In-Situ Cleaning of Sn EUV Sources

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Outline

- **Collector Cleaning Theory**
- **3D Flow Modeling**
- **Radical Probe & 0D Modeling of H Radicals**
- **Experimental Plans for Measuring the Probability of Etching and the Probability of Redeposition**
- **Beyond EUV (6.7 nm) Optics**
- **Beyond EUV (6.7 nm) Source**
- **Conclusions**

Theory

- Sn removal depends not only on etching by H radicals, but on SnH_4 dissociation and redeposition.
- Therefore, understanding of transport of SnH_4 is necessary. Described by diffusion-advection equation:

$$\frac{\partial n}{\partial t} = 0 = -\nabla \cdot (Dn) + \boldsymbol{v} \cdot \nabla n$$

- To solve this, we need:
  - Velocity profile **v** (SnH_4 will assume profile of H_2 flow)
  - Radical Flux
  - Probability of Etching

    $\Big\} \longrightarrow$ SnH_4 Inlet Boundary Condition
  - Probability of Redeposition → SnH_4 Outlet Boundary Condition
- Etch rate given by radical flux and probability of etching. Subtract deposition rate to get net removal rate.

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Modeling of H_2 Flow: Complete

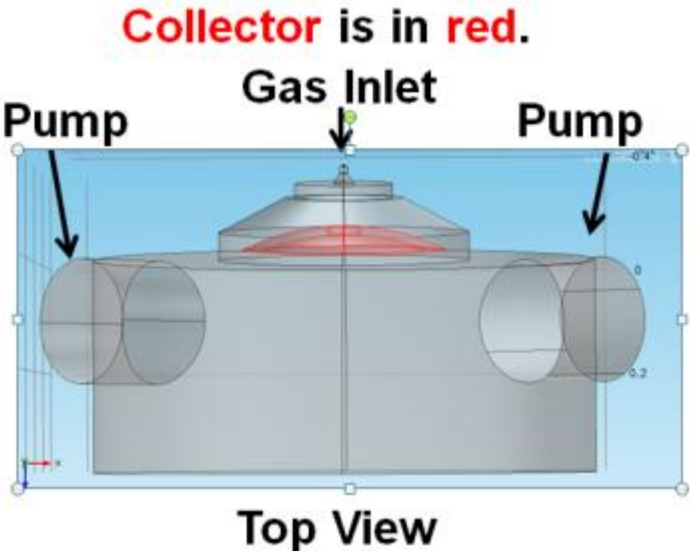
- Bulk gas is mostly H_2 (by orders of magnitude)
- Assumption: Flow in chamber can be decoupled from species and solved simply for H_2; the few non-H_2 particles will take on the H_2 velocity profile.
- Solve Navier-Stokes Equations for H_2 in XCEED.

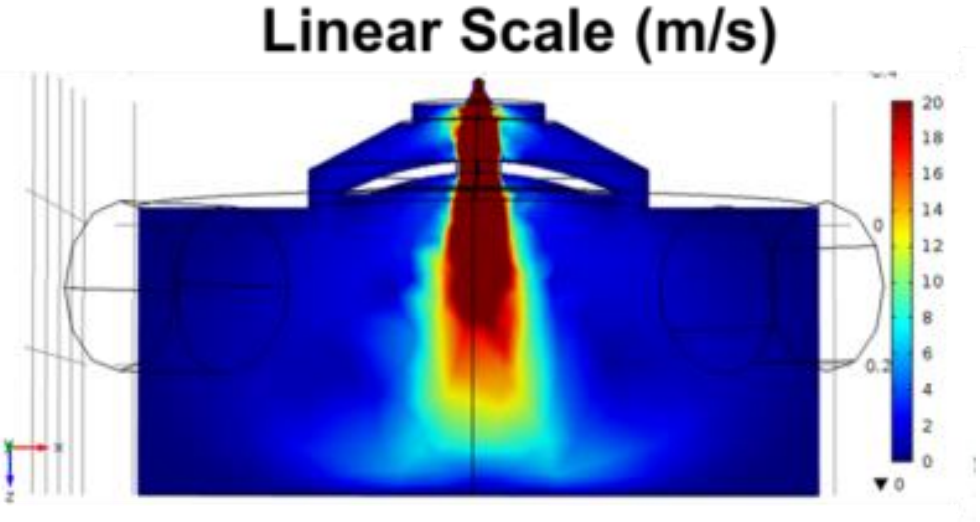
$$\rho\frac{\partial \mathbf{u}}{\partial t} - \nabla\cdot\eta(\nabla\mathbf{u}+(\nabla\mathbf{u})^T)+\rho(\mathbf{u}\cdot\nabla)\mathbf{u}+\nabla p = \mathbf{F}$$

$$\nabla\cdot\mathbf{u} = 0$$

- Velocity profiles shown below.

1.3 Torr, 3200 sccm (current operating conditions)

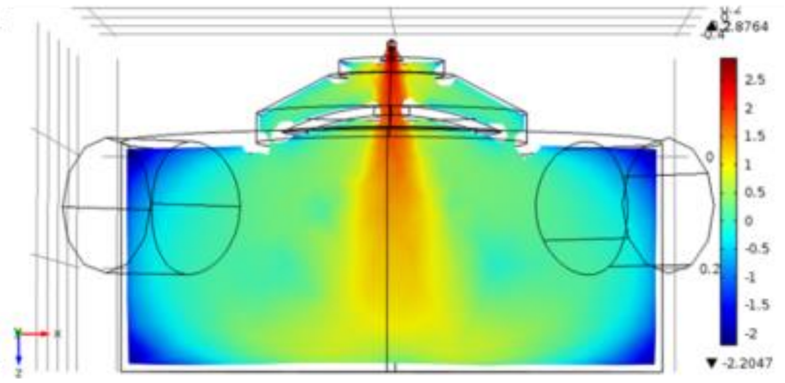




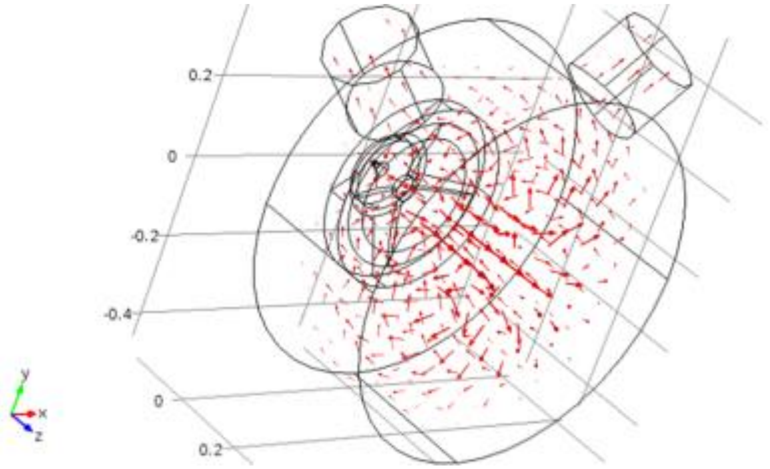
H_2 Flow (Continued)

1.3 Torr, 3200 sccm

Log Scale

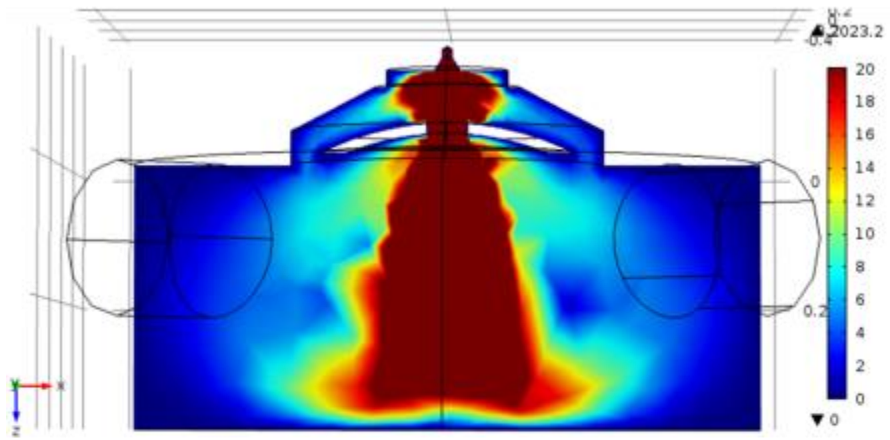


3D Arrow Profile

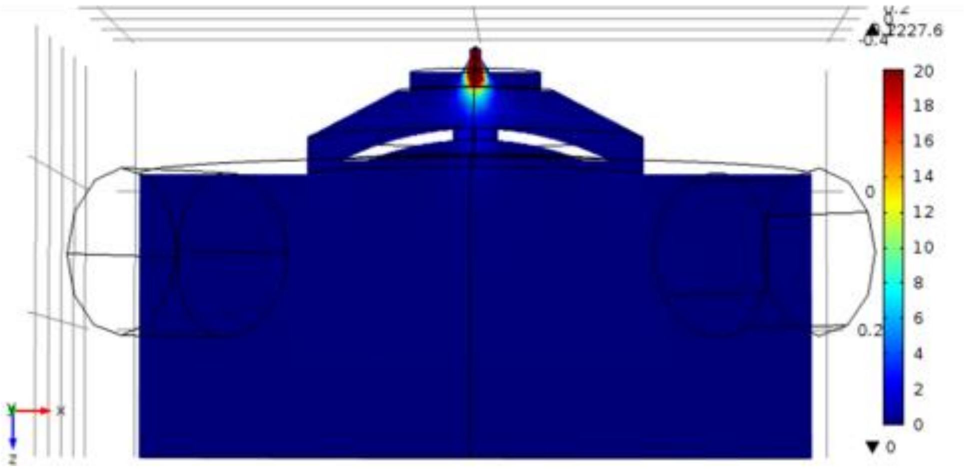


If pressure or flow change, velocity profile changes as expected:

260 mTorr, 3200 sccm



1.3 Torr, 1000 sccm



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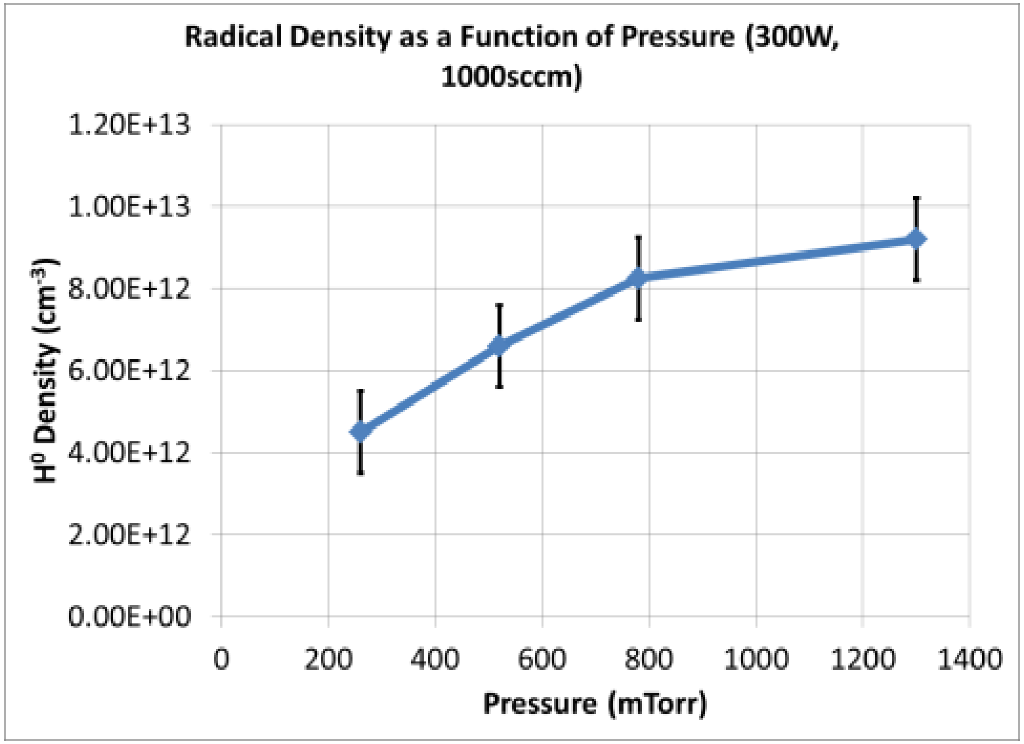
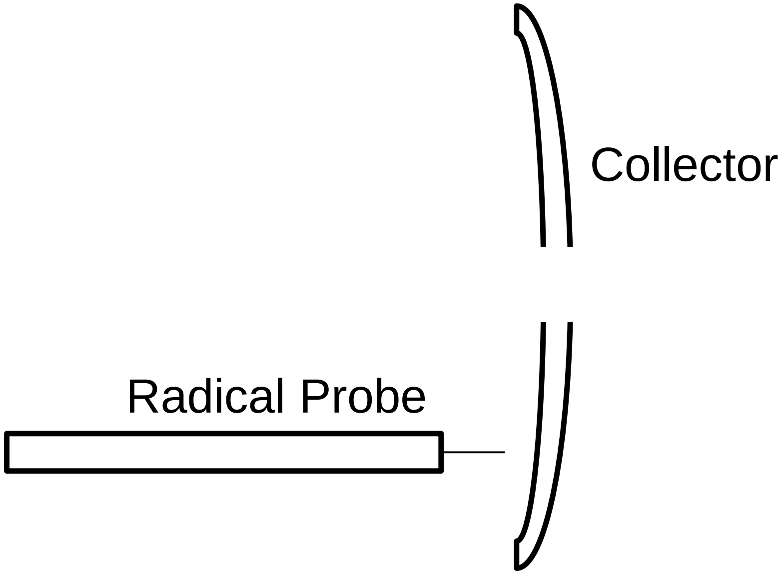
Radical Probe

- Catalytic probe: heats up due to radical recombination on catalyst surface.

$$Power = mc_p \frac{dT}{dt} = \frac{1}{2} W\gamma\Gamma A$$

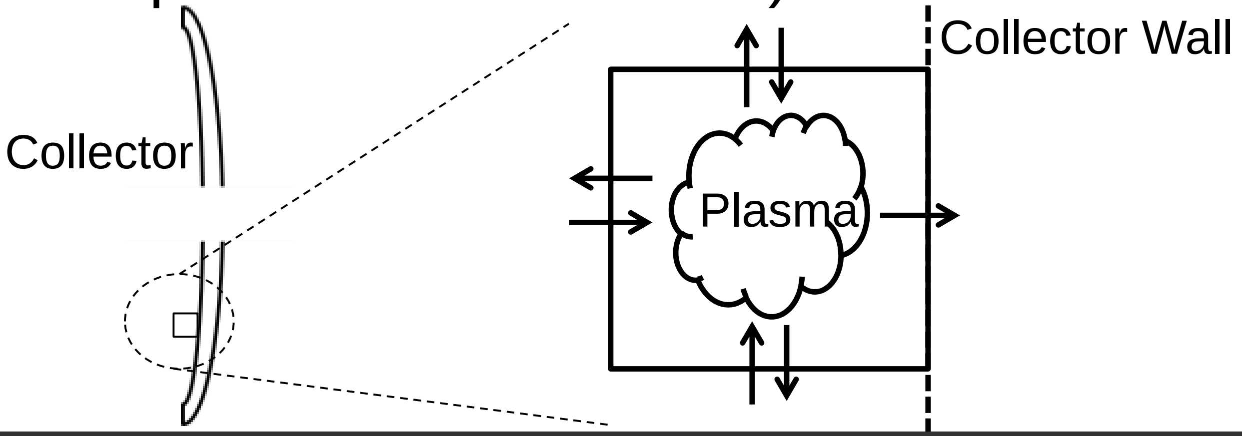
- A=probe area; W=Energy from Recombination; Γ=Radical Flux, γ=Recombination probability





Radical Probe Validation: 0D Model

- Plasma Chemistry Model: Reactions → Rate Equations
- Given n_e and T_e, what densities of ions and radicals are produced?
- Domain size: $1 cm^3$
- Assumptions:
  - Plasma is uniform inside cube (valid for the small domain)
  - One face touches collector; ions and radicals lost to collector
  - No gain/loss through other faces (plasma next to the domain is approximately same as plasma inside domain)
  - Quasineutrality



Reactions

- Rate coefficients k either found directly in literature or calculated up from reaction cross-sections.
- Rate coefficients k will be dependent on T_e.

$$H_2{}^+ + H_2 \overset{k_1}{\rightarrow} H_3{}^+ + H$$

$$H_2{}^+ + e \overset{k_2}{\rightarrow} 2H$$

$$H_3{}^+ + e \overset{k_3}{\rightarrow} H_2 + H$$

$$H_2 + e \overset{k_4}{\rightarrow} H_2{}^+ + 2e$$

$$H_2 + e \overset{k_5}{\rightarrow} 2H + 2e$$

$$H_2 + e \overset{k_6}{\rightarrow} 2H + 2e$$

$$H + e \overset{k_7}{\rightarrow} H^+ + 2e$$

$$H_3{}^+ + e \overset{k_8}{\rightarrow} 2H + H^+ + e$$

$$H_2 + e \overset{k_9}{\rightarrow} 2H + 2e$$

Equations

- Rate of Change = Gain - Loss
- For steady-state, rate is set to 0.
- Equations solved with ode45 in MATLAB until steady-state is reached.

$$\frac{dn_H}{dt} = k_1 n_{H_2} n_{H_2^+} + 2k_2 n_e n_{H_2^+} + k_3 n_e n_{H_3^+} + 2(k_5 + k_6) n_{H_2} n_e + 2k_8 n_e n_{H_3^+} + 2k_9 n_{H_2} n_e - k_8 n_H n_e - \frac{A}{V} \frac{n_H v_{H,th}}{4}$$

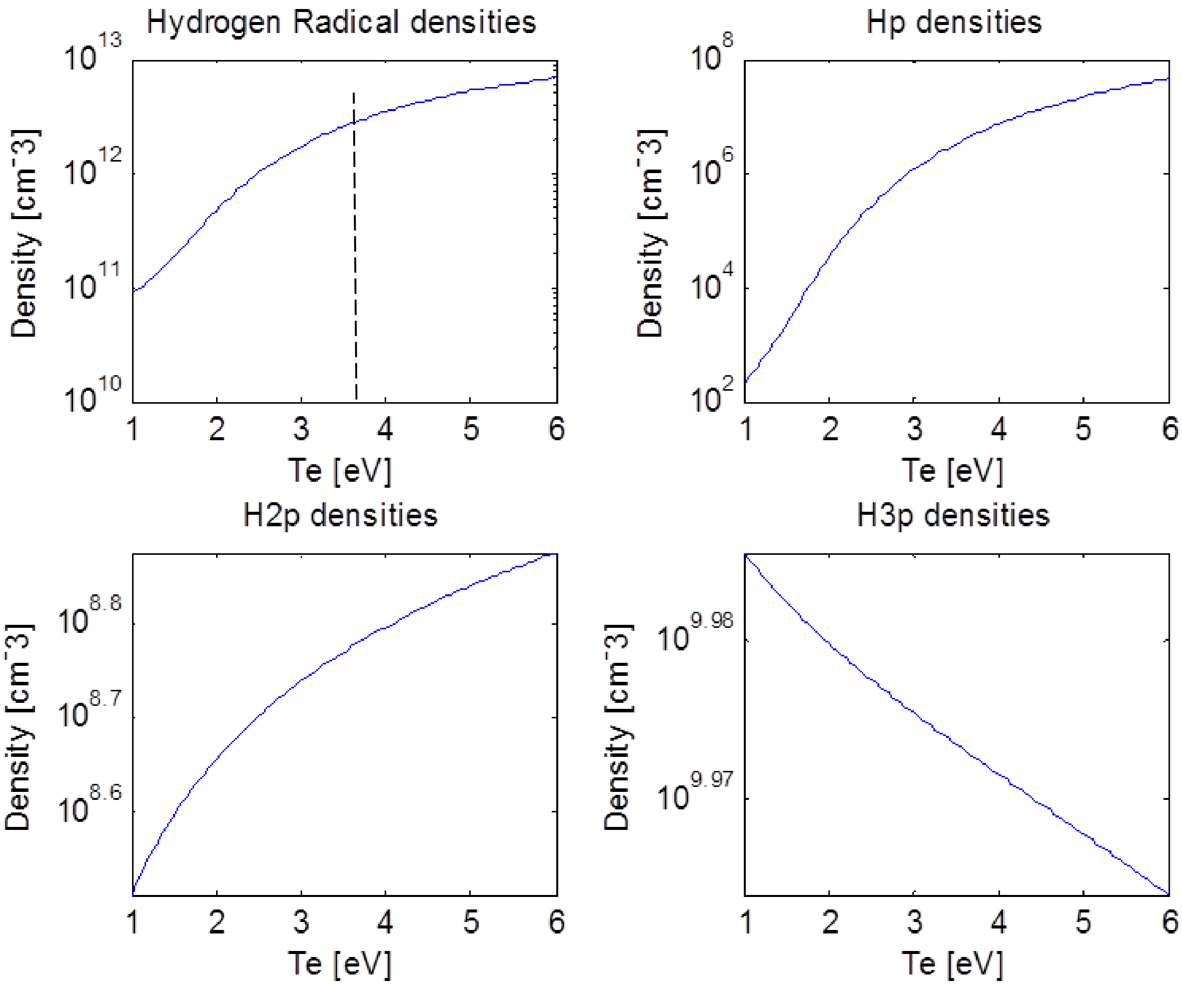
$$\frac{dn_{H^+}}{dt} = k_7 n_H n_e + k_8 n_e n_{H_3^+} - \frac{A}{V} n_H v_{H^+,Bohm}$$

$$\frac{dn_{H_2^+}}{dt} = n_e - n_{H^+} - n_{H_3^+}$$

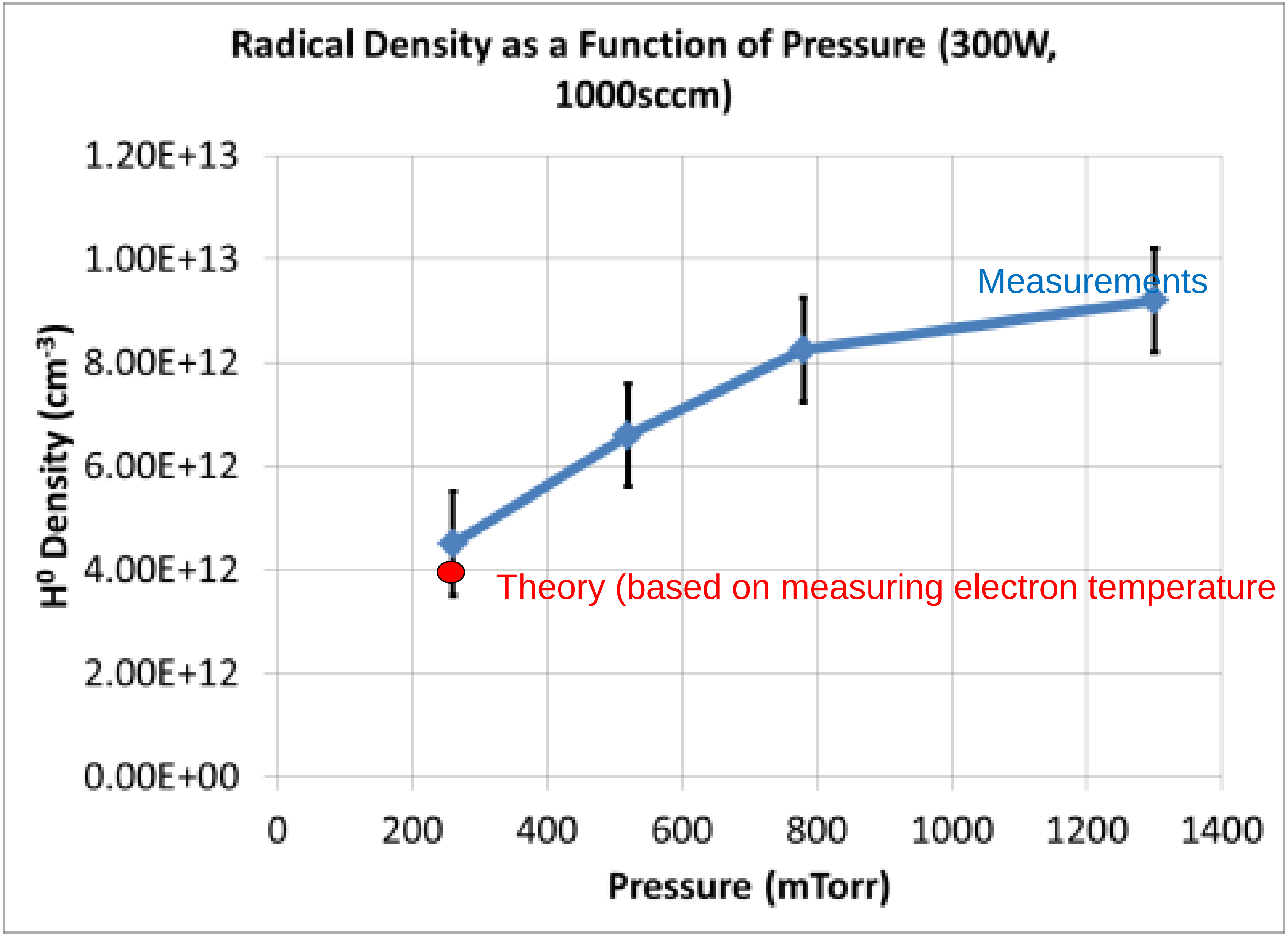
$$\frac{dn_{H_3^+}}{dt} = k_1 n_{H_2} n_{H_2^+} - k_3 n_e n_{H_3^+} - k_8 n_e n_{H_3^+} - \frac{A}{V} n_H v_{H_3^+,Bohm}$$

Results

- n_e, T_e measured with Langmuir probe at 260mTorr (to allow for low-pressure regime for collisionless sheath equations)
- $n_e=10^{10}cm^{-3}$, $T_e=4.5eV$
- 0D Model at $n_e=10^{10}cm^{-3}$:
- 4.5eV: $n_H=4.4x10^{12}cm^{-3}$
- Well within error bar of radical probe measurement (4.5 +/- 1 x 10^{12} cm^{-3})
- Conclusion:
  Radical Probe works; it is a reliable experimental diagnostic.



Comparison of Model and Measurement



Measurements

Theory (based on measuring electron temperature and density)

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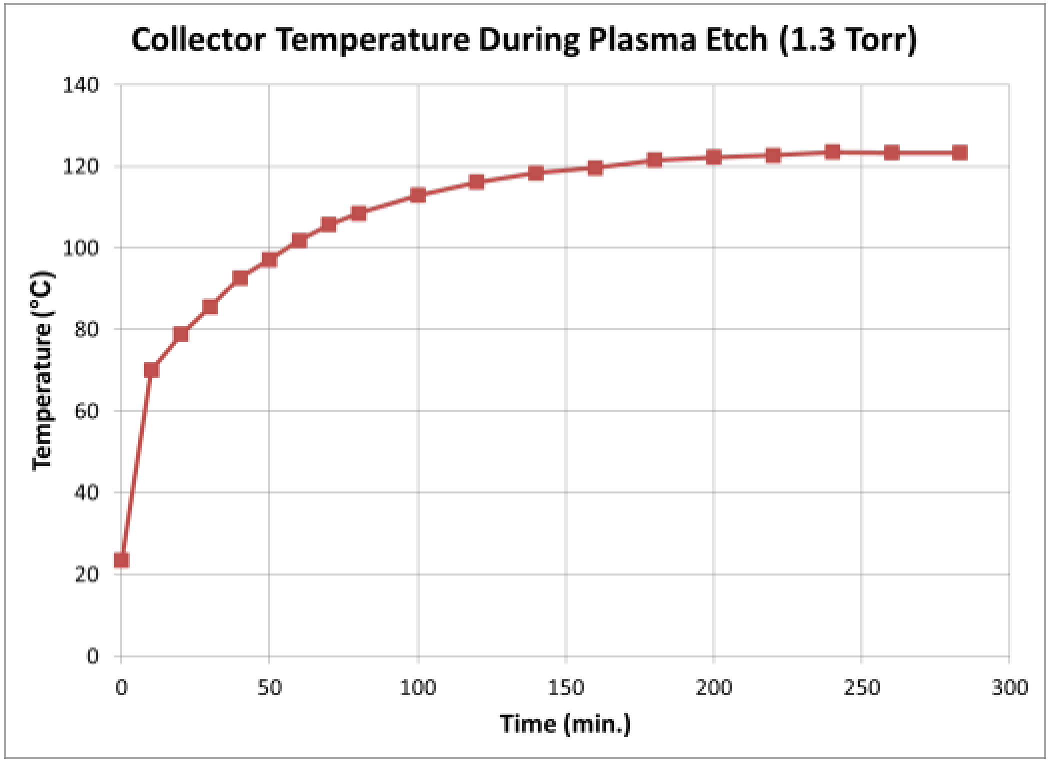
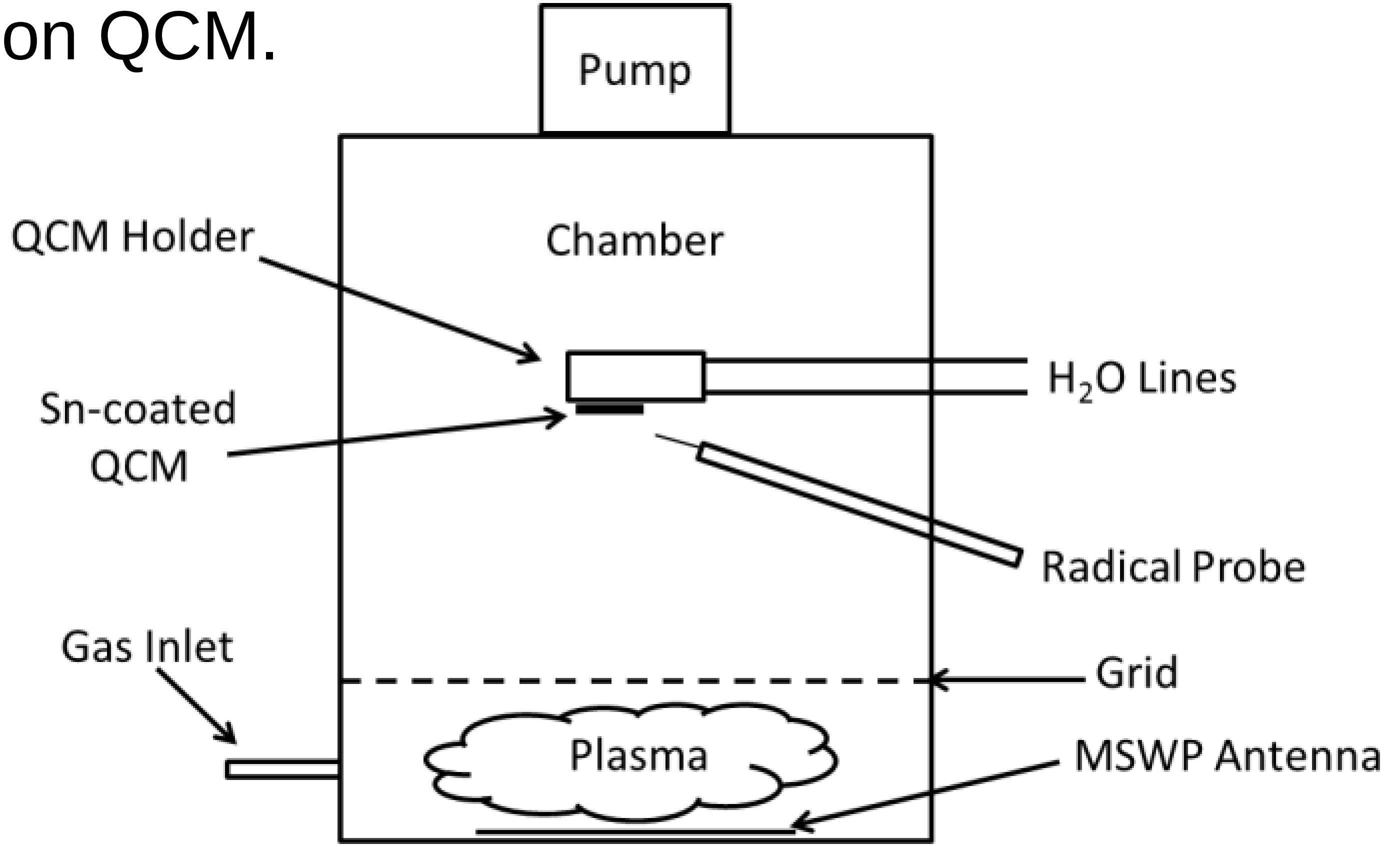
Future Experiments

- Scan radical probe radially over collector → radial n_H profile
- Also, need P(etching) and P(redeposition).
- P(redeposition) is dependent on temperature; P(etching) may be as well.
- Temperature can be measured on collector. Will need to perform the probability experiments as a function of temperature.



Probability of Etching

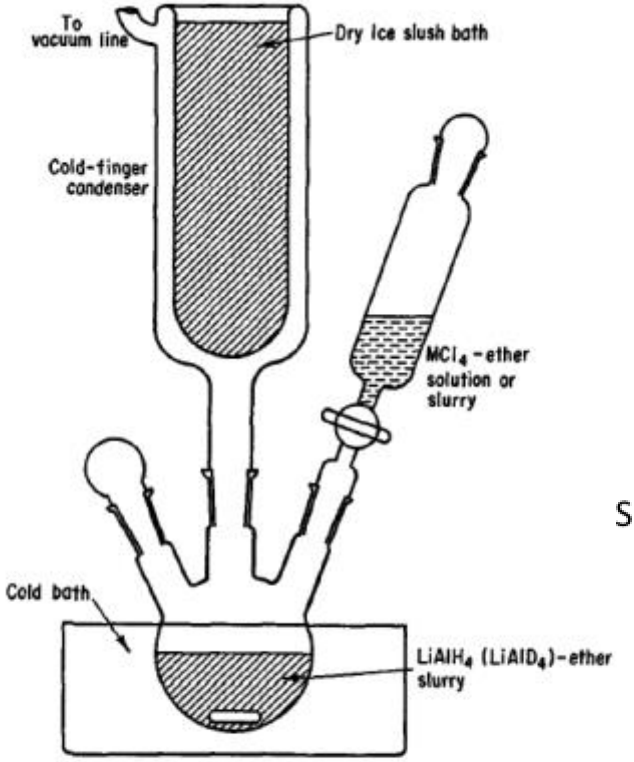
- Sn-coated QCM to measure etch rate
- QCM is small; no other source of Sn → No redeposition
- Temperature-controlled
- Remote plasma source with grid → only H_2 and radicals incident on QCM.



Probability of Redeposition

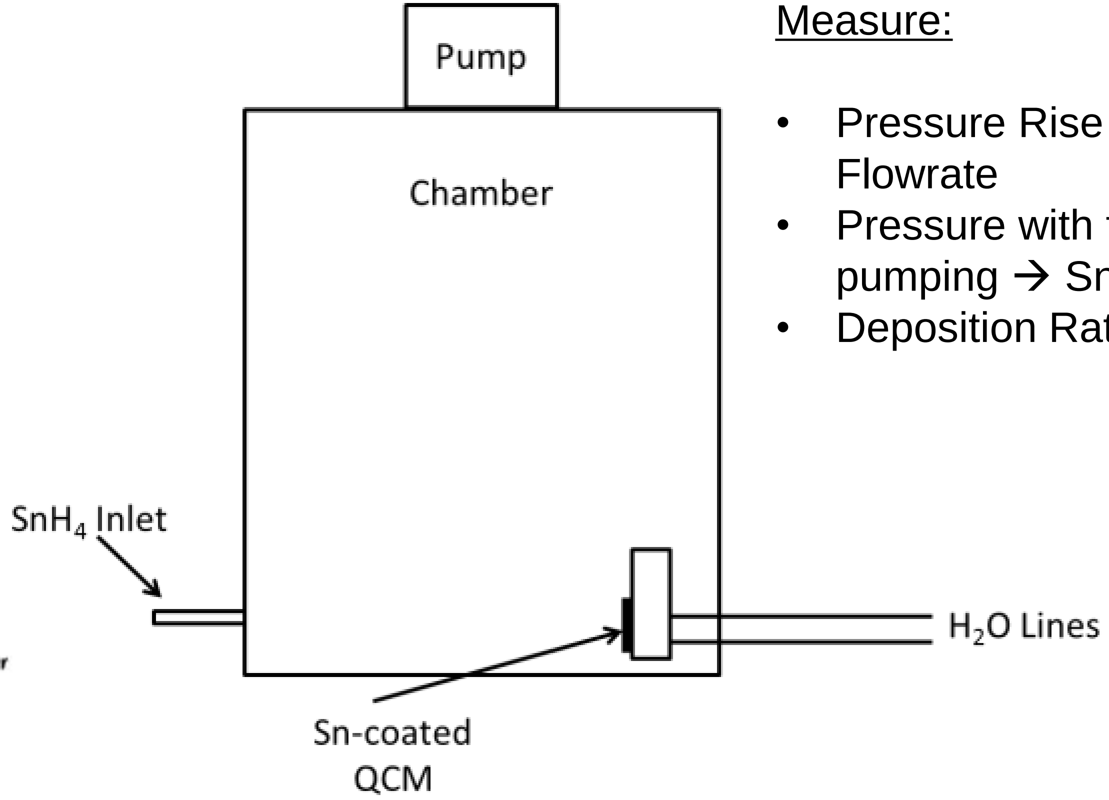
- Flow SnH_4 into chamber; measure deposition on temperature-controlled Sn-coated QCM.
- However, SnH_4 will need to be produced.
- One way: $SnCl_4 + LiAlH_4 \rightarrow LiCl + AlCl_3 + SnH_4$
- Possible Setup for SnH_4 Synthesis and Deposition:

SnH_4 source



Norman, et al., 1968

Deposition Chamber



<u>Measure:</u>

- Pressure Rise Time → SnH_4 Flowrate
- Pressure with flow and pumping → SnH_4 Density
- Deposition Rate on QCM

MSWP Chamber to be Used for Experiments

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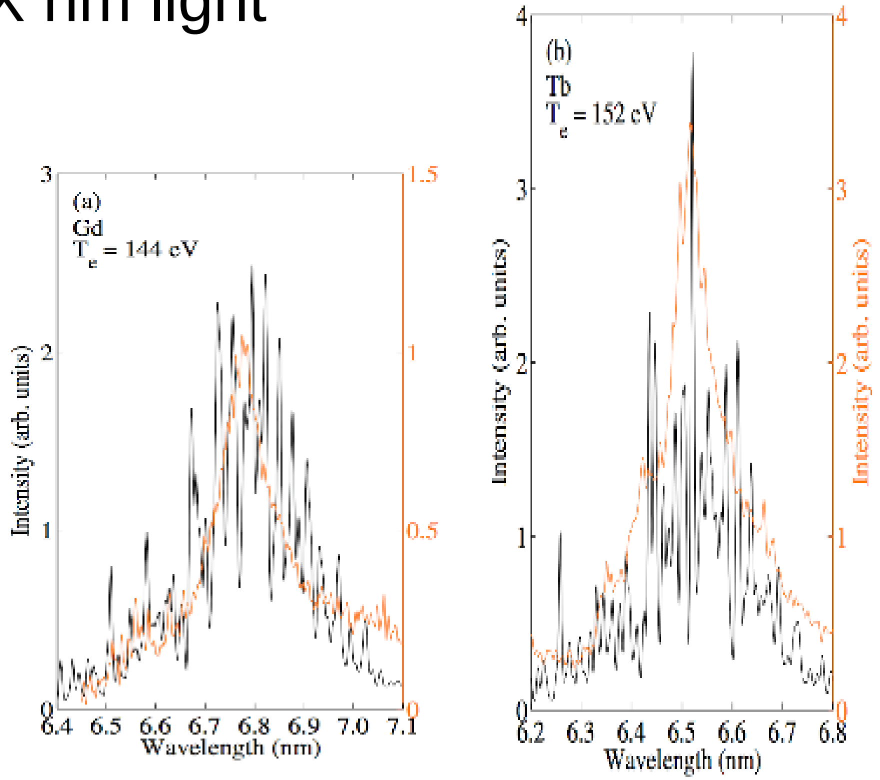
Beyond EUV

Transition to 6.X nm light

- Two fuels of importance: Gd , Tb
- Gd peak : 6.775 nm
- Tb peak : 6.515 nm
- La/B, LaN/B , LaN/B_4C frontrunner multilayer mirrors.
- Boron has K-absorption edge at 6.6nm.
- Theoretical R_{max} is high (~80%), but bandwidth is low (0.6%)
- However, real mirrors have yet to reach above 60%.
- This hinders development of BEUV.



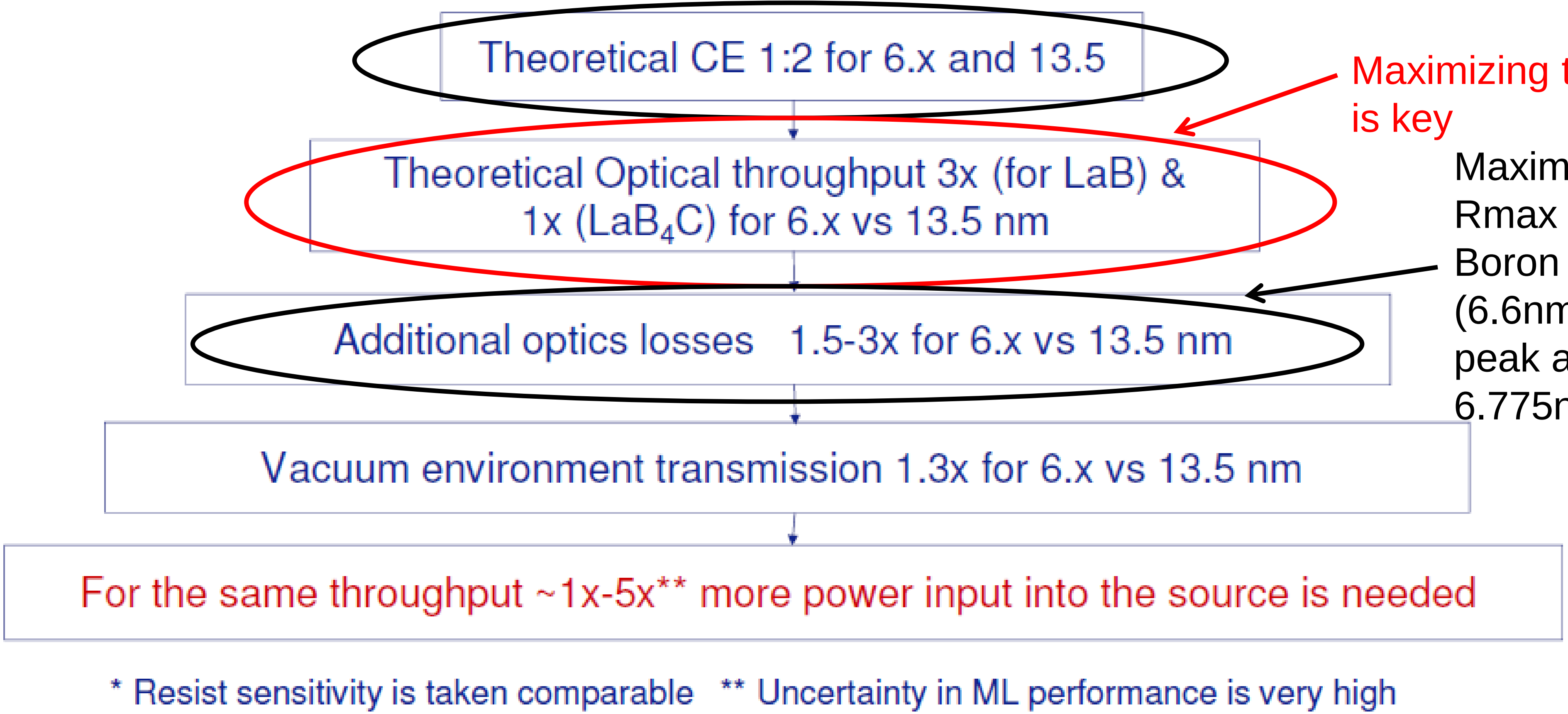
Kilban and O'Sullivan, 2010

For peak intensity **Tb is better than Gd.**

For peak MLM reflectivity **Gd is better than Tb.**

Feasibility of 6.7nm

Accounts for 0.6% bw



Theoretical CE 1:2 for 6.x and 13.5

Maximizing this is key

Theoretical Optical throughput 3x (for LaB) & 1x (LaB_4C) for 6.x vs 13.5 nm

Maximum Rmax at Boron K-edge (6.6nm); Gd peak at 6.775nm

Additional optics losses 1.5-3x for 6.x vs 13.5 nm

Vacuum environment transmission 1.3x for 6.x vs 13.5 nm

For the same throughput ~1x-5x** more power input into the source is needed

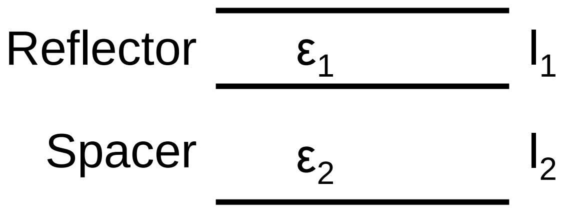
* Resist sensitivity is taken comparable ** Uncertainty in ML performance is very high

ASML & Zeiss, SPIE 2012

If we can maximize the reflectivity, 6.7nm stands a shot.

How an MLM Works

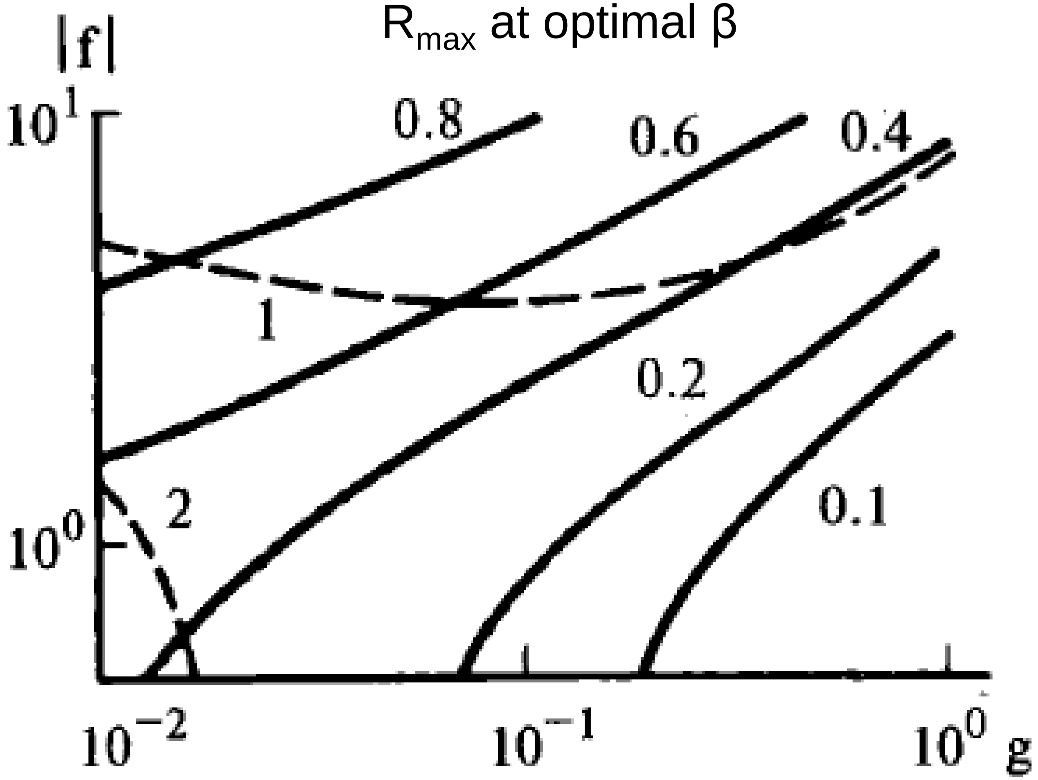
- Bragg Reflection
- Reflectivity is function of f, g, β
- Optimal β: $\tan \pi\beta_* = \pi(\beta_* + g)$



$$\beta = \frac{l_1}{l_2}$$

$$f = \frac{\mathrm{Re}(\varepsilon_1 - \varepsilon_2)}{\mathrm{Im}(\varepsilon_1 - \varepsilon_2)} \quad g = \frac{\mathrm{Im}\,\varepsilon_2}{\mathrm{Im}(\varepsilon_1 - \varepsilon_2)}$$

R_{max} at optimal β

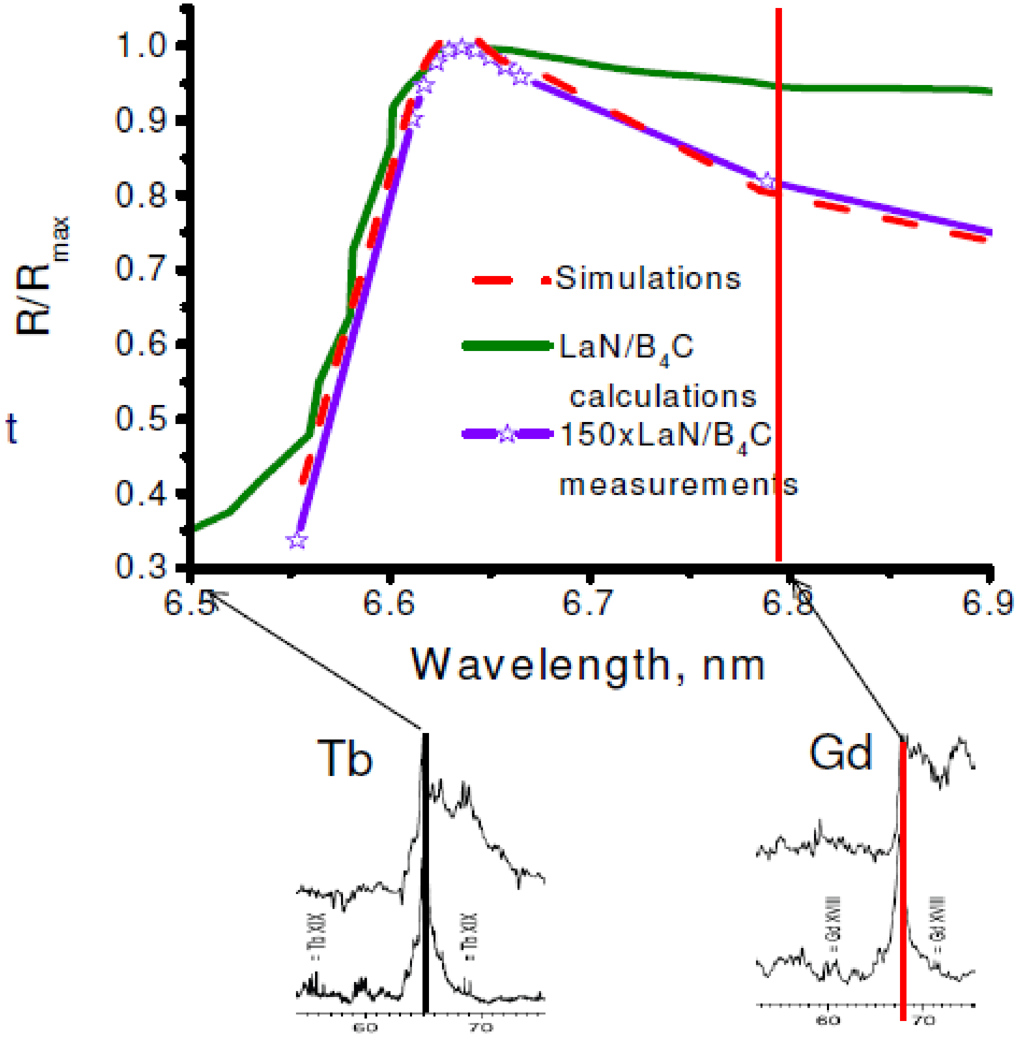


Kozhevnikov, 1995

- Minimize g: low Im(ε_2). Spacer should have lowest possible absorption.
- Maximize f: High Re(ε_1- ε_2). High permittivity contrast between materials.
- Ratio of l_1/l_2: Solving $\tan \pi\beta_* = \pi(\beta_* + g)$ yields optimal β.
- High f also leads to high bandwidth (low resolving power).

Wavelength “Mismatch”

- Spacer material is chosen for having an absorption edge just below wavelength of interest.
- Boron has K-absoprtion edge at 6.6nm
- Just above absorption edge, Im(ε_2) is very small.
- Gd peak at 6.775nm; Im(ε_2) a bit higher here → reflectivity lower.

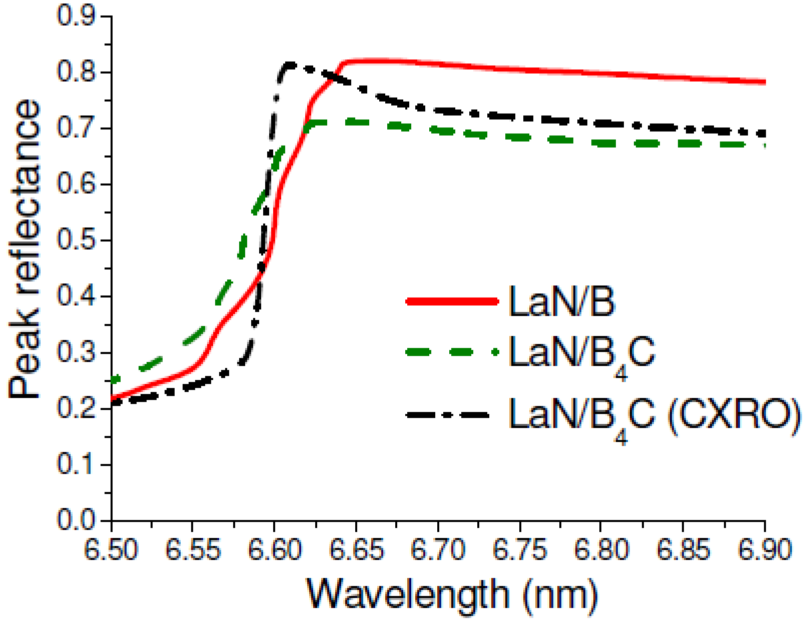


Makhotkin et al., 2012

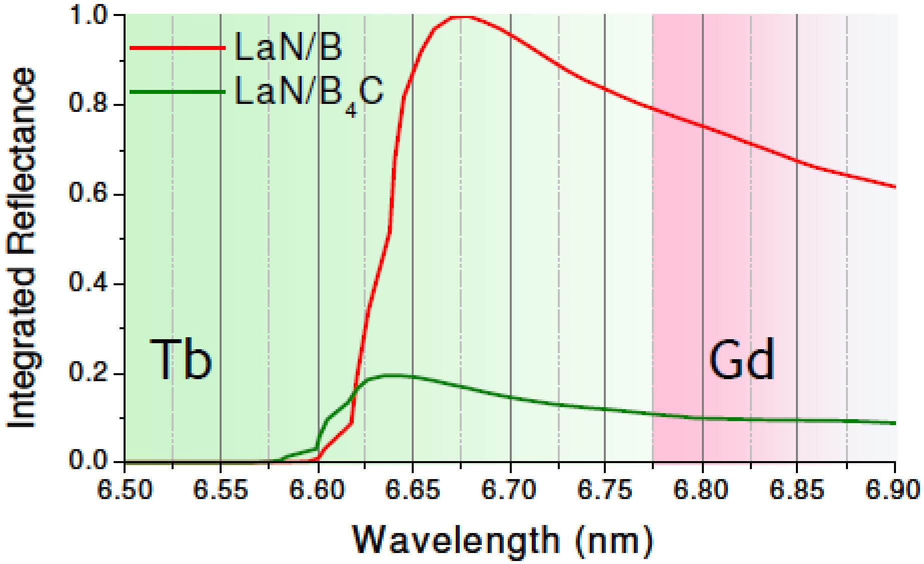
Importance of Every Percentage

- Every reflectivity percentage counts.
- For example, La/B mirrors have theoretical peak R only slightly above that of theoretical peak of La/B_4C.
- However, after going through a 10-mirror chain, that small difference removes a great deal of BEUV power.

Single Mirror R_{max}



Integrated reflectivity of 10-mirror chain



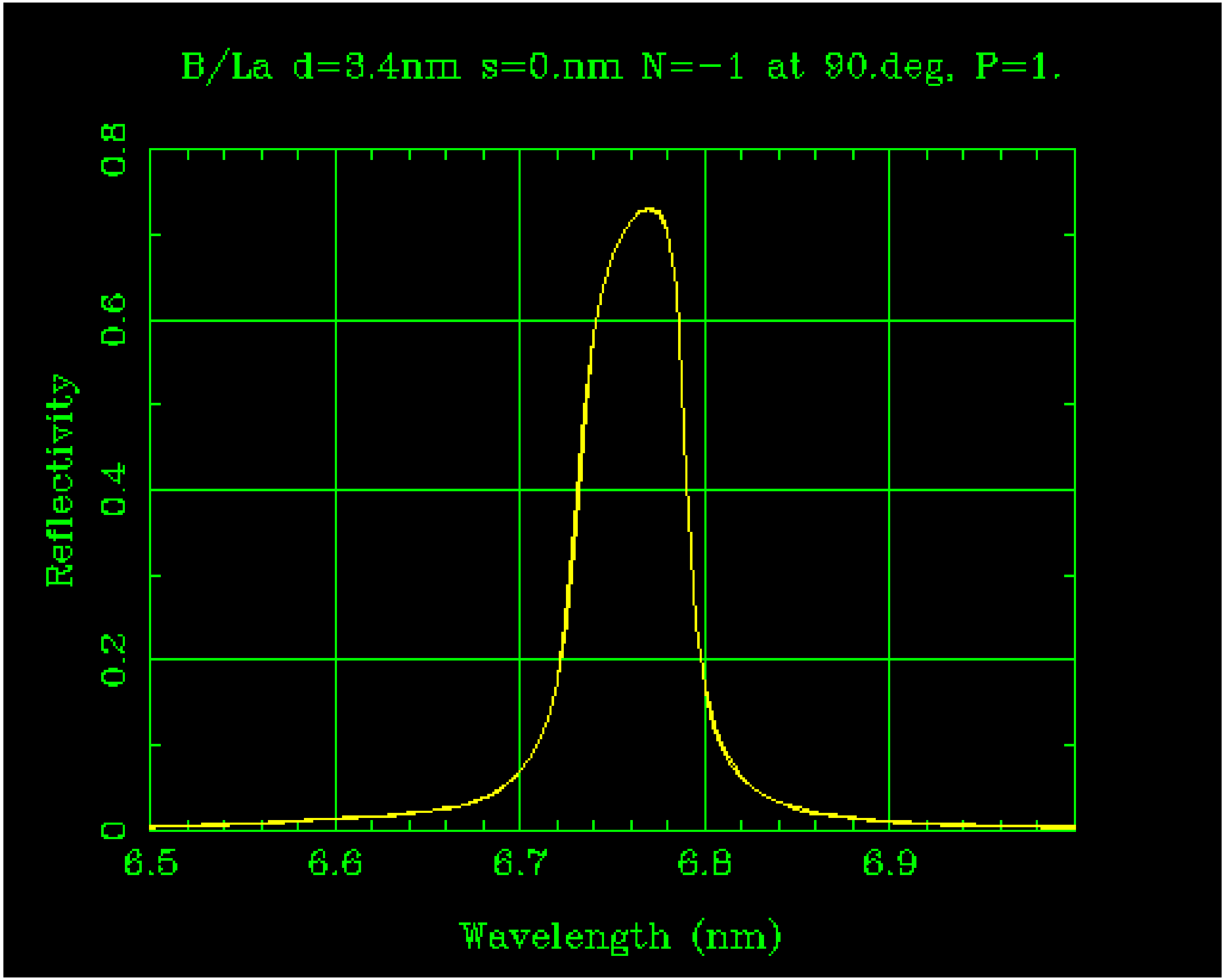
Makhotkin, 2013

Ways to Increase Real MLM Reflectivity

- Roughness and intermixing reduce permittivity contrast and reduce reflectivity.
  - Reduce intermixing: lower temperature, use compounds (such as LaN) that reduce reactivity.
  - Reduce roughness: use high mobility deposition (magnetron sputtering)
  - Ideal: ALD, potentially with ion polishing (a la Wulfhekel)
- B deposition more difficult than B_4C deposition, but B is more desirable (less-absorbing).
- Density Control
  - Density can be varied by deposition technique
  - Lowering density of spacer (boron) lowers its absorption
  - Potentially deposit some boron hydride film or B interspersed with H_2 bubbles

Density Effect

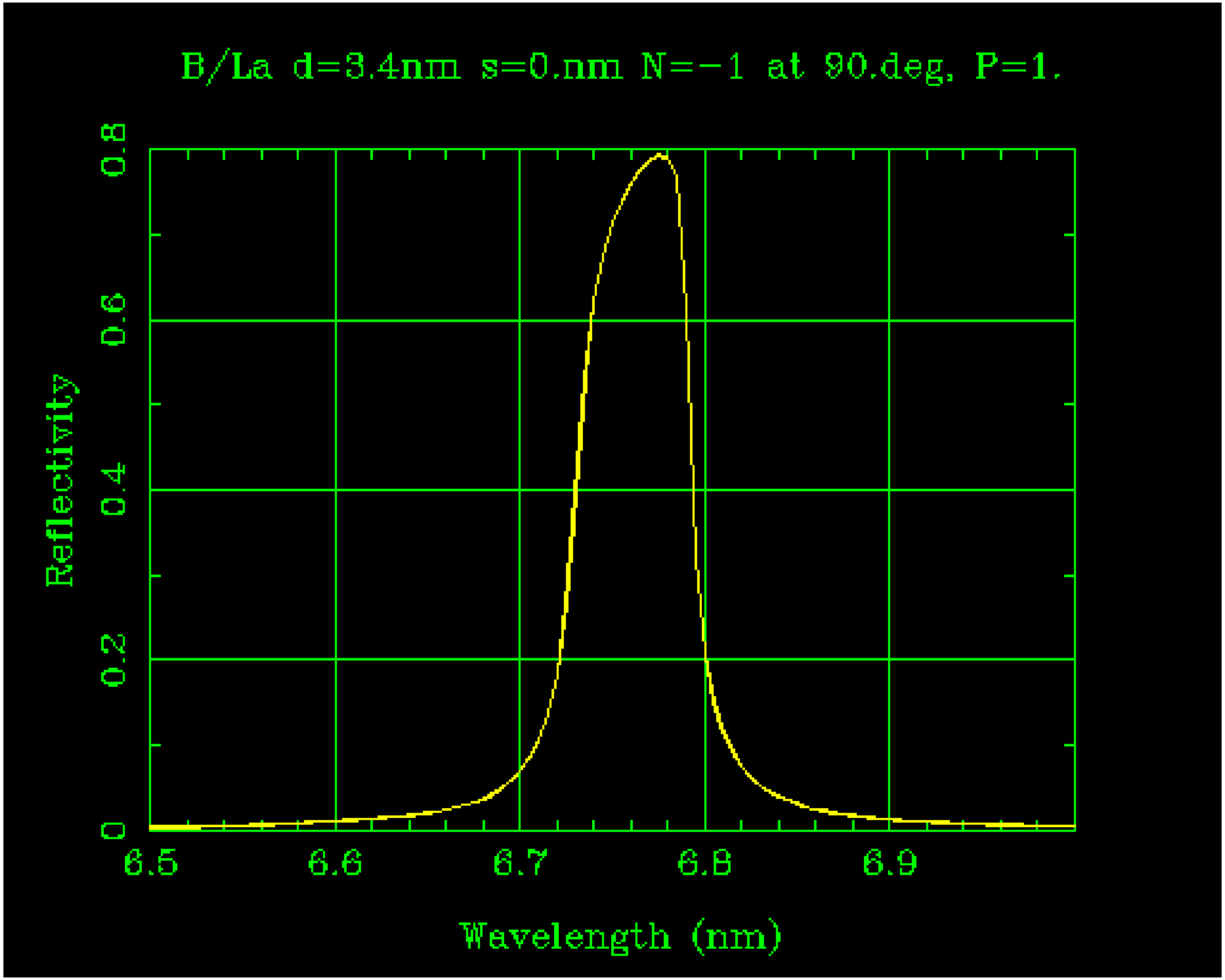
Example: semi-infinite mirror, Gd peak, La/B, β=0.35, ρ_B=2.37g/cm^3 (normal density)



Calculated on LBNL website <http://henke.lbl.gov/optical_constants/multi2.html>

Density Effect

Semi-infinite mirror, Gd peak, La/B, β=0.35, ρ_B=1.15g/cm^3



Note the reflectivity jump! Can we achieve this kind of density reduction?

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Beyond EUV Source

Source Problems

- Disadvantages: Gd and Tb have high melting temperatures (1,312°C, 1,356°C respectively)
- Require solid fuel injection
- Fuel must be dense enough to have high CE , yet transmittance is an issue.
- Fuel must be large enough to utilize full laser spot.

Solution

- Form hydrocarbon particle with Gd/Tb embedded
- H/C have low 6.5 nm absorption cross section
- IR transmittance of most hydrocarbons > 90%
- Resulting spherical fuel large enough to absorb all IR energy but metal density low enough to allow EUV transparency.

Element	Absorption Cross Section (cm^2/mg)	Energy (eV)	Wavelength (nm)
Hydrogen	1.68	190	6.5
Carbon	6.27	190	6.5
Nitrogen	10.65	190	6.5
Oxygen	17.99	190	6.5
Gadolinium	23.74	185	6.7
Terbium	28.03	190	6.5

Fuel Synthesis Methods

Possible Methods

- Pulsed laser ablation of solid or gas target.
- Microplasma with gas or solid electrode.
- Plasma spray synthesis (spray pyrolysis) with oxygen-free environment.
- Magnetron sputtering in hydrocarbon atmosphere.

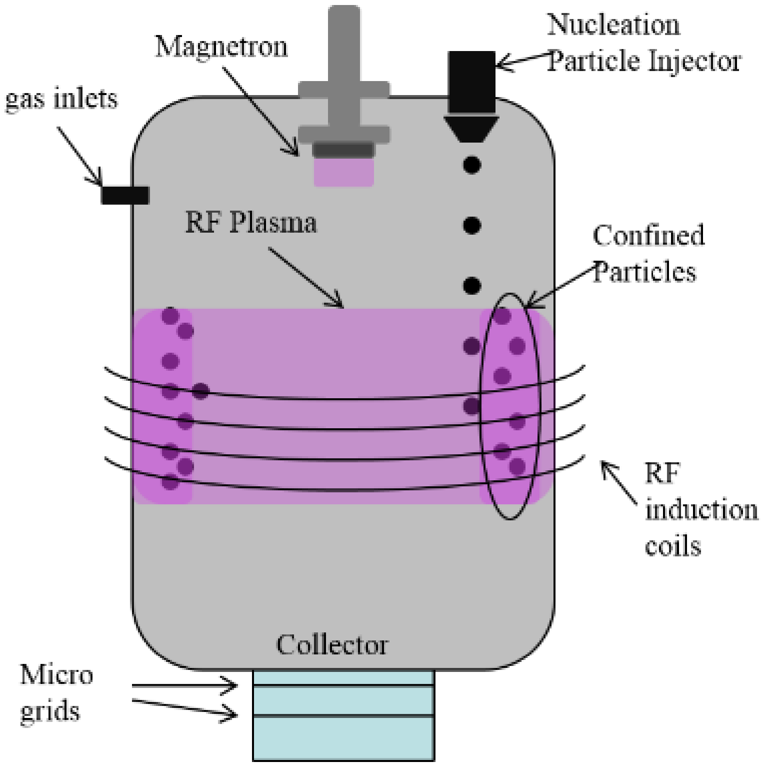
1. Not only is a magnetron simple and flexible, but particle size is mostly dependent on confinement time in plasma.
2. Also, because of charging of particles in the dusty plasma, agglomeration is likely lower.

- Particles would be made in a separate chamber, collected in a portable chamber and attached to existing EUV chamber.

Beyond EUV Particle Generator

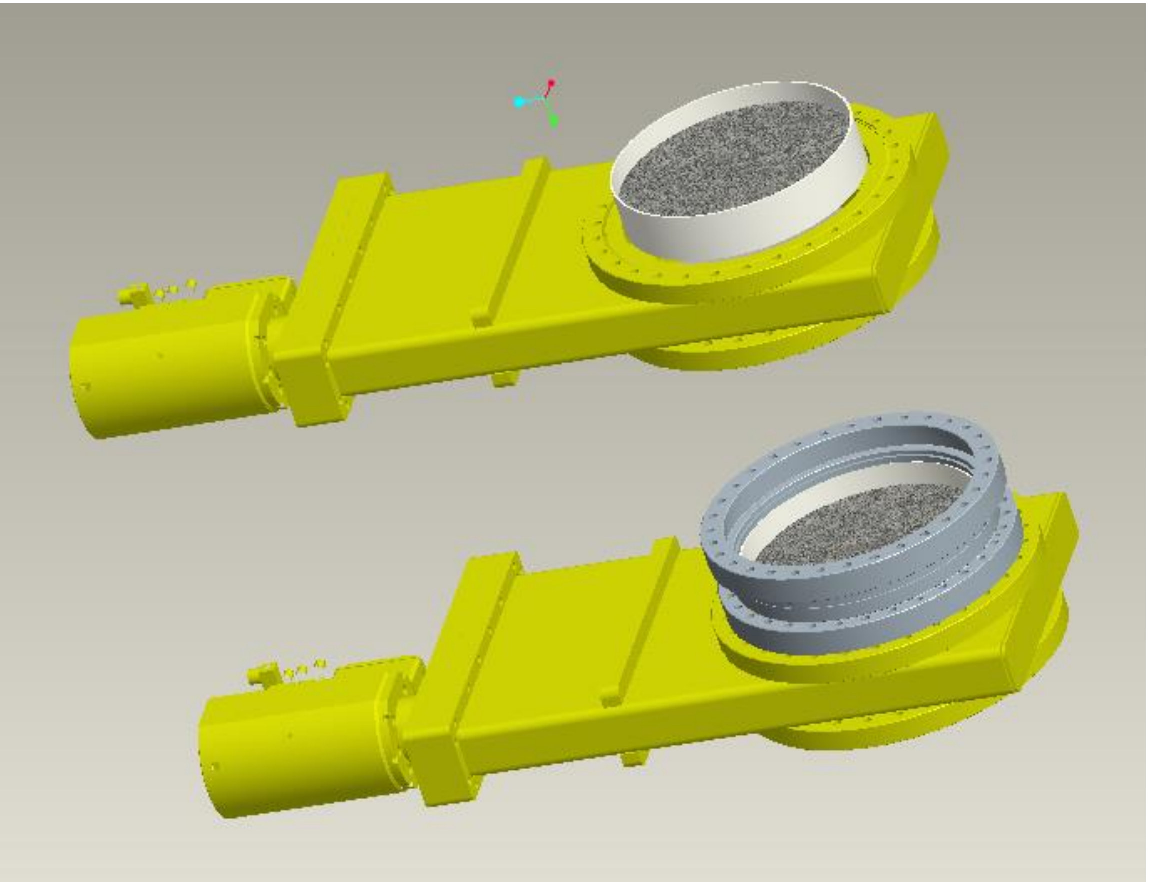
Magnetron Synthesis Method: Dusty Particles

- System consists of Gd/Tb magnetron target and an Ar/methane inductively coupled plasma.
- Initial hydrocarbon particles (100 nm diameter polyethylene spheres) are injected to provide nucleation sites for hydrocarbon monomers and Gd/Tb.
- Hydrocarbon monomers ionize and form branched polymers due to plasma polymerization on the surface of the polyethylene spheres.
- Gd/Tb is assumed to sputter and embed in the particles.
- Bottom "Collector" consists of microgrids that filter out particles larger and smaller than desired size.



Beyond EUV Particle Collector

Particle Collector design



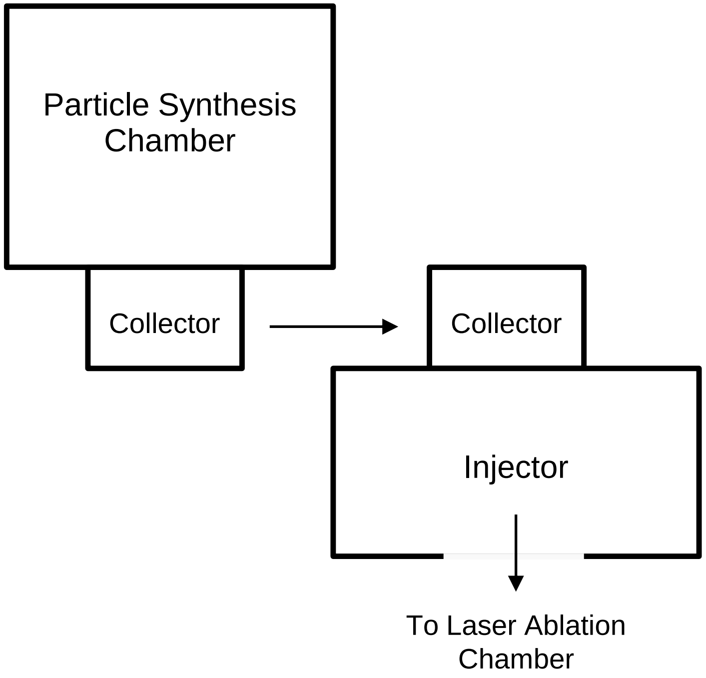
- Series of two grids with circular apertures.
- First grid allows particles greater than chosen size through. Larger particles are pumped out after particle synthesis complete.
- Second grid allows smaller particles than chosen size through. Pump below this grid takes away smaller particles.
- When completed, two gate valves above and below grids are closed in order to transport particles to injector system.

Beyond EUV

Possible Delivery Methods

- Suspend particles in liquid.
- Piezo-electric shaker coupled with an impeller.

- Overall system designed shown below.



Conclusions

- A theoretical framework has been developed for SnH_4 removal.
- Flow velocity profiles for use in diffusion-advection of SnH_4 have been computed.
- Radical probe measurements show nonlinear increase in radical density with pressure.
- 0D plasma chemistry model has been used to validate the radical probe as an experimental diagnostic.
- Currently, poor MLM reflectivity hinders BEUV development.
- Reflectivity can be raised by improving deposition techniques, enabling ALD, and reducing density of deposited B films.
- A new approach for a BEUV source has been proposed.
- With good MLM and source technology, BEUV may be able to succeed.

Acknowledgments

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- Thanks to undergraduate assistants Valentin Castro and Shanna Bobbins.

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