mass throughput equations

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

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



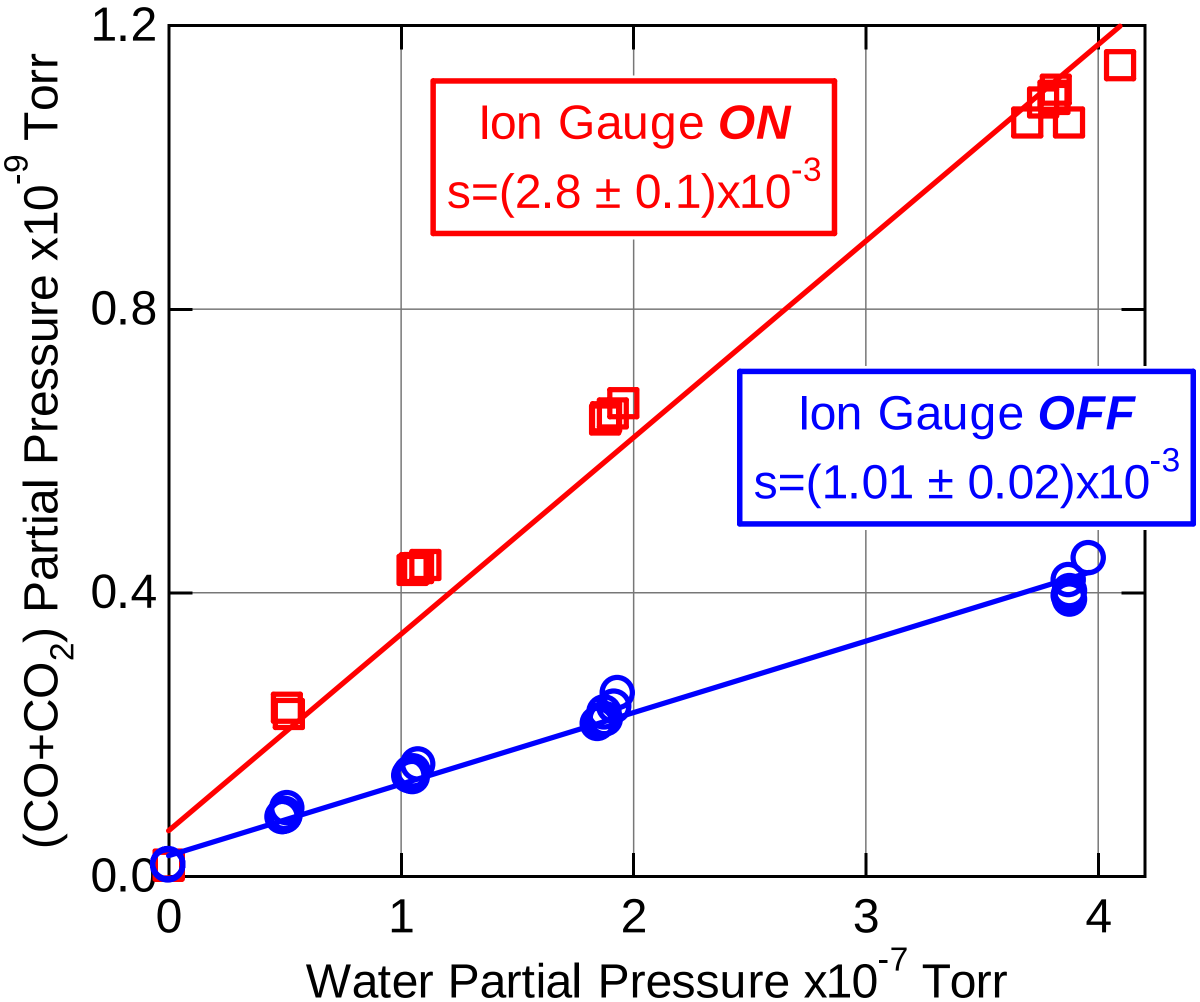
- CO & CO_2 **NOT** from contaminated water supply
- Produced by water interaction with chamber
  - C-species displaced from unbaked chamber walls by water
  - Reaction of water with C in hot tungsten/iridium filaments

Ancillary tests to find source(s) of CO & CO_2

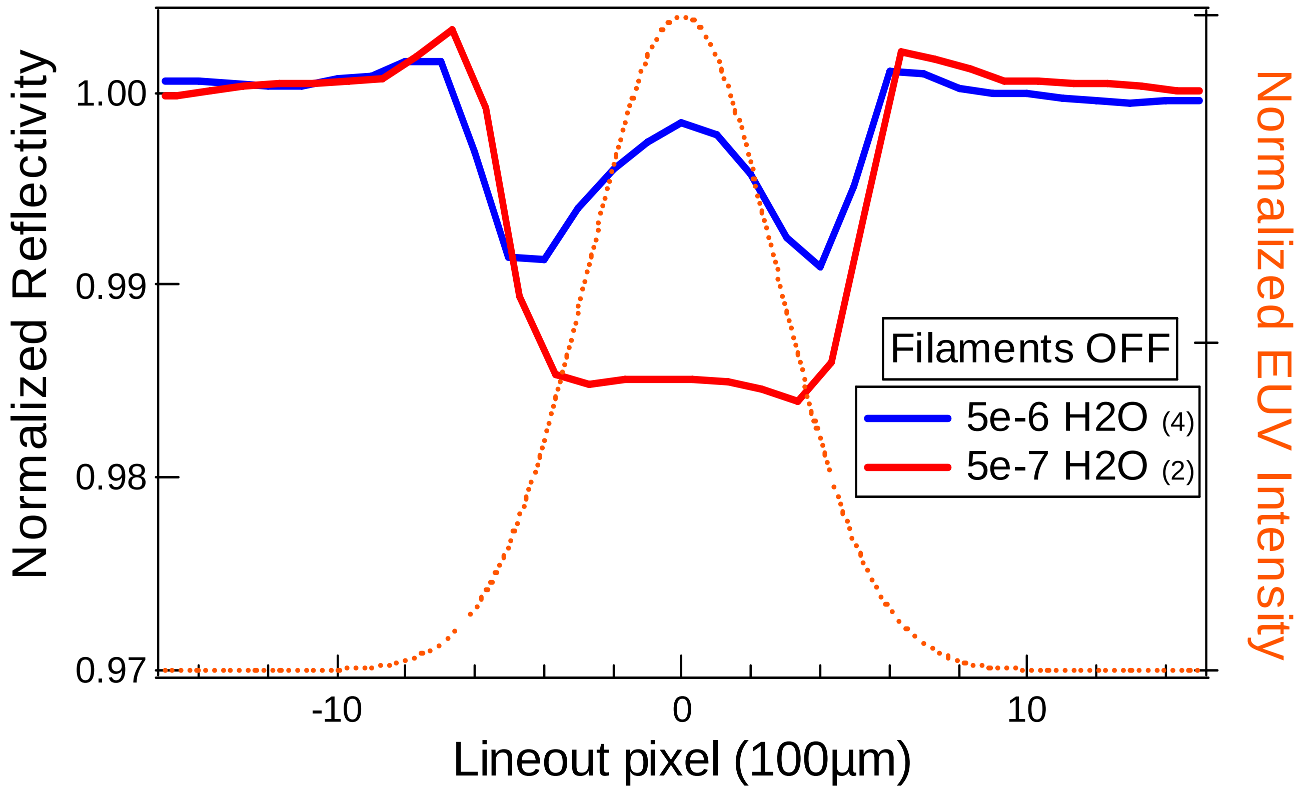
- C-species generated at rate proportional to water partial pressure
- Chamber contains two filaments: IG, RGA
- Is rate of C-species production different with only RGA on?

YES!

- CO & CO_2 3x smaller with IG off
- Likely reduced further if RGA also off



Non-Gaussian spatial distribution: "donut"

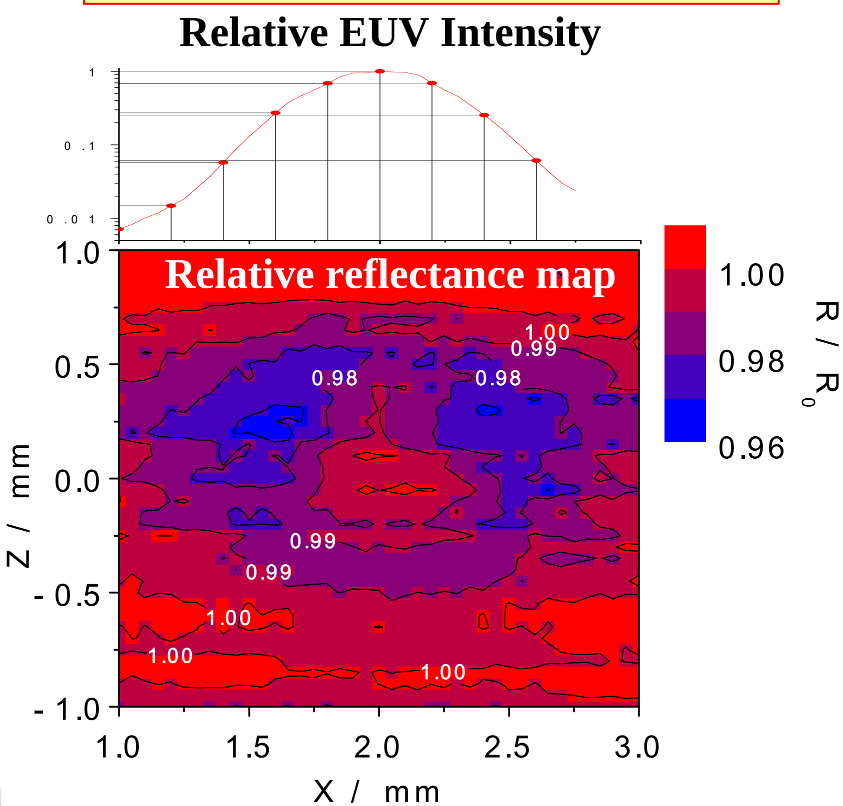


- "Donut" effect does not occur with filaments (need to show w/+w/out fil at 5e-6 h2o)
- Observed in two different exposure chambers with different filament locations
- No effect from adding CO or CO_2 at higher H_2O pressures

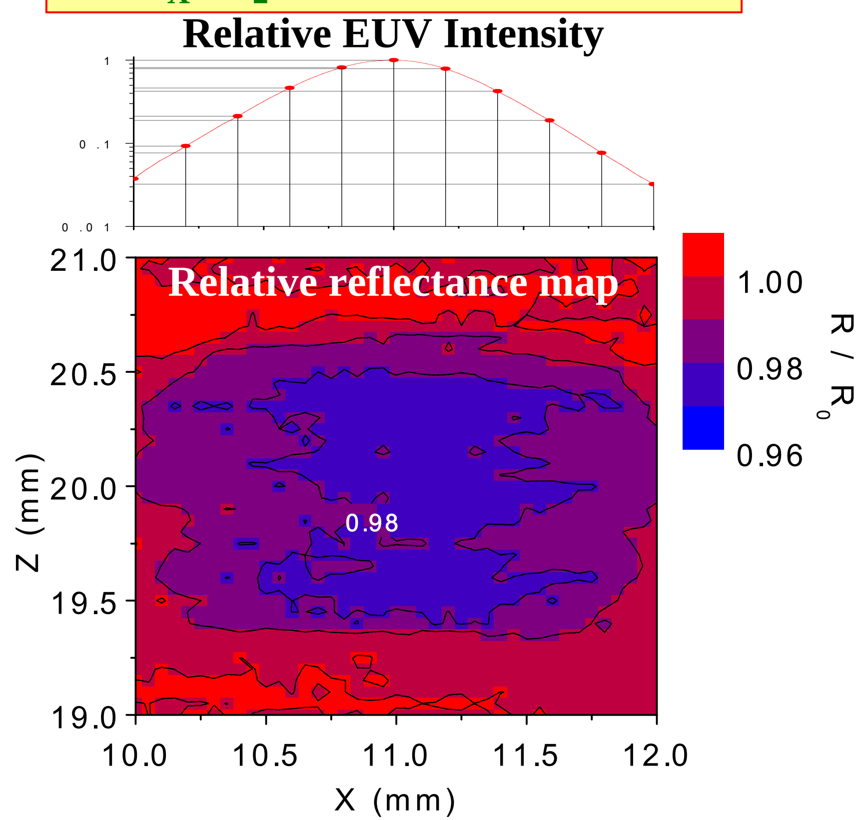
Japanese Ru-cap ML data from 2006 SPIE Microlithography

Y. Kakutani, M. Niibe (*LASTI, University of Hyogo)*
Y. Gomei, H. Takase, S. Terashima, S. Matsunari, T. Aoki, K. Murakami, Y.Fukuda (*EUVA)*

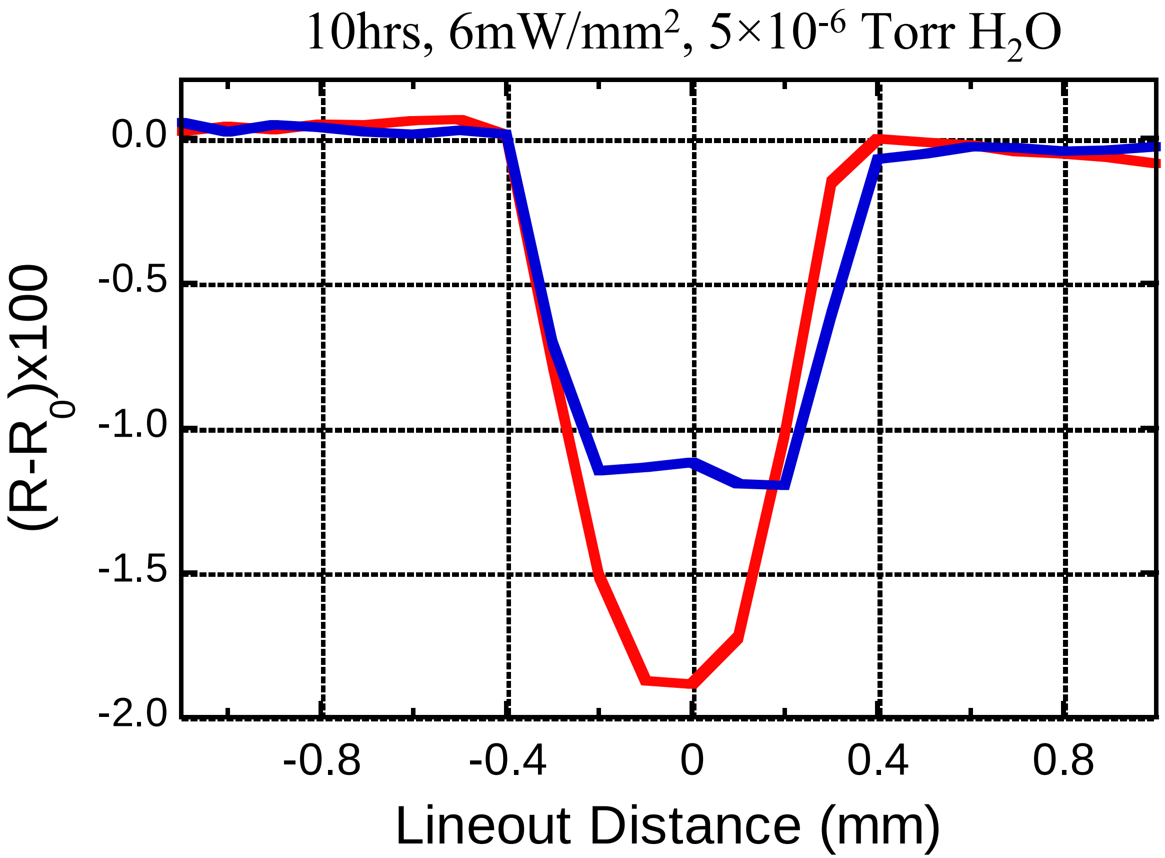
- Narrow-band: ~13.5 nm ±1%
- Intensity: 100-150 mW/mm^2
- 5 hr exposure (2200 J/mm^2)
- H_2O ~ 3×10^{-7} Torr
- **CO_X/ H_2O ~ 0.1 (“Dirty”)**



- Quasi-narrow-band: 13-14 nm
- Intensity: 120-150 mW/mm^2
- 2 hr exposure (1000 J/mm^2)
- H_2O ~ 9×10^{-7} Torr
- **CO_X/ H_2O ~ 0.002 (“Clean”)**



Reduce background carbonaceous species



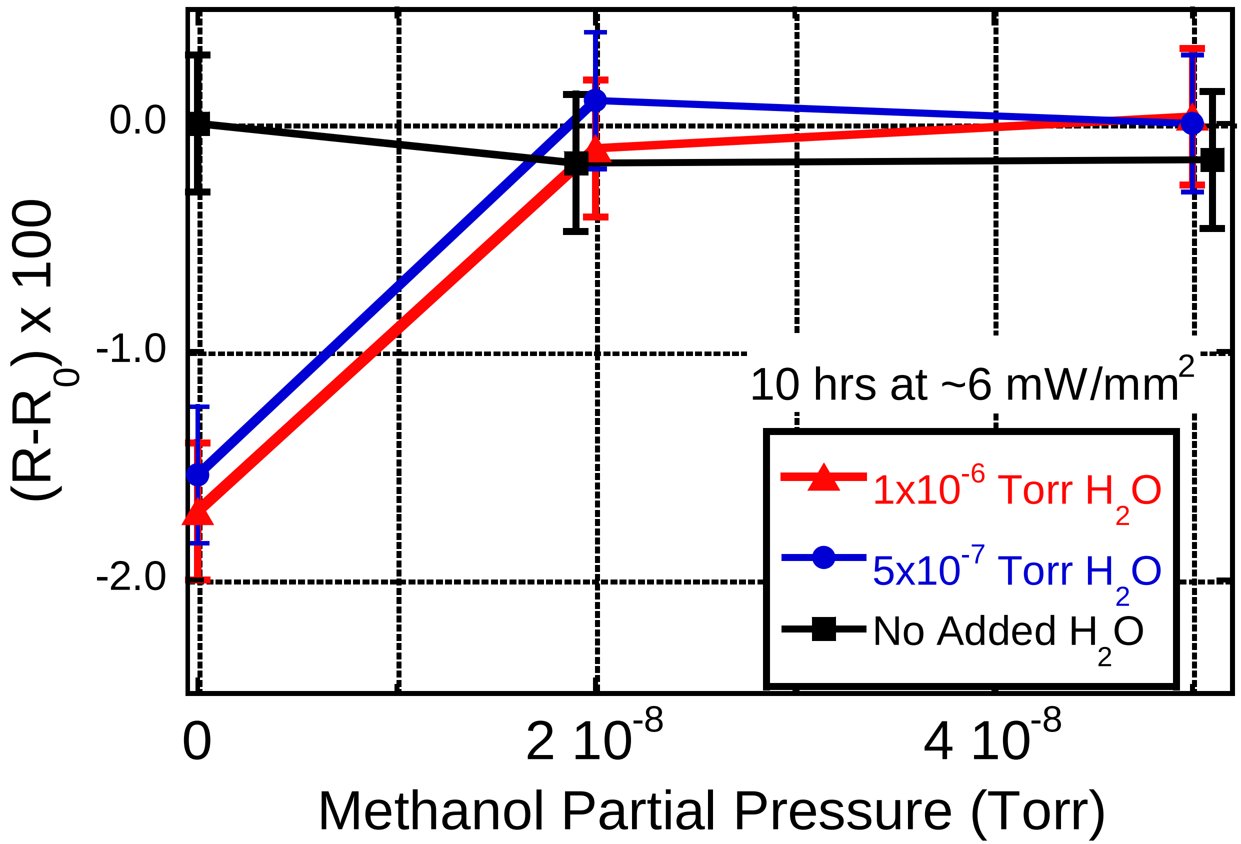
$\frac{PP(CO_X)}{PP(H_2O)} \sim 1\times10^{-3}$

$\frac{PP(CO_X)}{PP(H_2O)} \sim 2\times10^{-4}$

Damage rate *increased* after cleaning chamber and gas lines

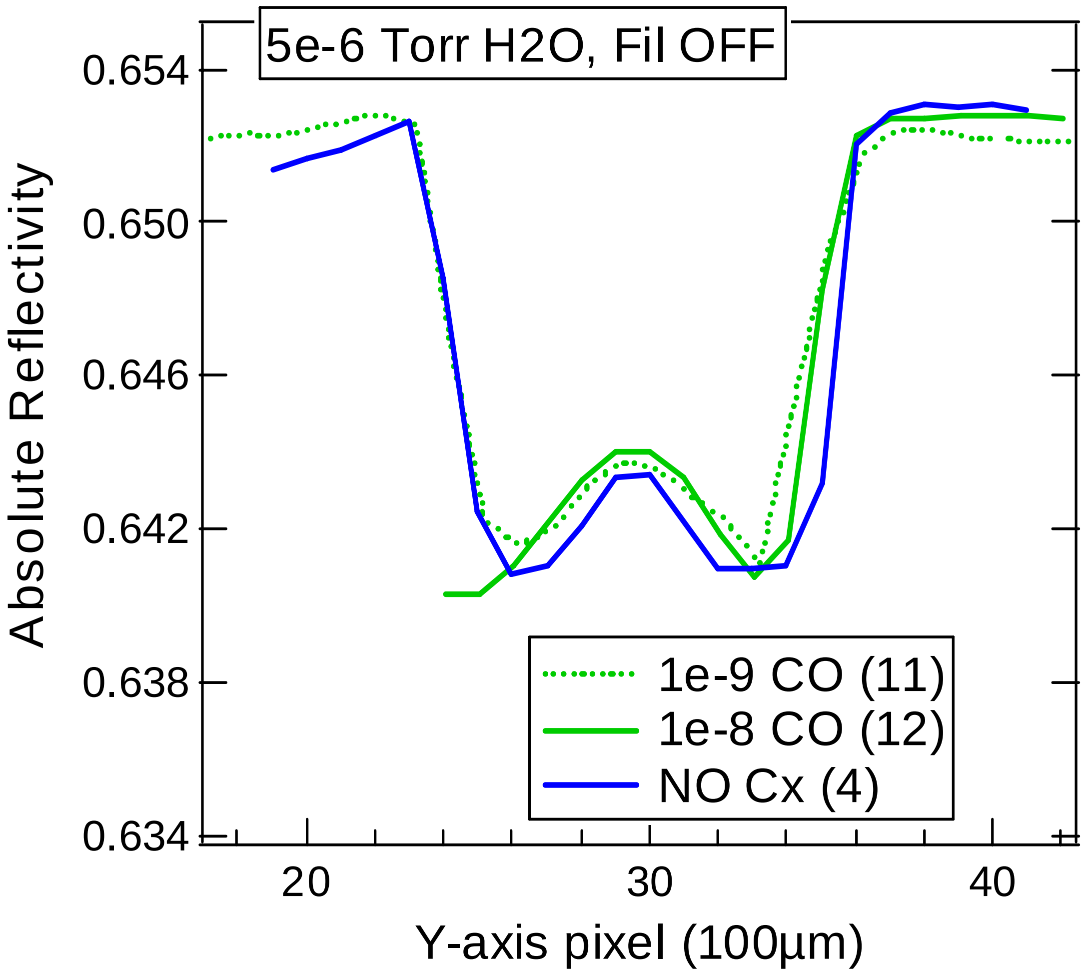
- Ancillary tests verified water supply is *NOT* source of CO_X
- H_2O in UHV is known to produce C-species
  T. E. Madey, J. Vac. Sci. Technol. A5 (1987) 3249
  - Dissociatively adsorbed H_2O displaces stable C on SS walls
  - Primary source of CO & CO_2 in UHV: hot filaments + H_2O

Small admixture of methanol mitigates damage

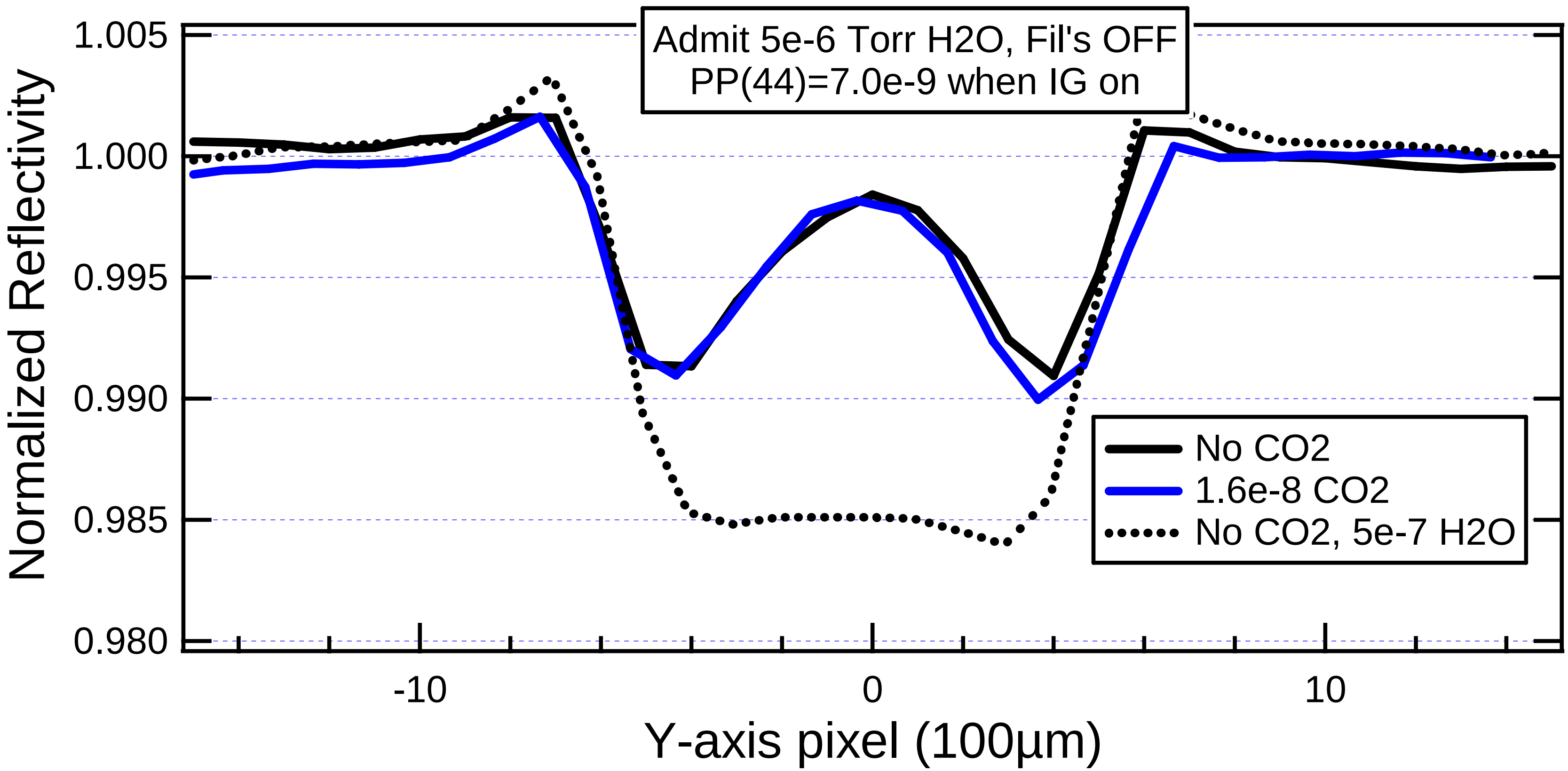


- Just 2×10^{-8} Torr methanol prevents measurable damage from water
- Very little damage from low levels of methanol alone
- Trace levels of C-containing compounds (e.g., CO_X) in ambient background may also mitigate H_2O+EUV damage

No effect from admission of CO at high H_2O

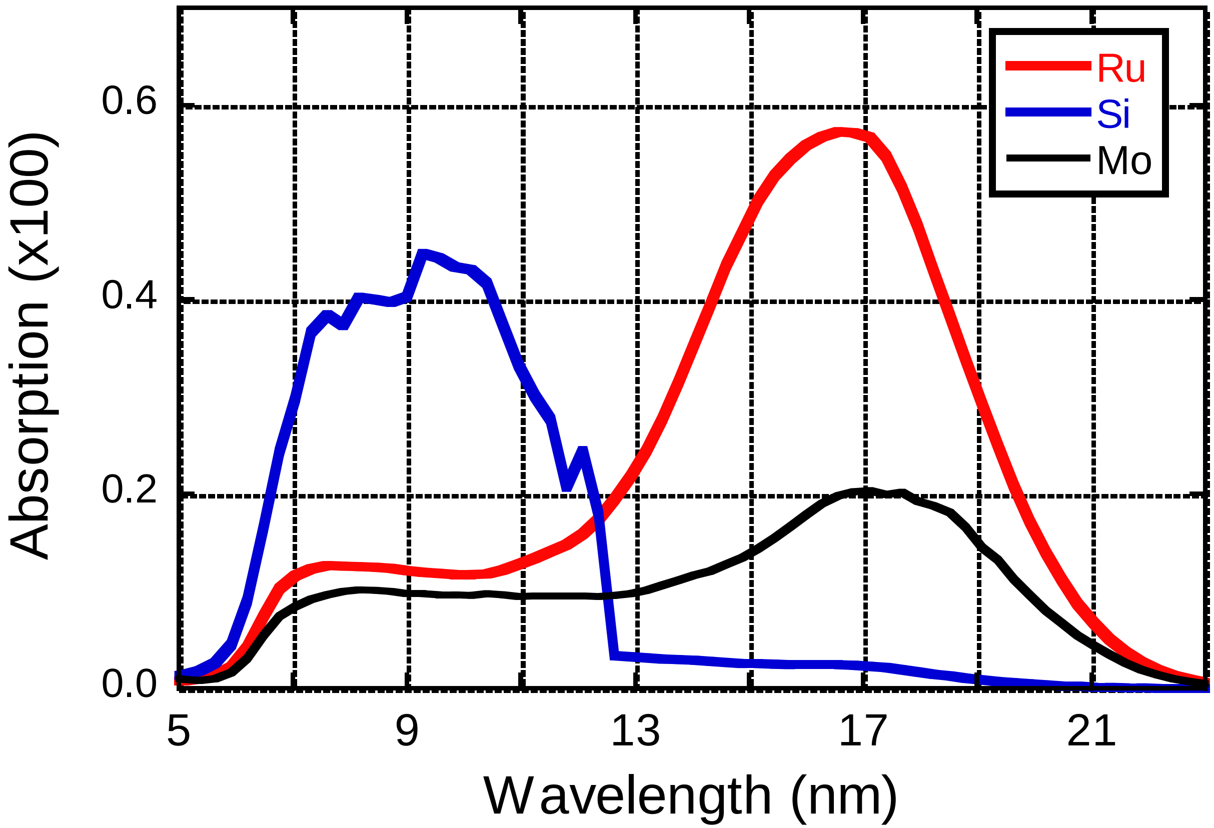


No effect from admission of CO_2 at high H_2O

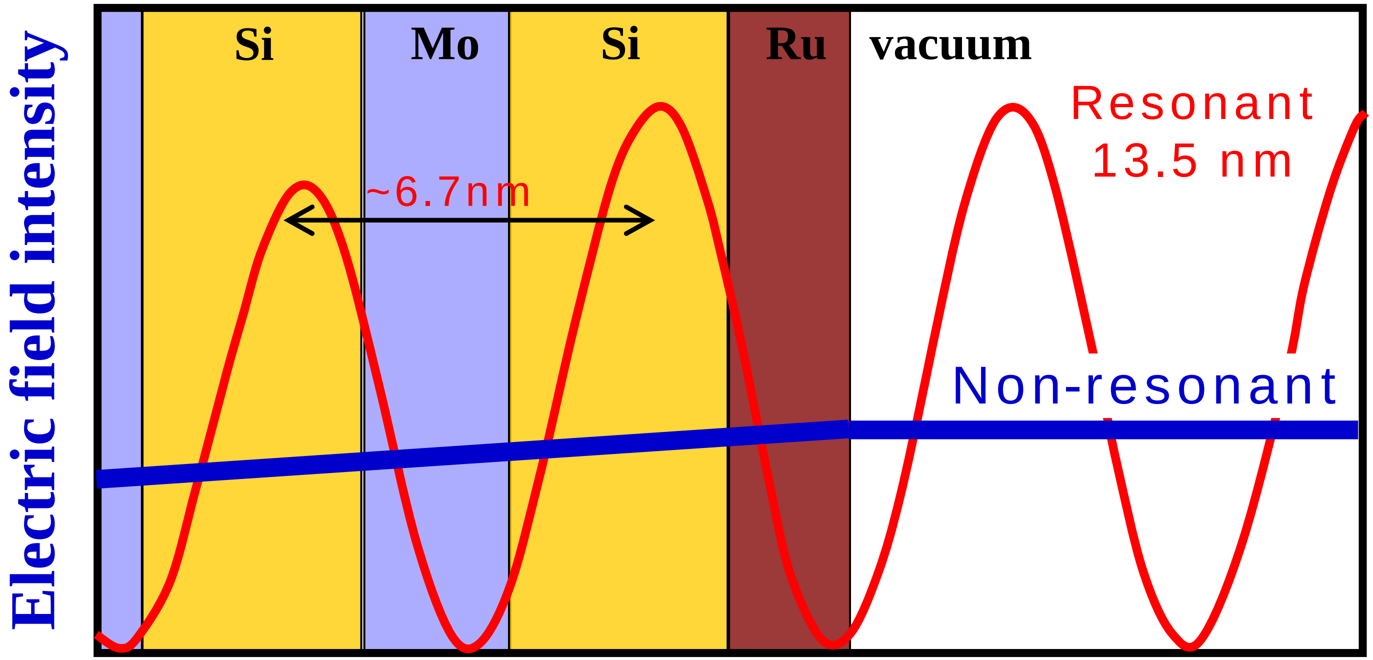


Potential effect of wavelength on damage rate (II)

Absorption of Zr-filtered "white light" by 2nm of **Ru**, **Si**, **Mo**



Potential effect of wavelength on damage rate



- C-growth and *surface* field correlated for Si-cap MLs
  M. Malinowski, C. Steinhaus, M. Clift, L.E. Klebanoff, S. Mrowka, and R. Soufli, SPIE Proc, **4688,** 442 (2002)
- Surface of cap layer near minima for *design wavelength (13.5nm)*
- Total field much larger for non-resonant light (no standing wave)
- Potentially greater damage for broad-band exposure compared to equal dose of 13.5nm.