Advanced Fuel (Sn and Li) EUV Source Development, Debris Characterization, and Optics Testing at the University of Illinois

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Outline (1)

What comes out of a DPP that could damage mirrors?

- **Measurements of Ion Energy Spectra from a XTS 13-35 DPP in Xe with and without mitigation** Poster CoP 05

Does it really damage them, and what does that damage look like?

- **Exposure of Candidate Condenser-Optic Materials for 10 Million Shots**
- **Before and After Comparison of samples by AES, XPS, AFM, SEM, XRR, and XRD** Posters CoP 02 and CoP 09

Do these results make sense?

- **Comparison of Predicted Erosion (from knowing ion flux) to Actual Erosion (from SEM cross-sections)** Poster CoP 07

Outline (2)

Sn and Li have higher conversion efficiencies. Can mirror erosion be balanced by the condensing fuel?

- **Theoretical modeling of surface balance including an external plasma** Poster CoP 03

Does it work in practice?

- **Surface Cleaning of Optics by Plasma Exposure (SCOPE) Experiment.** Poster CoP 04
- **Diffusive behavior of Li on surfaces** Poster CoP 01
- **Chemical plasma etching of Sn** Poster CoP 10

Can we stop the Sn or Li from getting to the mirror in the first place?

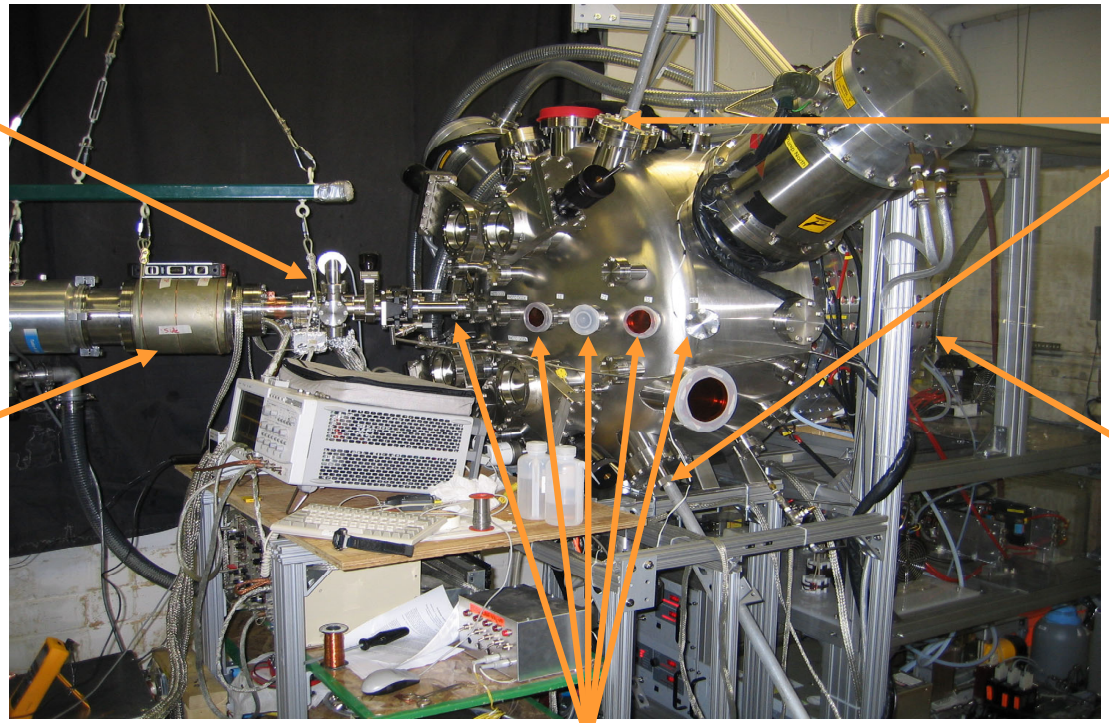
- **Plasma mitigation in the Illinois Debris-mitigation EUV Applications Lab (IDEAL)** Poster CoP 06

XCEED

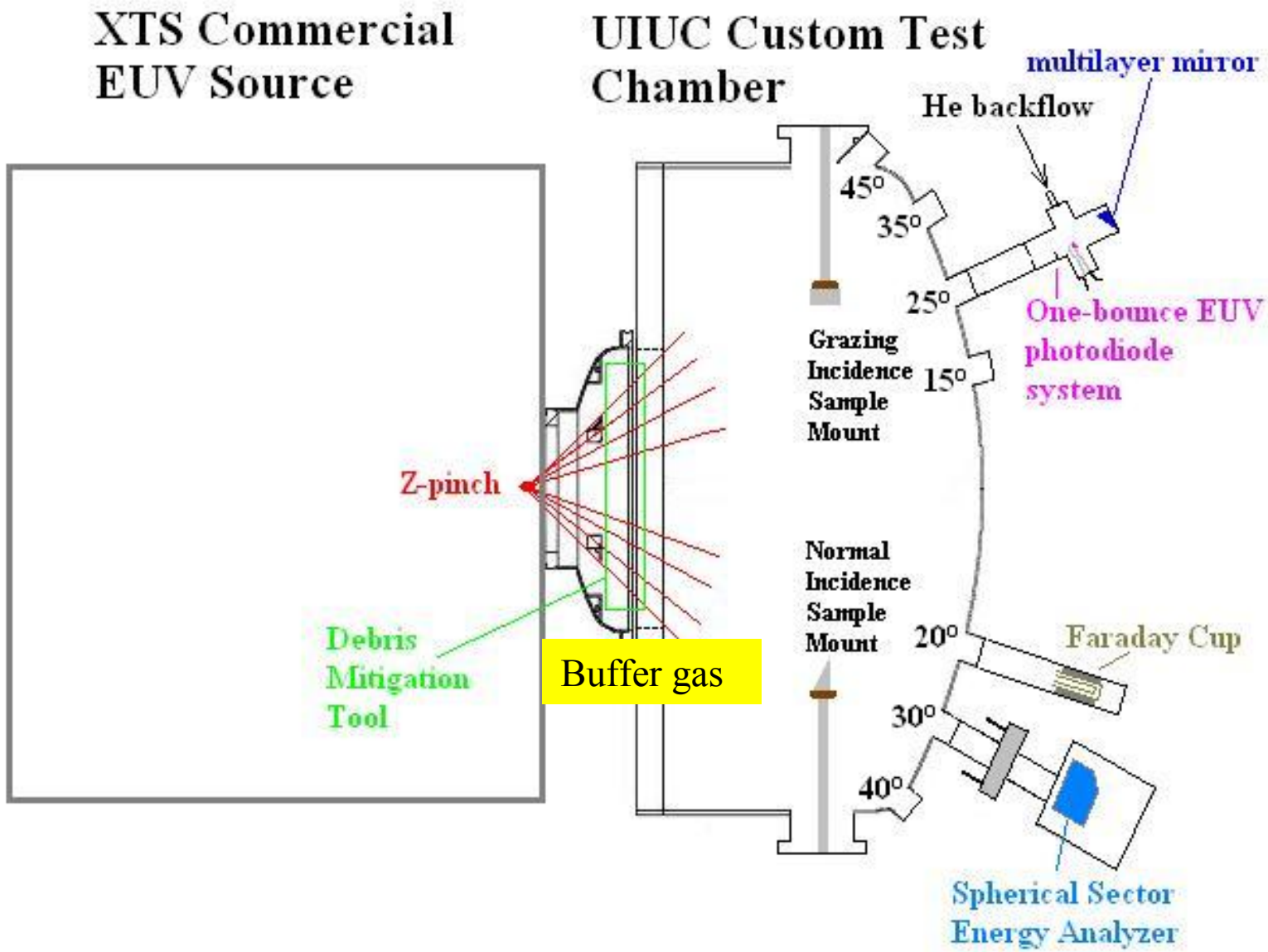
Xtreme Commercial EUV Experiment Diagnostics

- XTS 13-35 source, 256 Hz with Xenon
- Foil trap debris tool and gas buffer
- EUV monitor and debris diagnostics

CoP 05



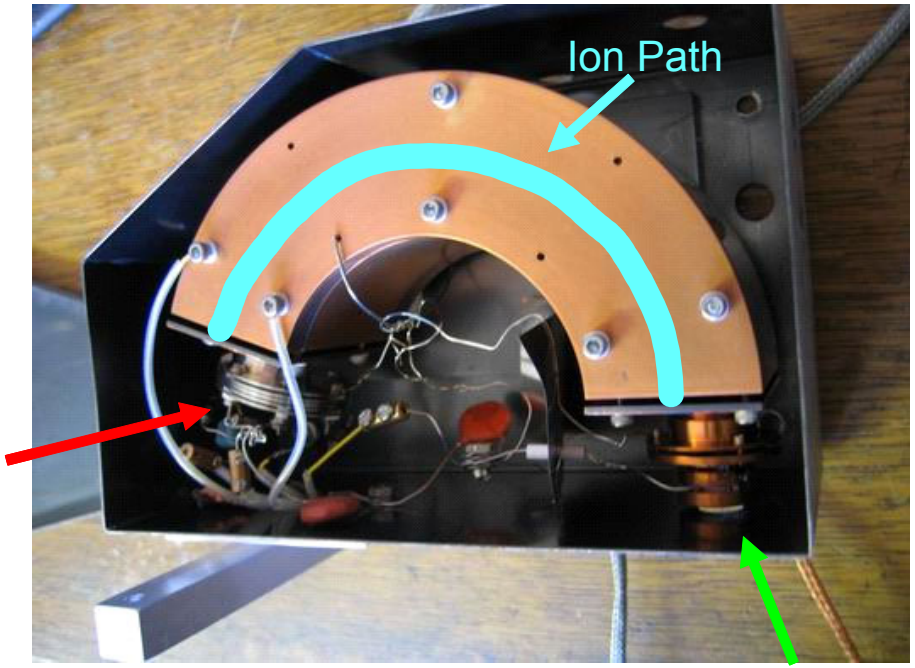
XCEED Schematic and Materials



ESA Theory and Operation

Top and bottom spherical sectors charged to a voltage difference (ΔV) governed by:

$$\frac{E}{q} = \frac{\Delta V}{\left(\frac{r_1}{r_2} - \frac{r_2}{r_1}\right)}$$

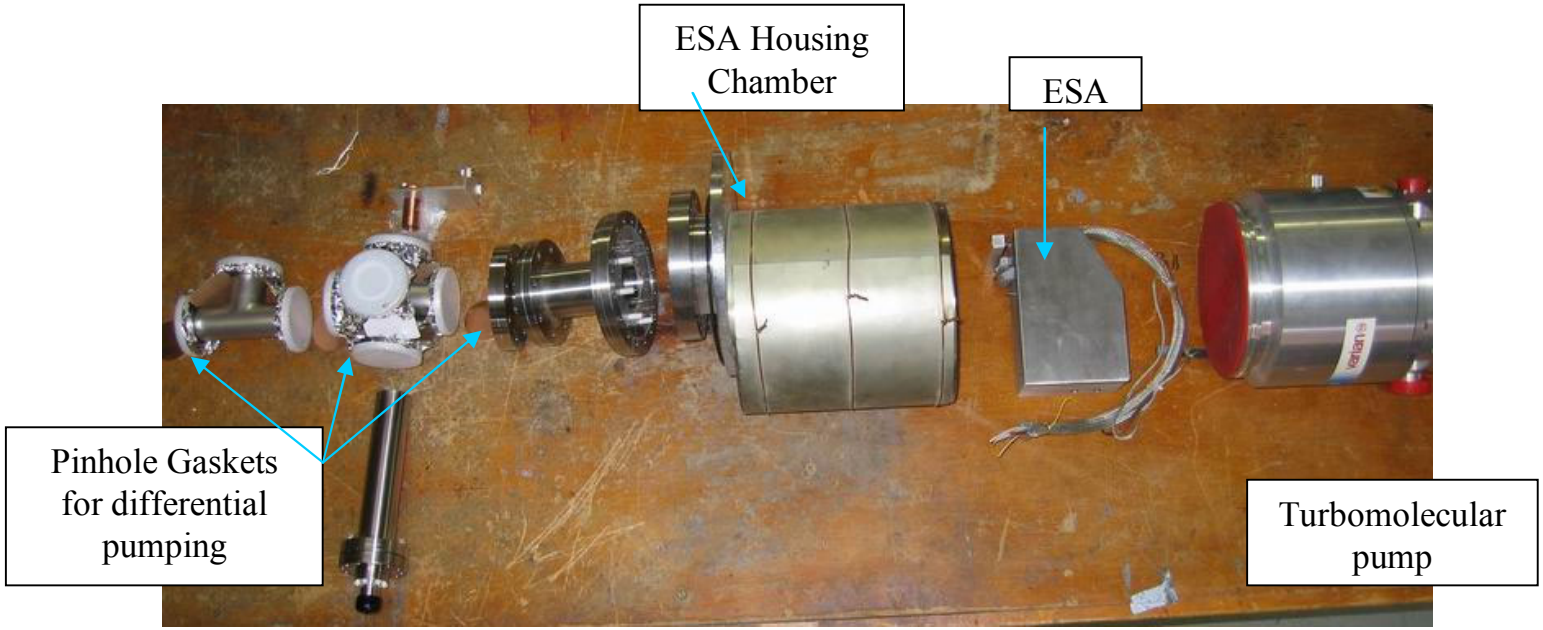


Device resolution includes terms for aperture size (ω = 0.5 - 2 mm), included angle of the analyzer (φ =160°), and the distance from the exit of the sector field to the final exit aperture (δ =1.07 cm)

$$\frac{\Delta E}{E} = \frac{\omega}{\left(R\left(1-\cos\varphi\right)+\delta\sin\varphi\right)}$$

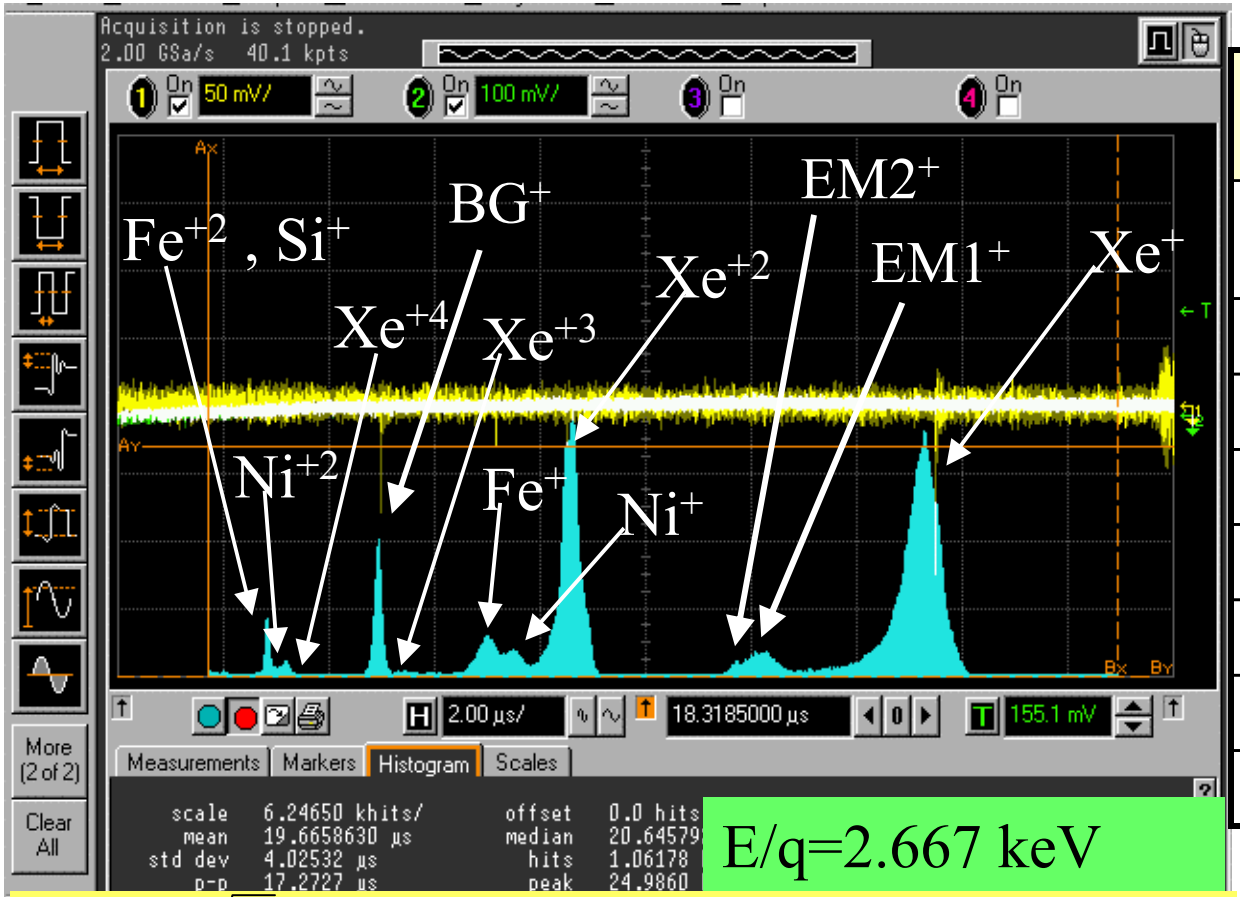
We used an aperture size of 1 mm, and ΔV up to 10 kV. The time of flight distance was 150cm. Energy resolution exceeded expectations.

Energy analyzer moved from port to port to get angular resolution



- **Main tank connection is at the left**
- **Copper blank gaskets with drilled orifices used to control differential pumping levels**
- **Energy analyzer has separate magnetically shielded housing backed by 500 l/s turbopump**

Spectra of debris at 2.667 keV (for 1+) with minimal buffer gas



Specie	Predicted Time (us)	Actual Time (us)
Fe2+, Si+	11.04, 11.07	11.15
Ni2+	11.32	11.31
Xe4+	11.97	11.87
Xe3+	13.82	13.77
Fe+	15.61	15.33
Ni+	16.00	15.80
Xe2+	16.93	16.93
Xe+	23.94	23.59

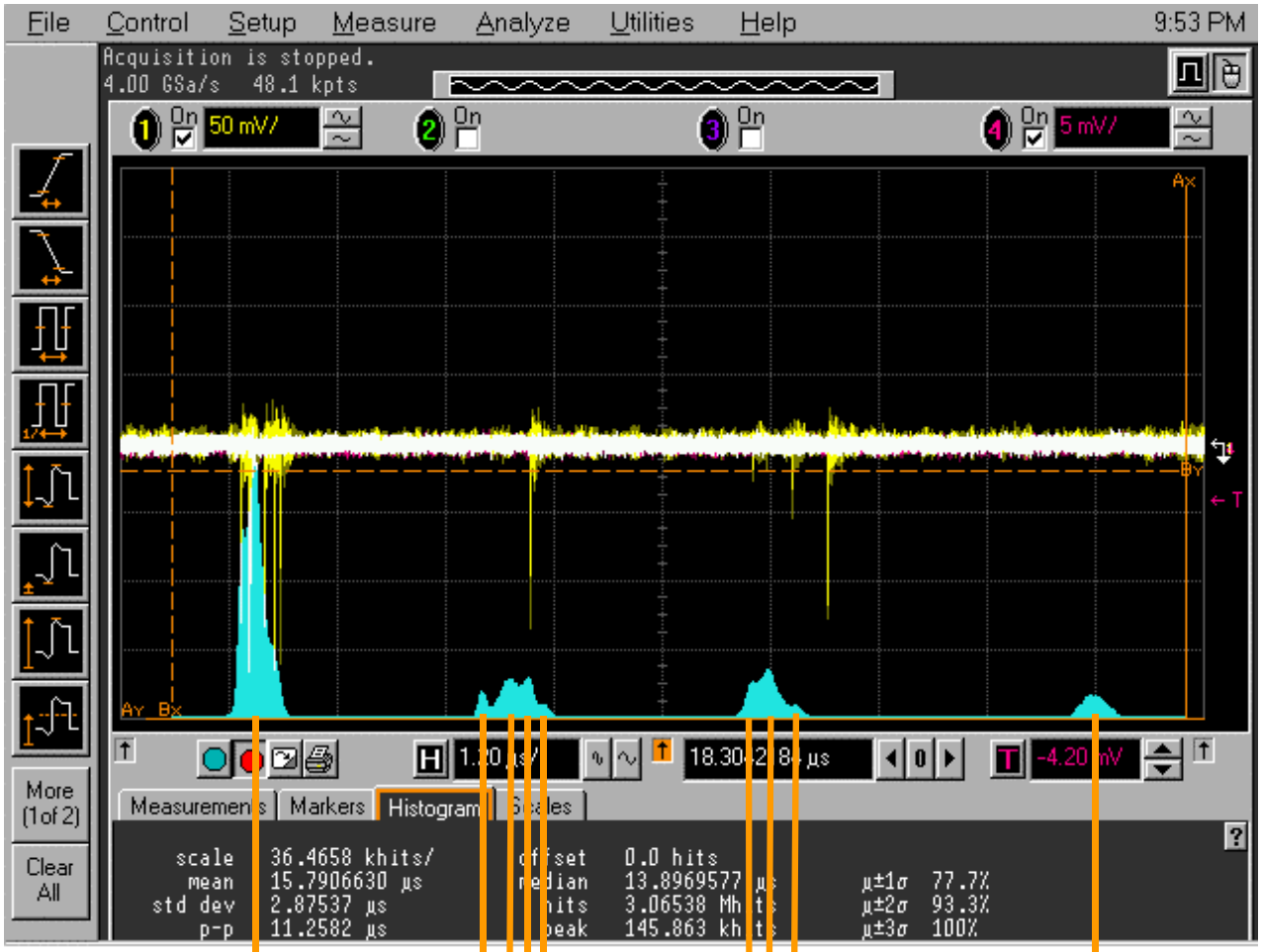
E/q=2.667 keV

$$t = \frac{d\sqrt{m}}{\sqrt{2E}}$$

Distance to source = 150 cm

BG = Buffer Gas, EM = Electrode Material

Resolution is very high ---isotopes can be resolved !



Xe^{+2}

$^{X2}EM2^{+1}$ $^{X5}EM2^{+1}$ $^{X6}EM2^{+1}$ $^{X8}EM2^{+1}$

$^{129}Xe^{+1}$ $^{131}Xe^{+1}$ $^{132}Xe^{+1}$

$EM1^{+1}$

EM = Electrode Material

8,000 eV 4,000 eV 4,000 eV 4,000 eV

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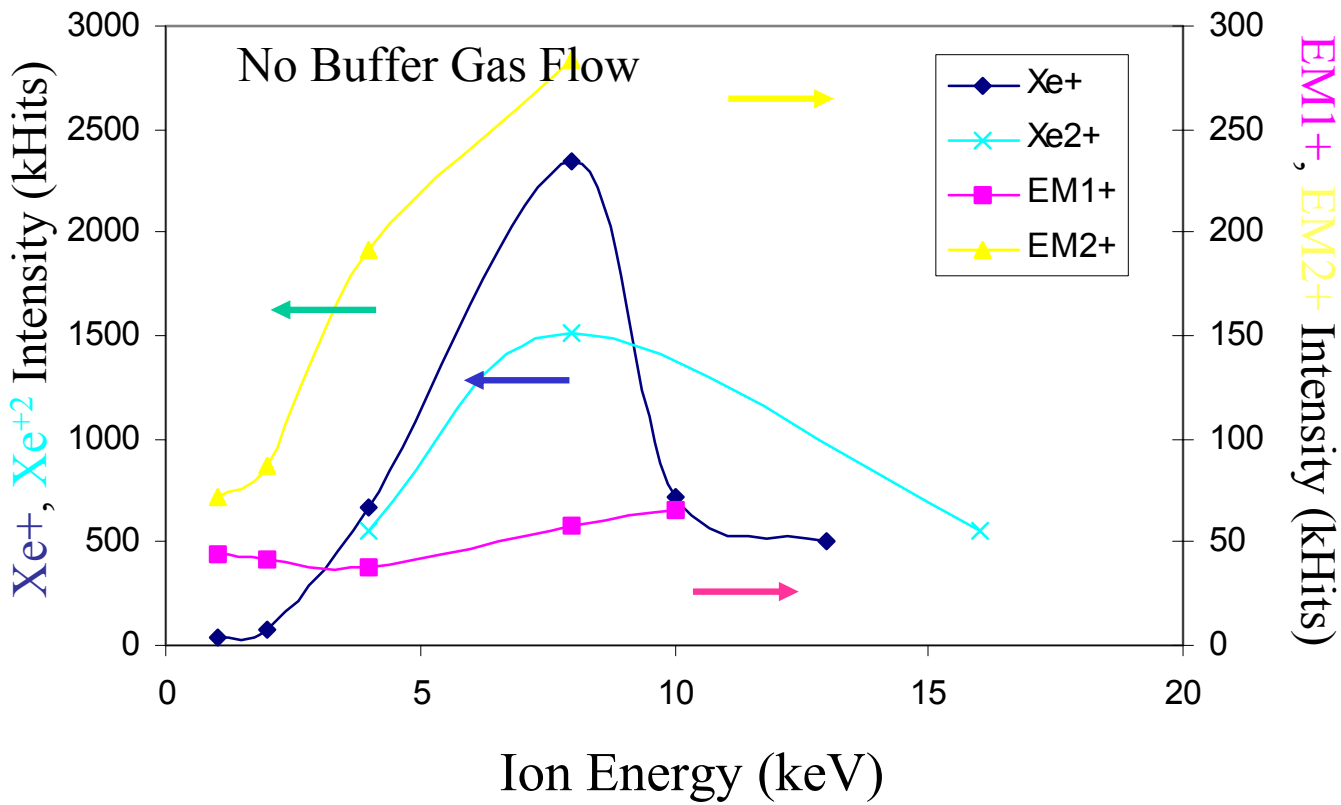
Energy Spectra (without buffer gas)

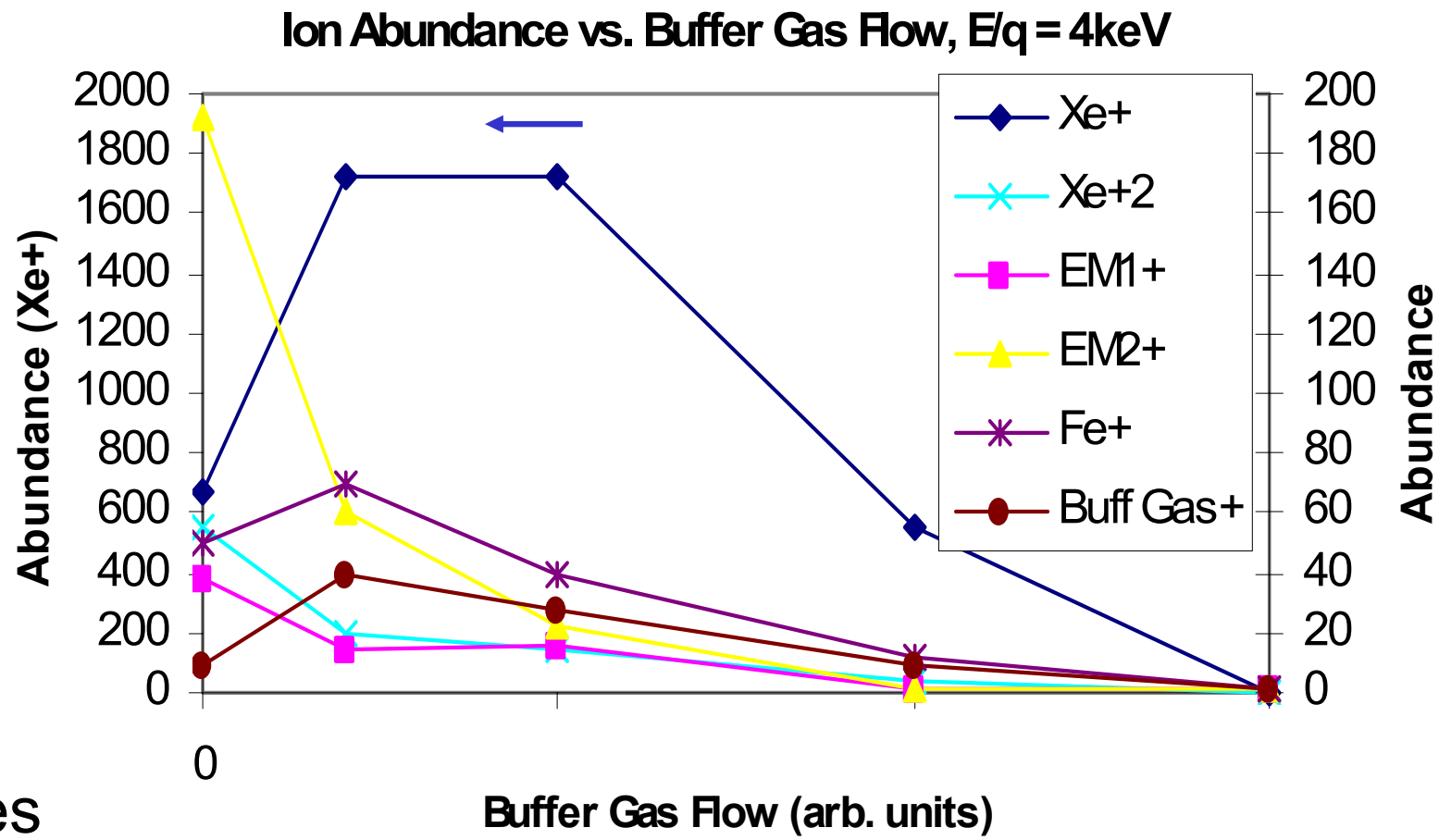
- Xe^{+} and Xe^{++} dominate spectra
- Significant electrode materials present



CoP 05

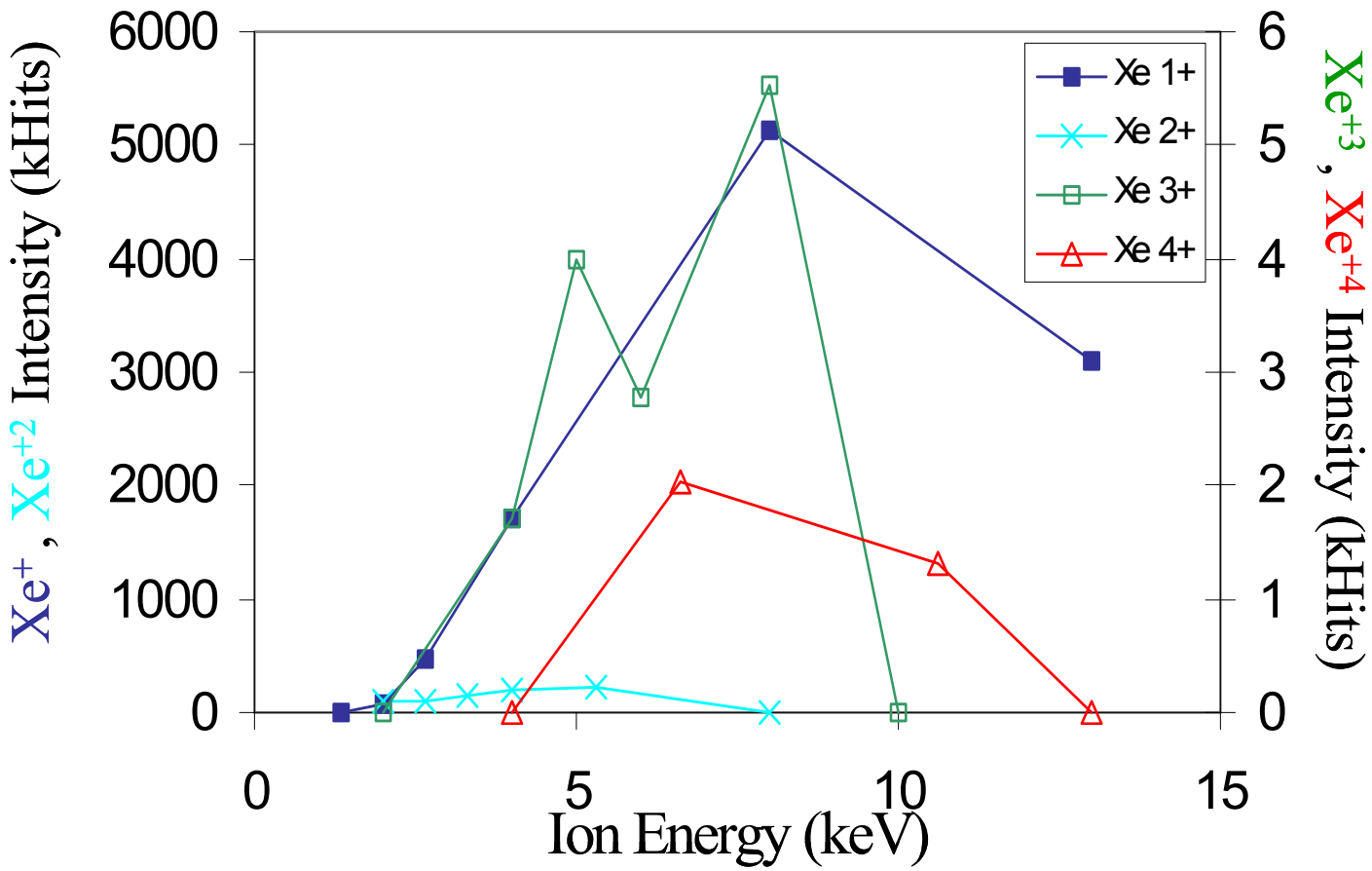
Variation with buffer gas flow rate

- Signal at one energy, (4keV for + 8keV for ++)
- Buffer gas quickly reduces impurity fluxes



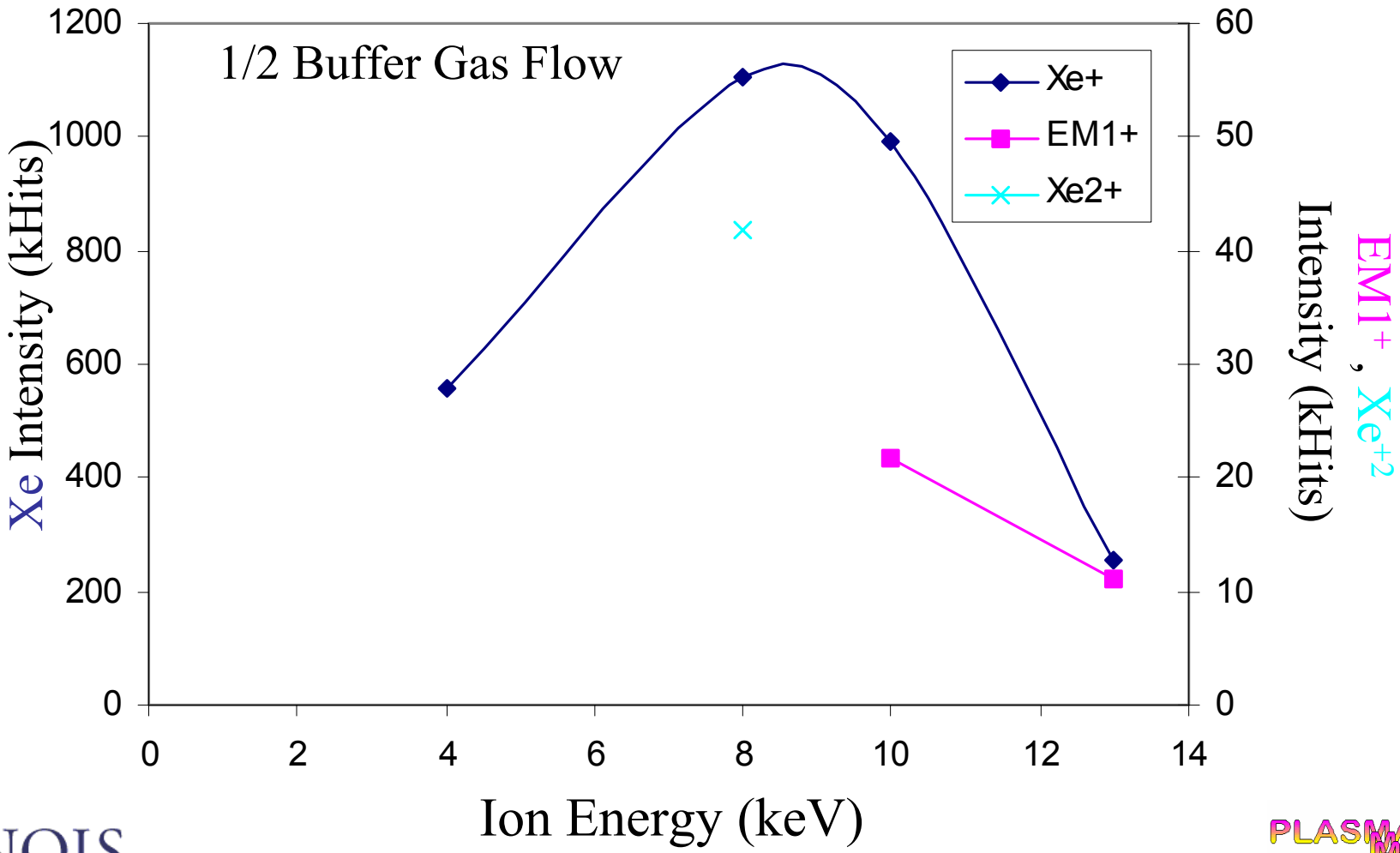
Xe charge states

- Only up to +4 is seen
- At low flow, and lower energy, +2 dominates
- Mean energy is around 8 keV



Samples exposed to this spectra

- Mean energy is 8.4 keV. Xe^+ is only significant species



Samples exposed to 10 million pulses, with full debris mitigation

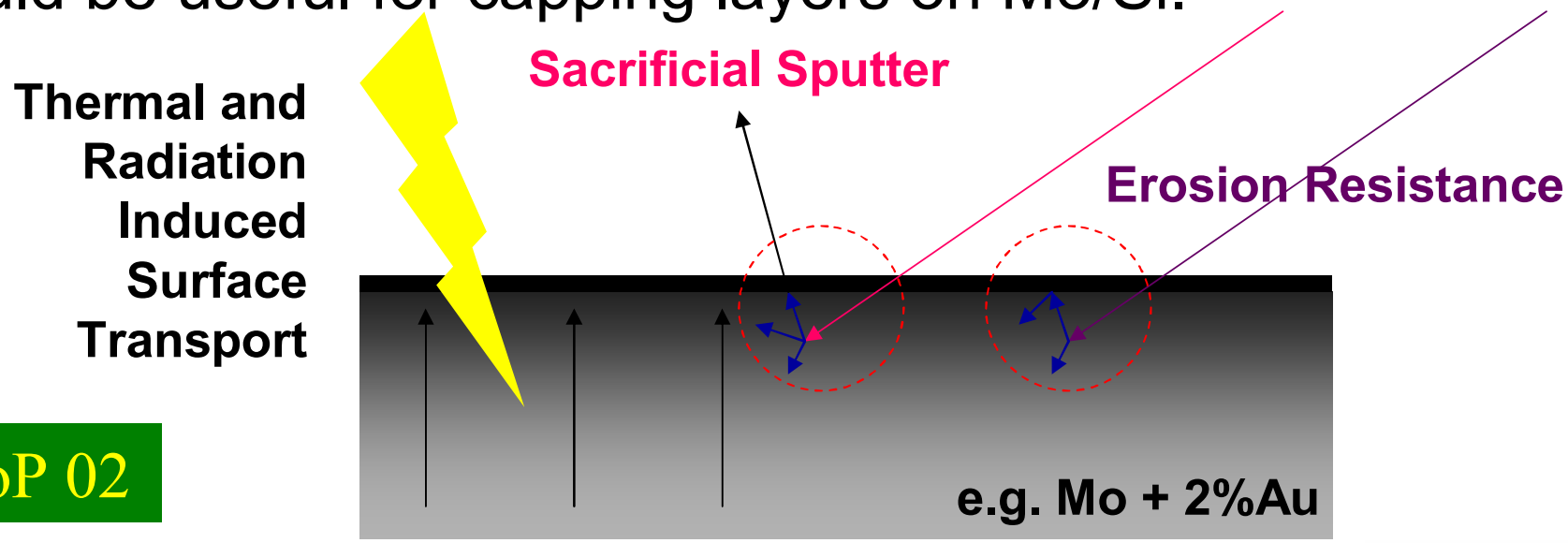
- At normal incidence
  - Ru-capped Si/Mo bilayer (ML1 from LLNL)
  - Si (from LLNL)
  - Mo (from LLNL)
  - C (from LLNL)
  - Au (from LLNL)
- At grazing incidence (23 degrees)
  - Ru (from LLNL)
  - Pd (from LLNL)
  - Au/Mo Gibsean alloy (from UIUC)

CoP 09

- Analyzed pre- and post-exposure with AES, AFM, XPS, SRR, and XRD

Gibbsian Segregation

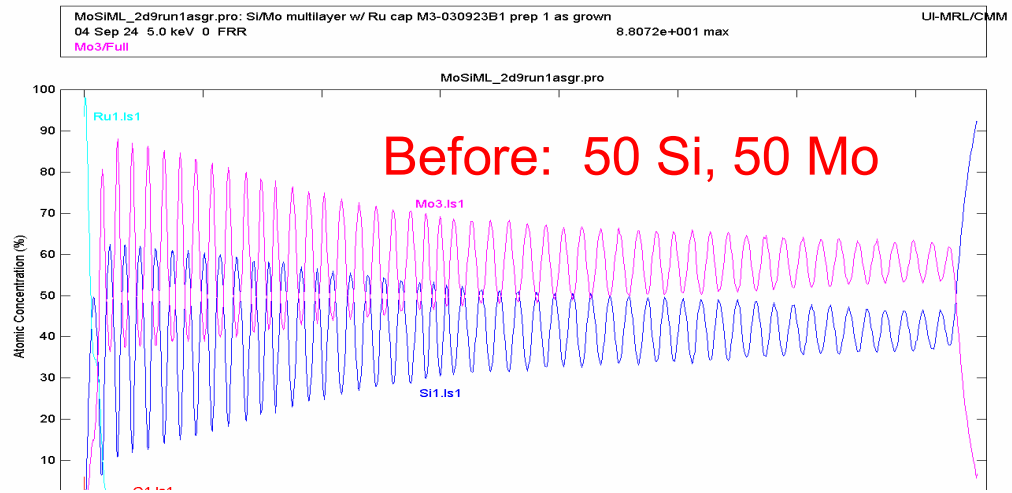
- Heating and radiation-induced effects promote migration and surface segregation of certain materials depending on the surface binding energy.
- VFTRIM studies have shown reduction in Mo sputtering by 2-3.
- Potential to maintain low surface roughness.
- Could be useful for capping layers on Mo/Si.

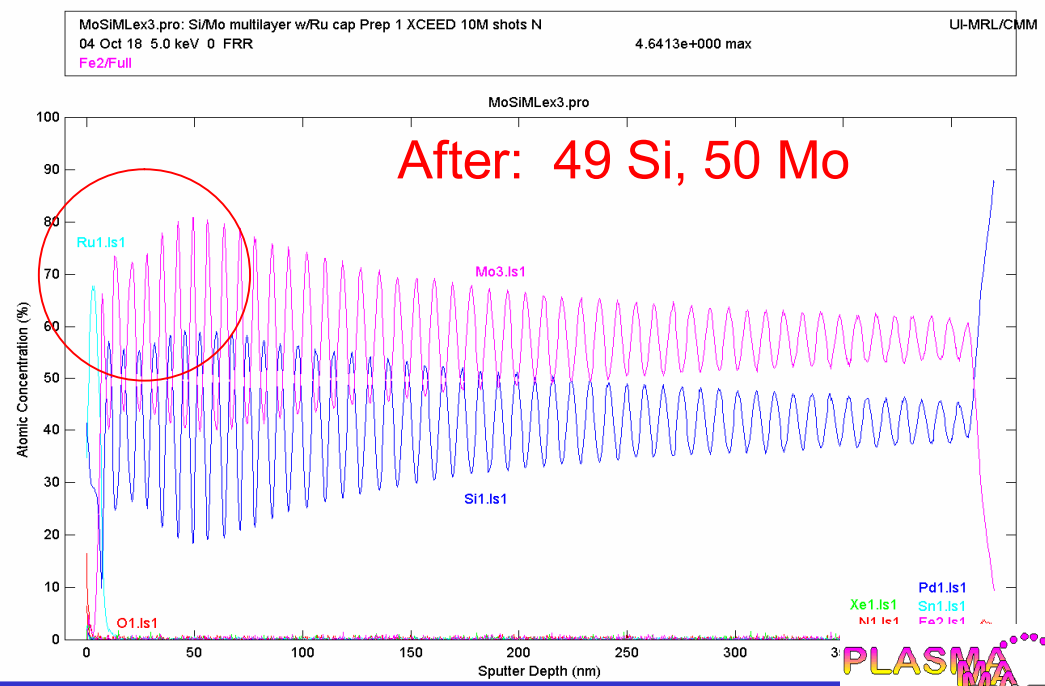


CoP 02

AES on ML1 — shows erosion

- Ru capping layer is eroded and some is pushed into the first Si layer.
- The first Si layer is largely removed too with bilayer mixing present.

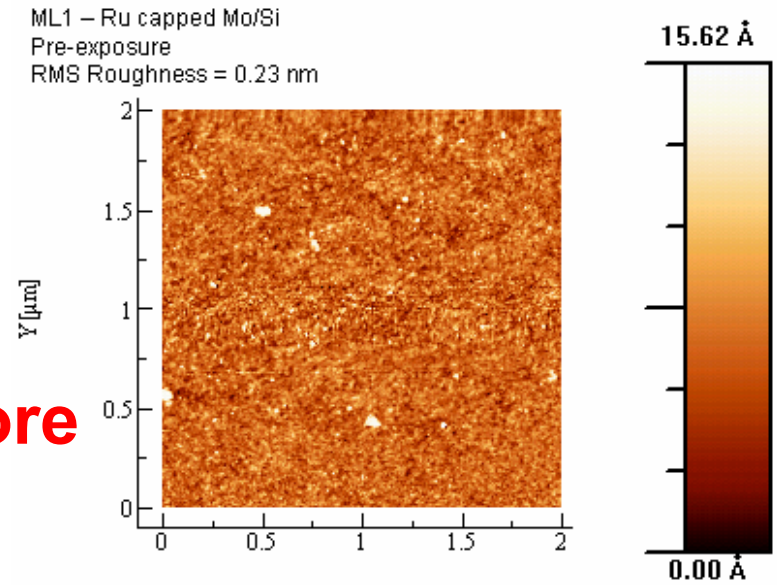




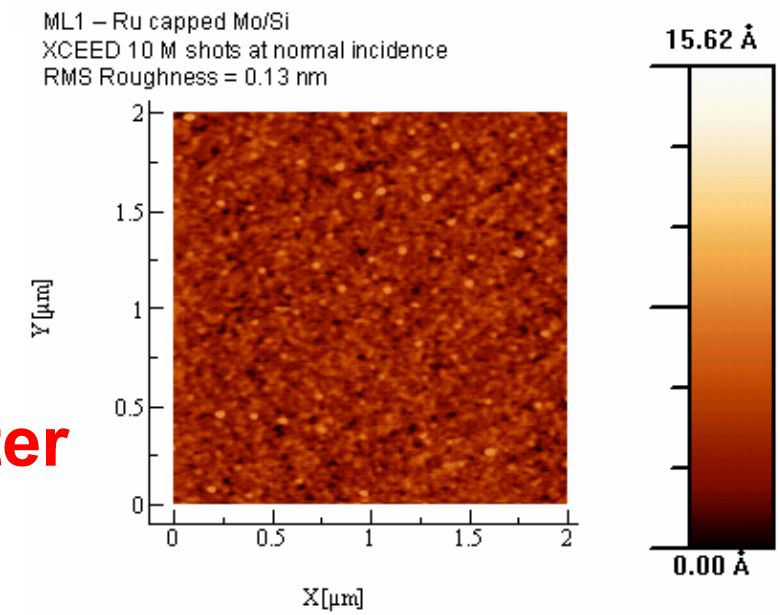
AFM shows ML1 is smoothed

- RMS roughness values change from 0.23 nm to 0.13 nm.
- Probably due to Ru removal, since the underlying Si is smoother.

Before

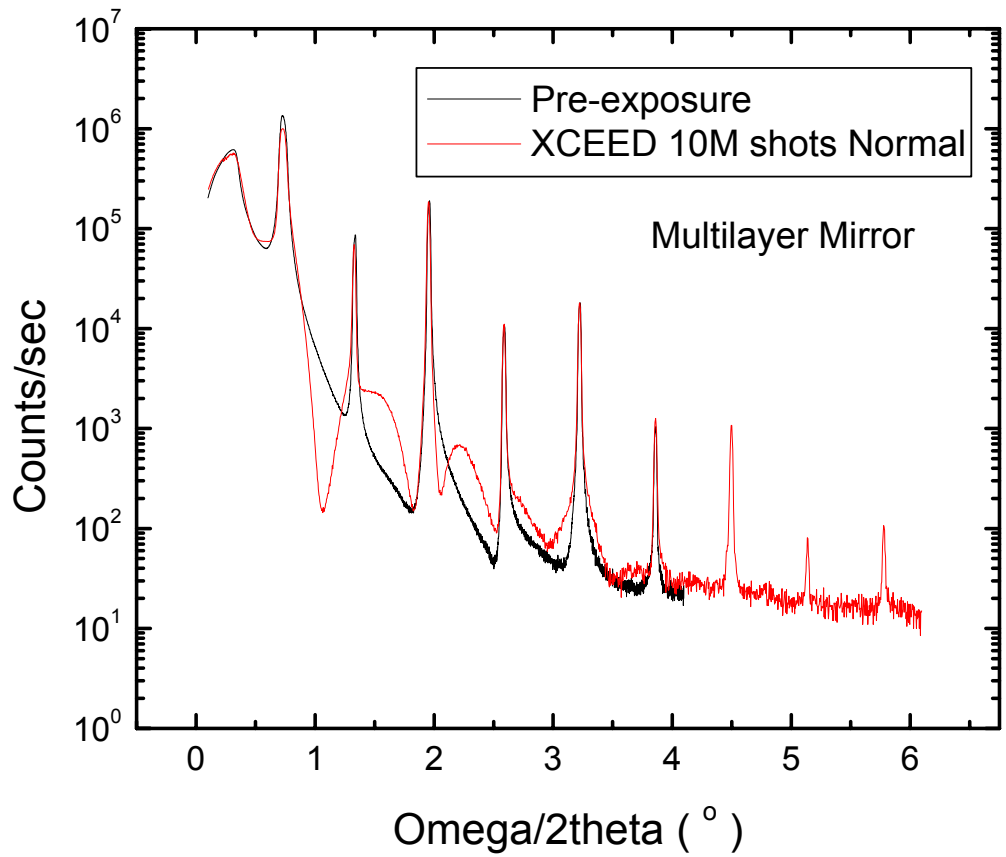


After



XRR confirms smoothening

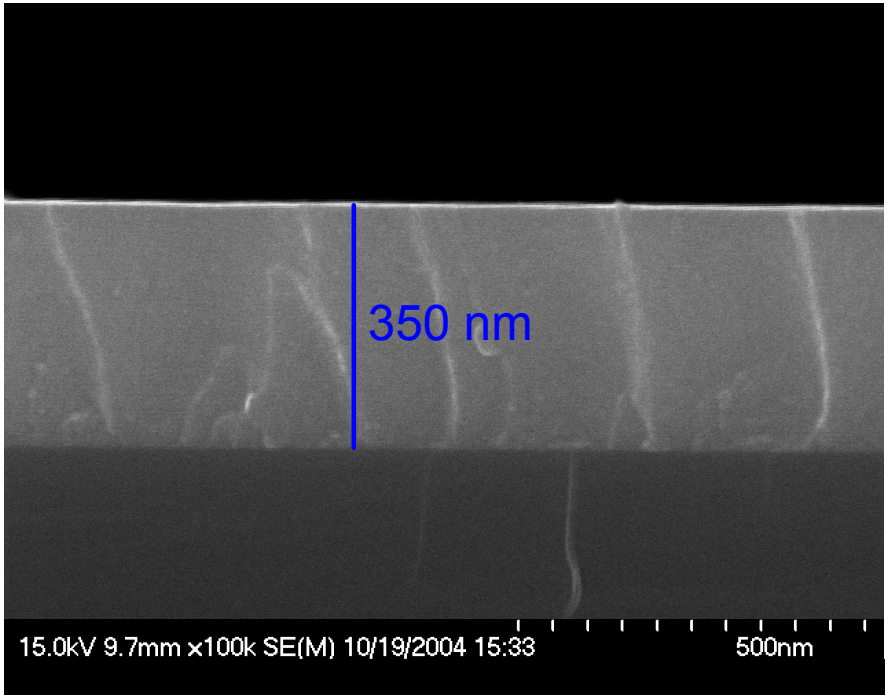
- Pre-exposure RMS roughness = 0.25 nm.
- Post-exposure RMS roughness = 0.15 nm.
- Matches well with AFM results.



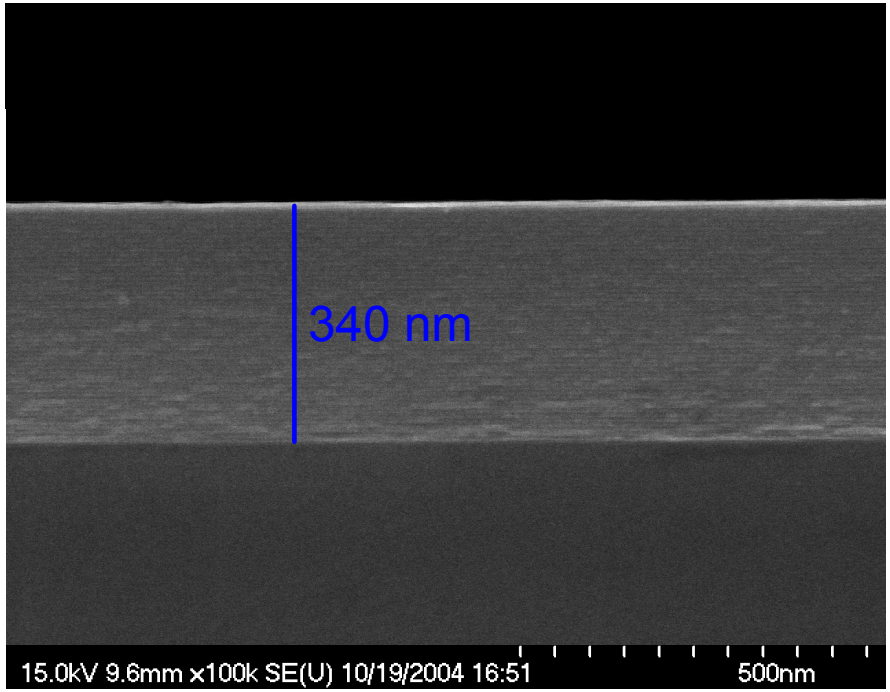
CoP 09

SEM Confirms Erosion

Pre-exposure



Post-exposure



Loss of around 10nm

Predicted Erosion vs. Measured

Assumed all ions were 8.4 keV Xe^+, used TRIM sputtering yields and measured value of flux to predict the change in thickness

Normal Incidence

Target Element	Predicted Change in Thickness (nm)	Experimental (nm) +/- 2
C	1.1	
Au	33.0	
Mo	6.5	
Si	5.8	
Si/Mo ML1	8.5	

Grazing Incidence

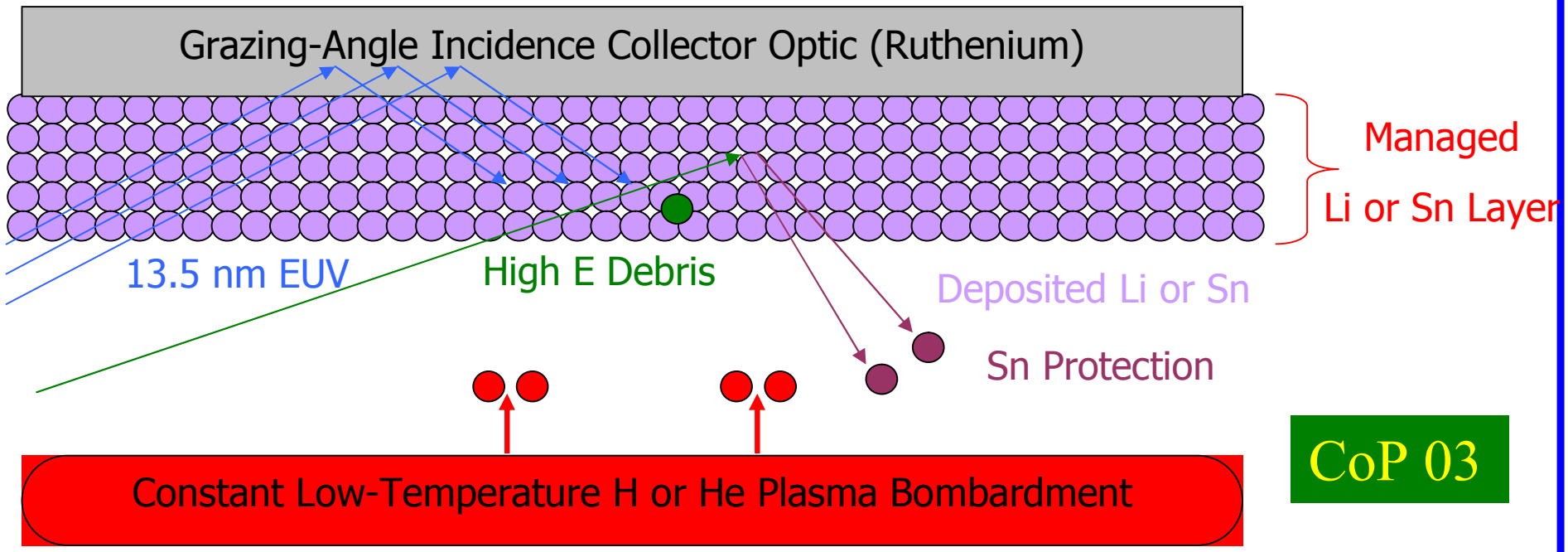
Target Element	Predicted Change in Thickness (nm)	Experimental (nm) +/- 2
Pd	18	
Ru	11	
Au/Mo	10	

CoP 07

Advanced Fuels (Sn and Li)

- The problem with advanced fuels is that they are condensable. They will deposit on the mirror surfaces.
  - However, we just learned that the pinch creates an erosive ion flux.
- Can these be balanced with some help?
  - Temperature can be varied to control evaporation.
  - A secondary plasma can be added to create additional sputtering.
  - The plasma could even be reactive (etching).

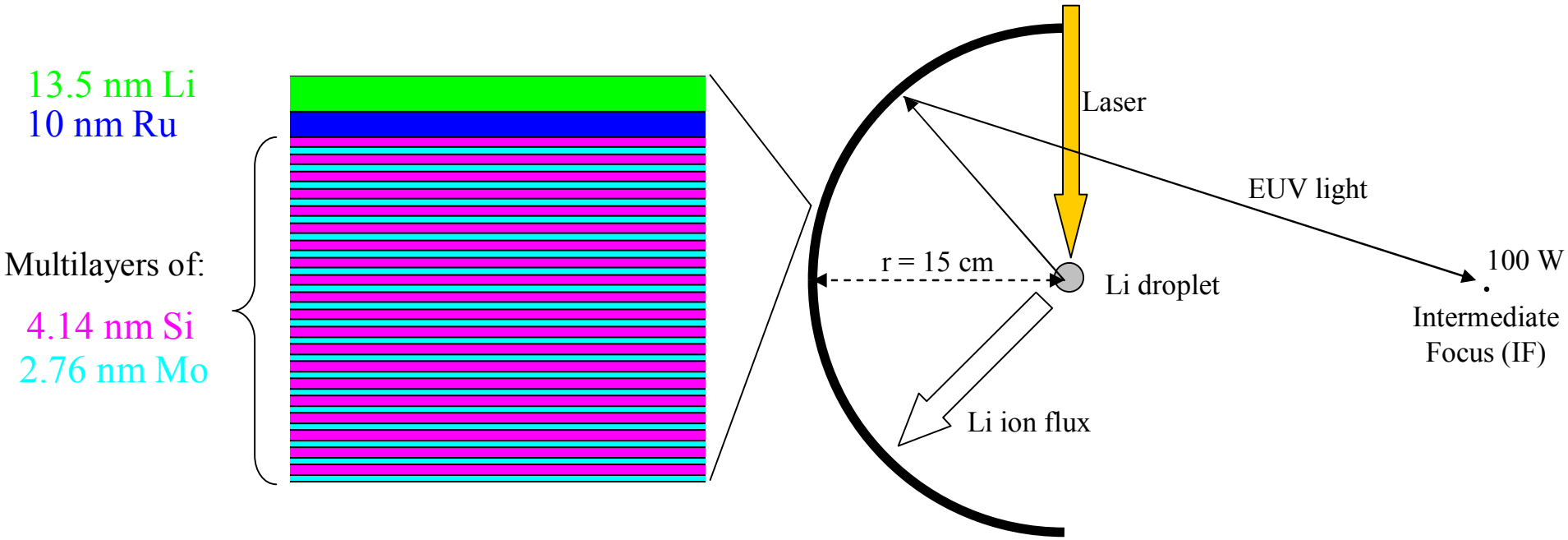
Managing Condensable Vapor



CoP 03

- Continuously clean mirror surface with minimal degradation
- Low-energy plasma process
- Can be used in combination with segregated alloy materials for low sticking coefficients
  - Weakly bound Li or Sn
  - High surface binding energy

Example of Modeling – Debris from a Li LPP

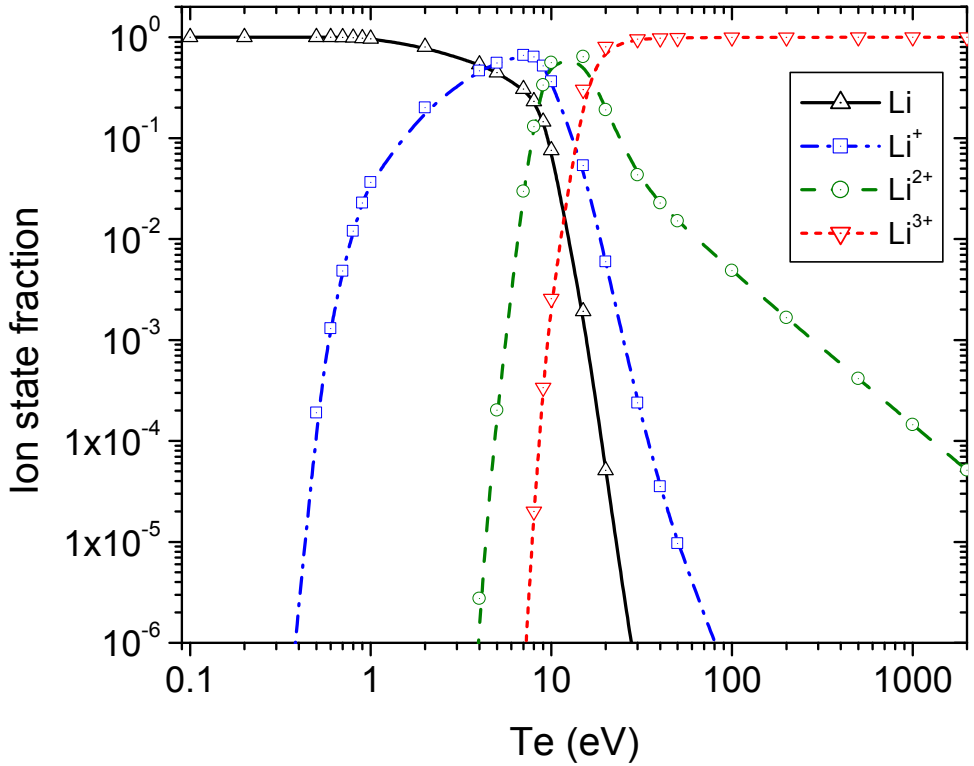


CoP 03

- Mirror assumptions
  - Collects 2π steradians (1/2 of light emitted)
  - Mirror surface area = 0.14 m^2
  - Reflectivity = 65%

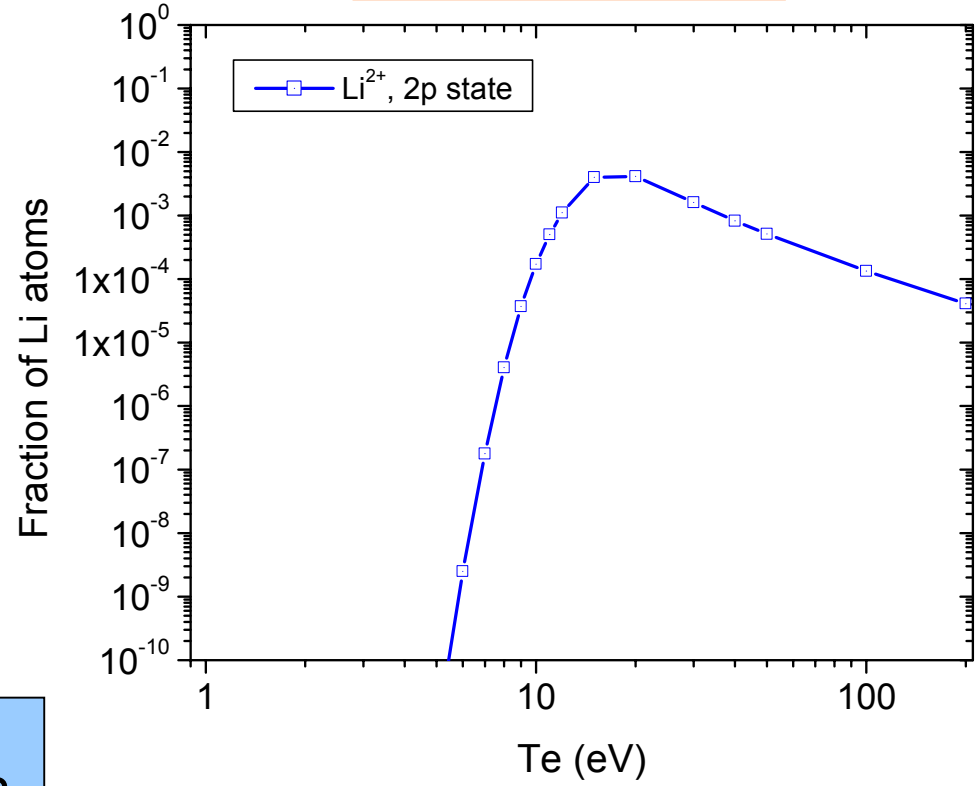
Results of LTE Analysis

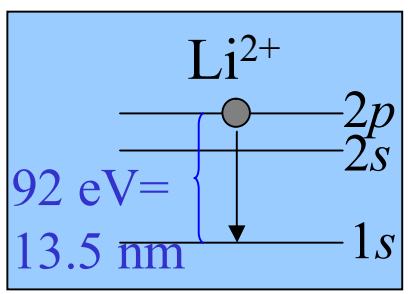
Ionization states of lithium vs. temperature



Population of the 2p excited state of Li^{2+}

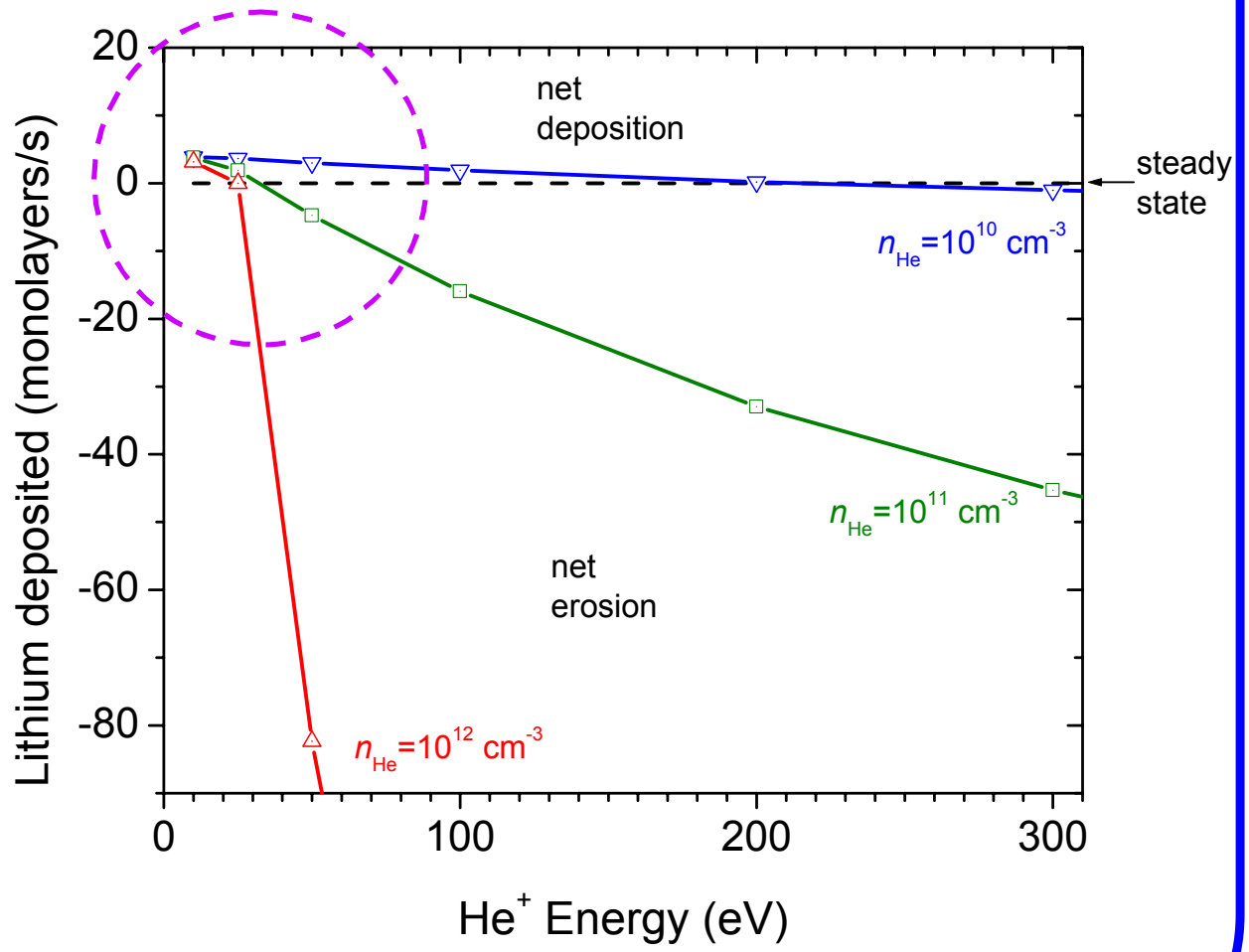
0.0039 @ 15 eV





Plasma Cleaning Requirements

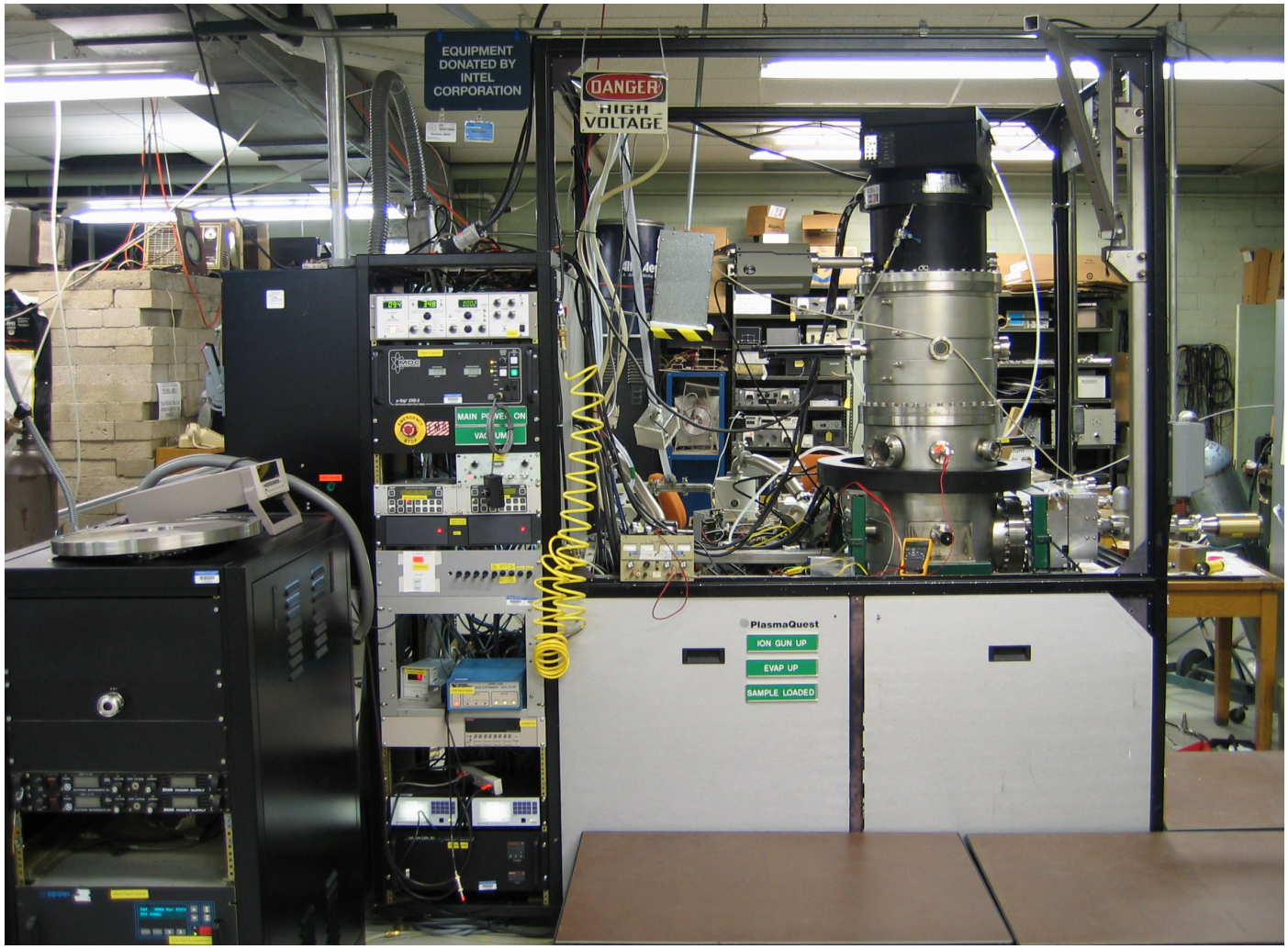
- In our Li study, to achieve a steady state surface rate balance condition, we add a He plasma.
- Depending on density possible, adjust bias to balance sputtering yield and deposition rate.
- For conventional plasma conditions, Li can be removed below the Ru or Mo sputtering threshold.



SCOPE Experimental Setup

Surface **C**leaning of **O**ptics by **P**lasma **E**xposure

- Li^+ Ion Beam
- Quartz Crystal Microbalance
- E-Beam Evaporator
- Substrate Heater with DC/RF Biasing
- RGA
- High Density Helicon Plasma
- Langmuir Probe
- LabVIEW Controlled



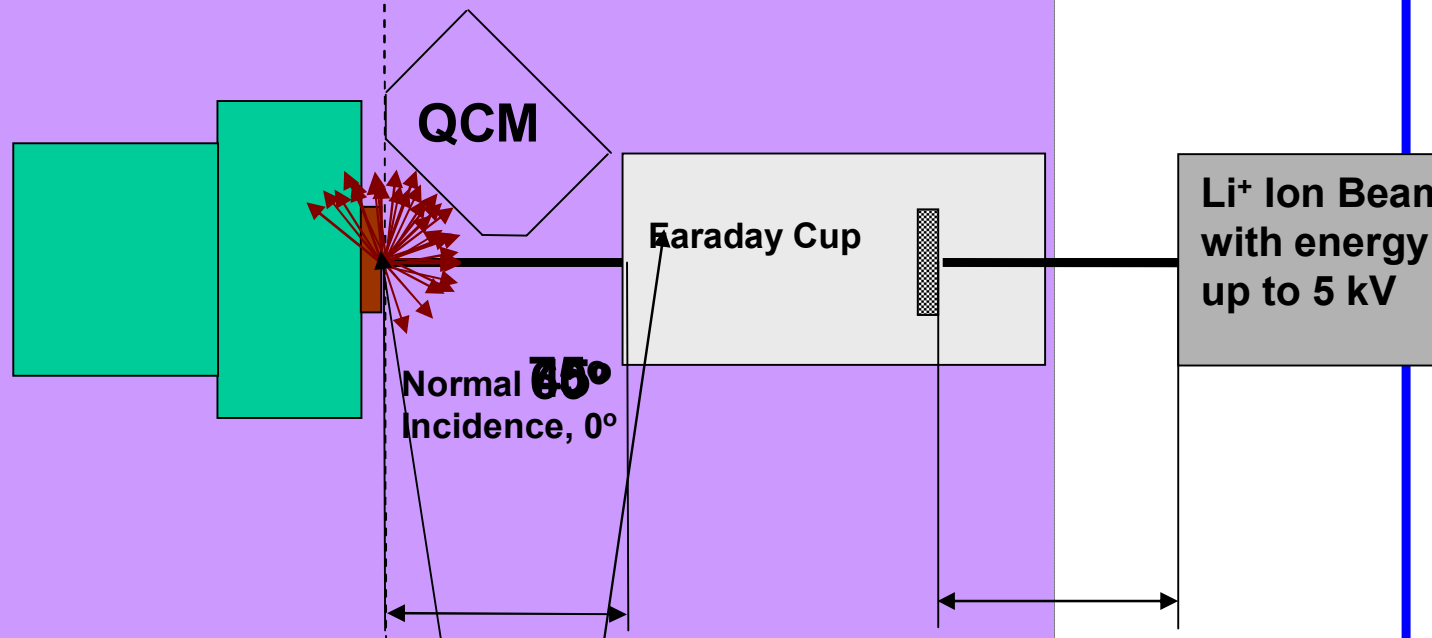
CoP 04

Li Coating on Ru/Si, Pd/Si

He, Ar, Ne, or H Plasma: Various n, Te

Sputter samples at the same working distance as characterization.

Characterize Beam Profile at a set working distance.



A correlation factor between amount deposited on the QCM and actual amount deposited on the sample will be determined.

Same 25 mm working distance

~ 25 mm working Distance

Li from E-Beam Evaporator

Sputtered material angular distribution is approximated by a cosine distribution

Drawing to scale

1 cm

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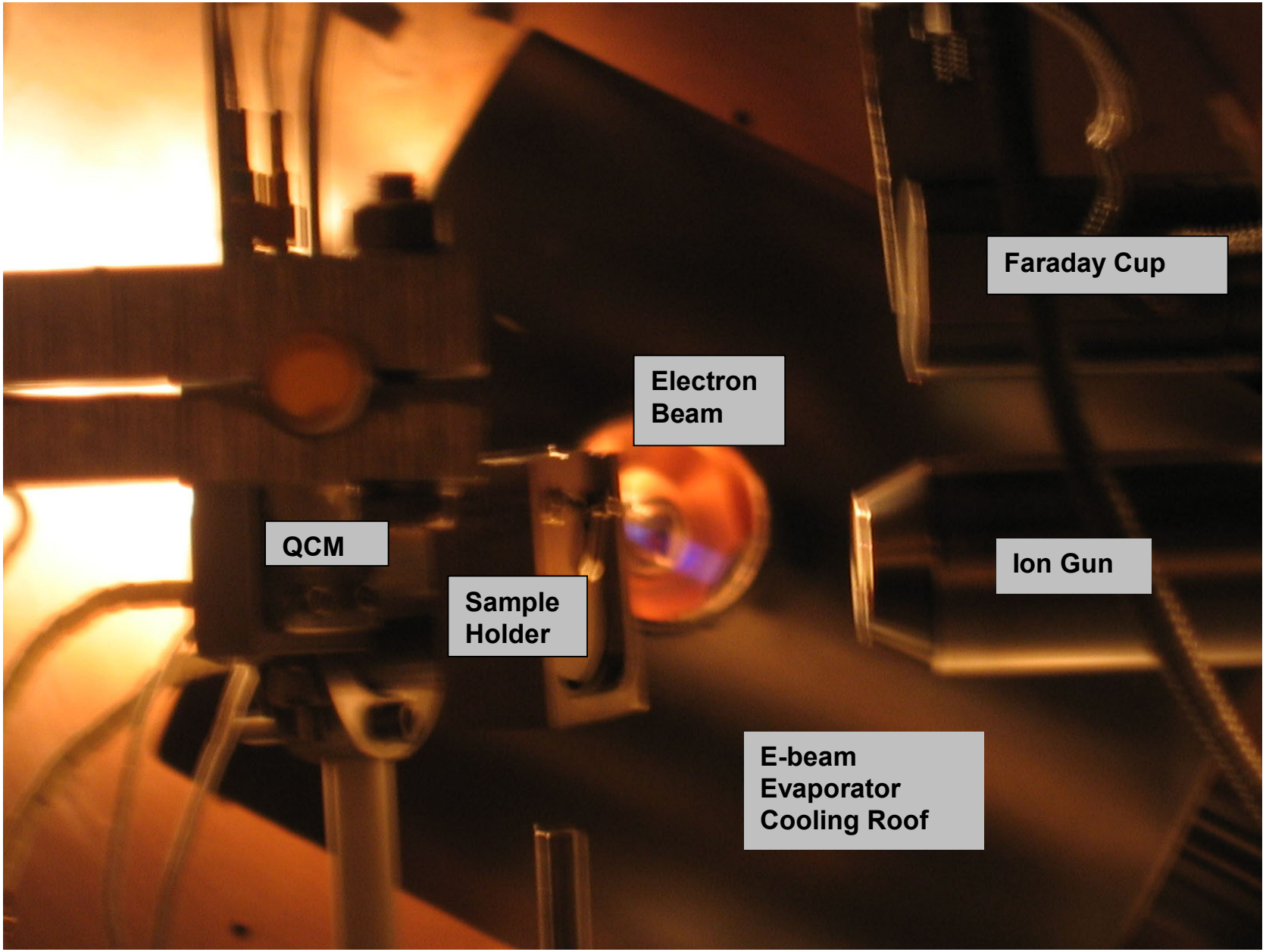
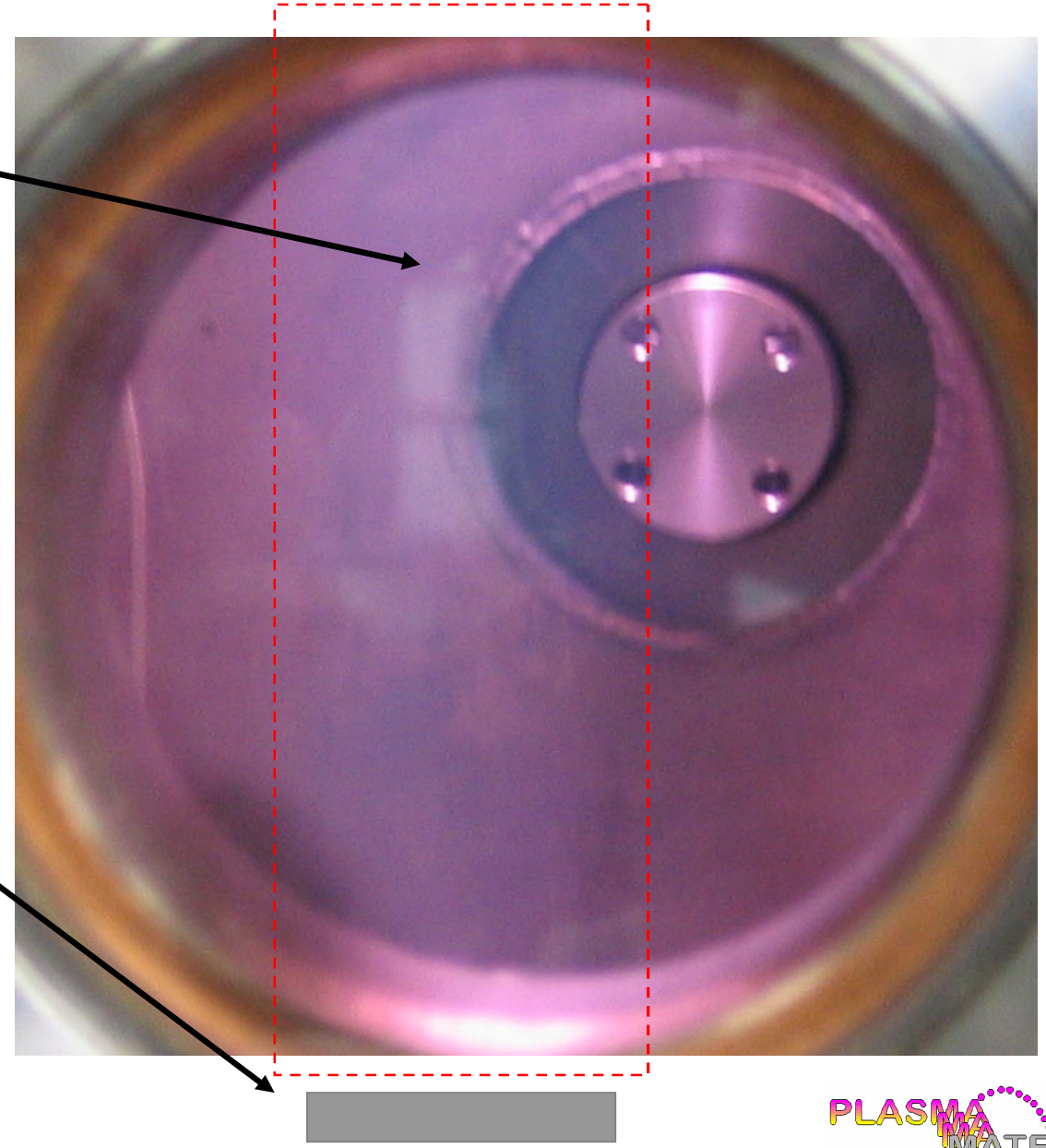
Picture of SCOPE at work



He Plasma Beam

Confined helium helicon plasma beam in the center of the chamber

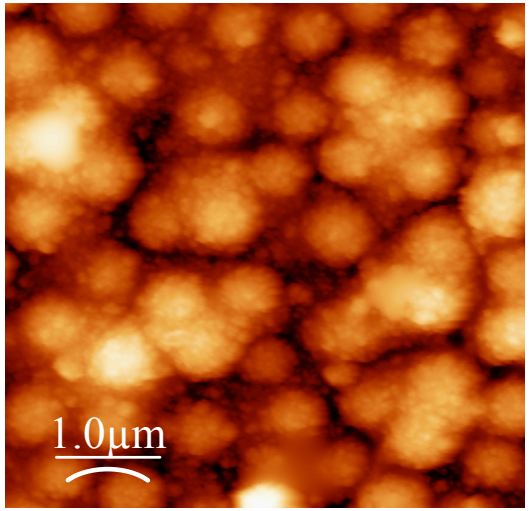
Substrate heater and mirror samples located below in beam path



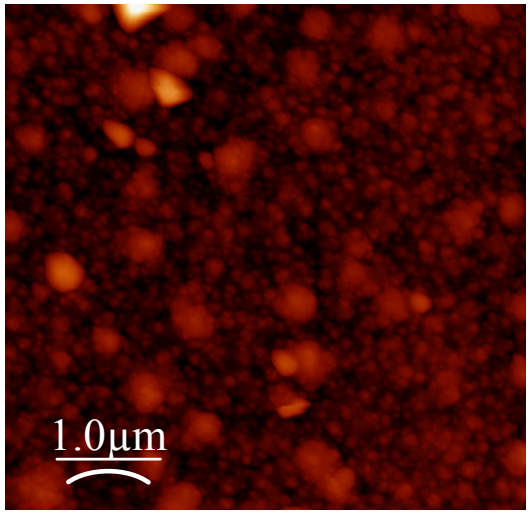
Can Li simply be evaporated away?

Evaporated Li at 25ºC and 250ºC then compared in an AFM

25º C



250º C



- High surface tension of Li creates “beads” on the surface
- Addition of heat causes Li to evaporate, but leave behind contaminants
- Where does the Li go?

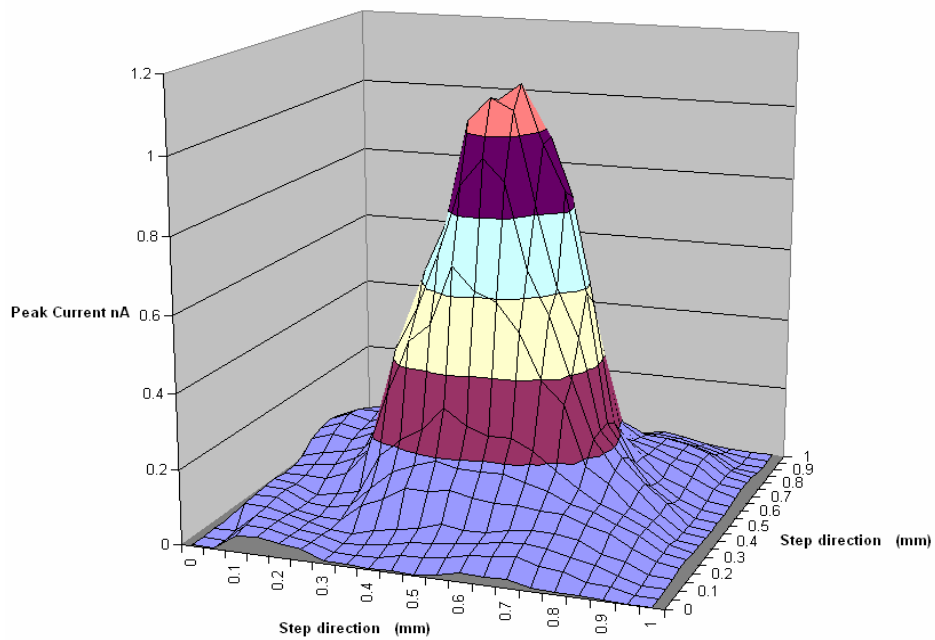
CoP 01

Li Diffusion Experiment

- Implant a known concentration of Li ions at a known position.
- Measure depth profile of Li in spot and all around it using TOF-SIMS.
- Heat sample and repeat analysis.

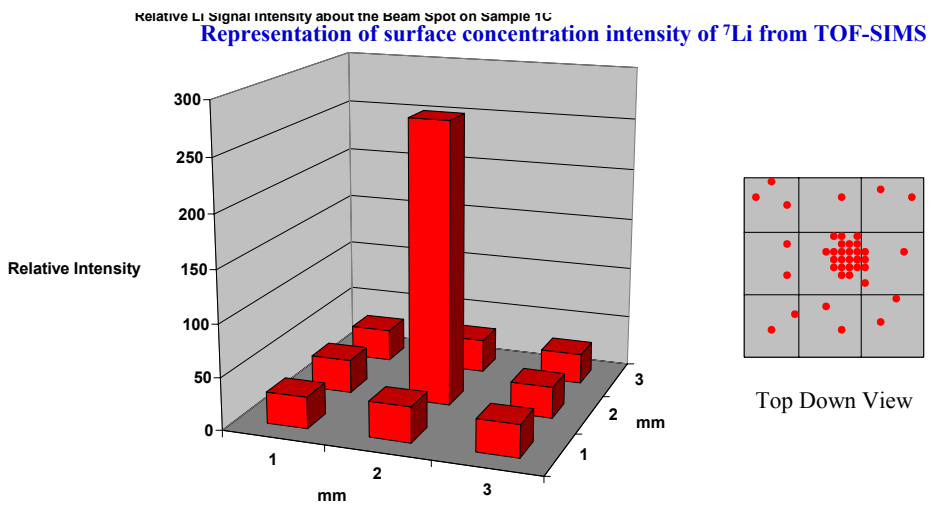
Beam profile for 1 keV Li beam

[total beam current of 40 nA, FWHM of ~210 microns]

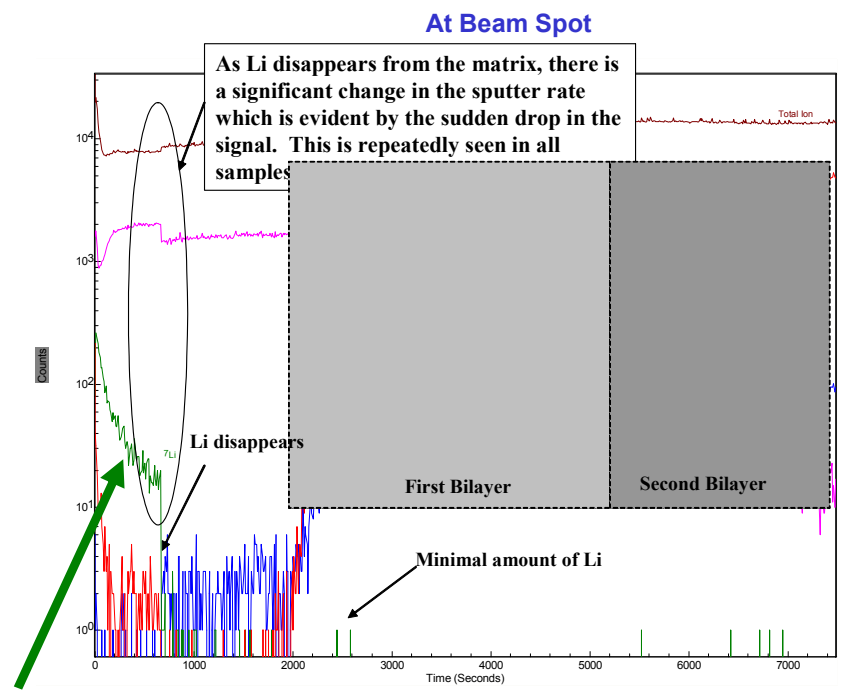


Diffusion results at 25ºC

- Virtually no radial diffusion
- Depth profile – stays in Ru capping layer
- Some diffusion along Ru grain boundaries



- Li signal was confined to the Beam impingement area.
- Little to no radial radial diffusion, as was the case with all of the 25º C samples.

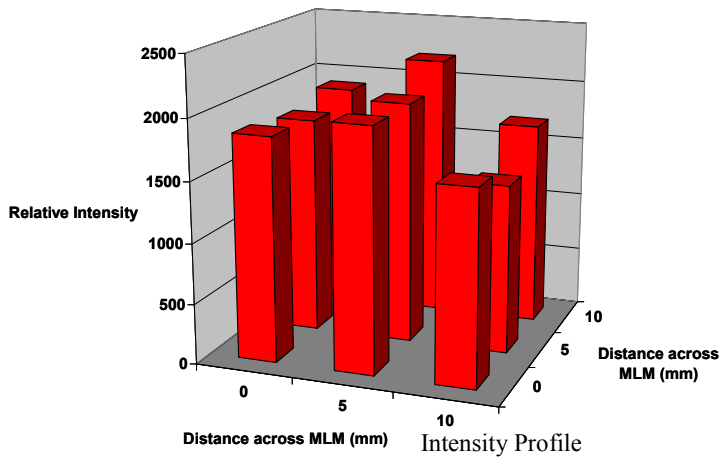


Li signal

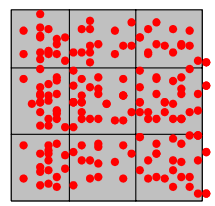
Diffusion results at 250ºC

- Extreme radial diffusion along surface
- Uniform coverage over 15 mm x 15 mm sample

Representation of surface concentration intensity of ^{7}Li from TOF-SIMS



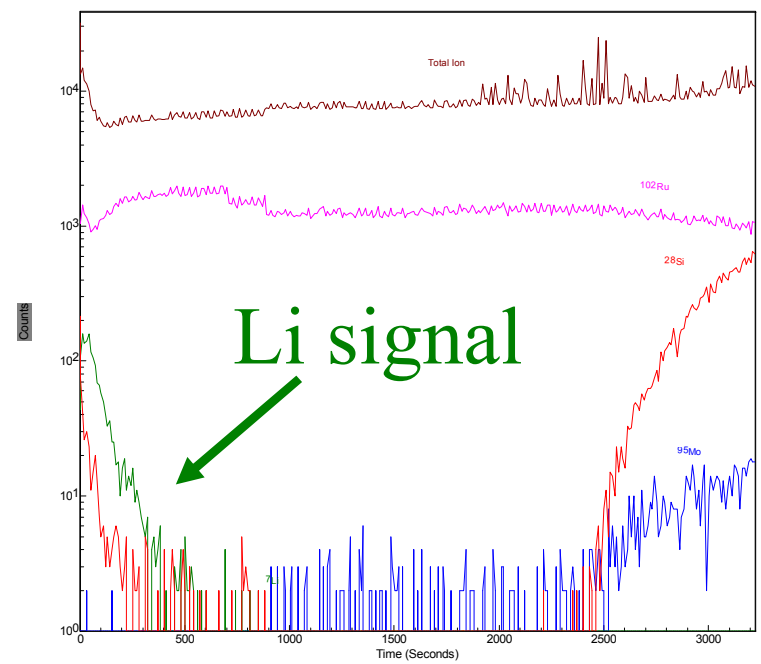
Intensity Profile



Top Down View

- Again, Li signal was NOT confined to just the Beam spot area.
- Li uniformly underwent radial diffusion and was uniform throughout the entire surface area of the 15 mm x 15 mm sample

At Beam Spot

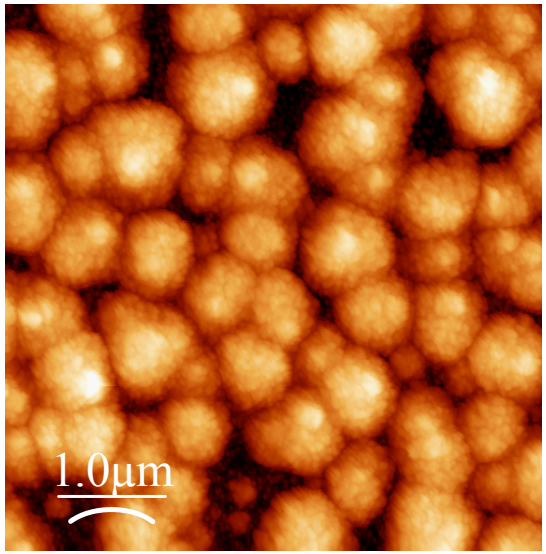


Cleaning by Plasma Bombardment

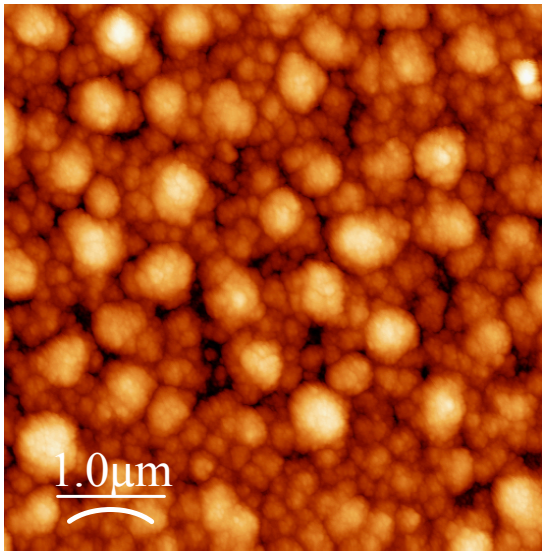
- Increased bias breaks up Li “beads” into smaller sizes
- Removal is accomplished

CoP 04

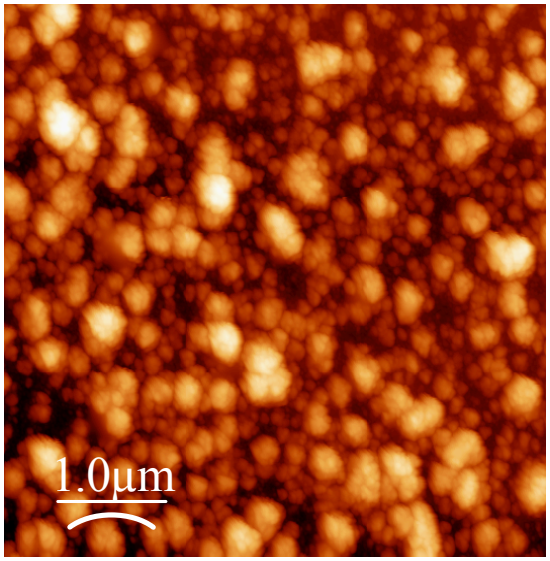
1000 W He plasma, 250° C



0 V bias



-50 V



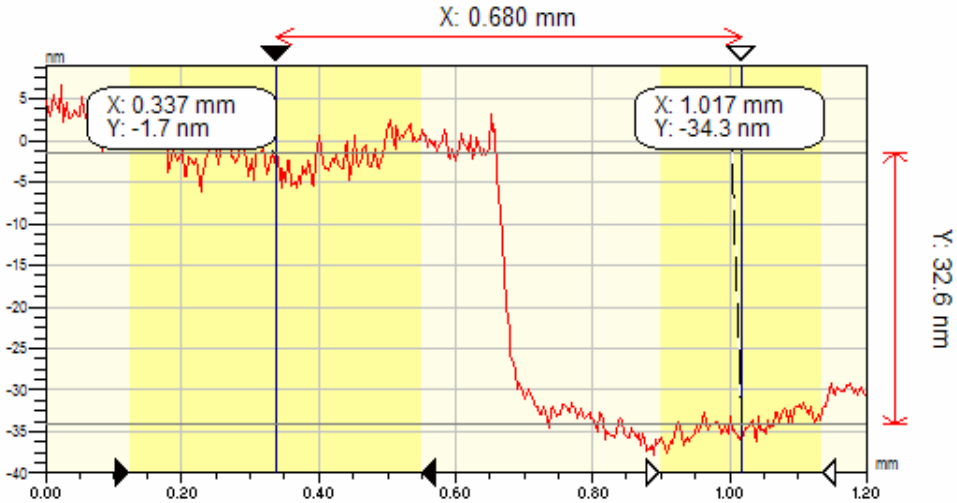
-100 V

Will This Work For Sn?

- Vapor pressure of Sn is very low compared to Li.
- Sputtering rate of Sn for He is also low at low levels of bias.
- Selectivity is needed so base mirror material is not damaged.
- Try plasma etching recipes using chemistry!

Plasma Etching and Profilometry

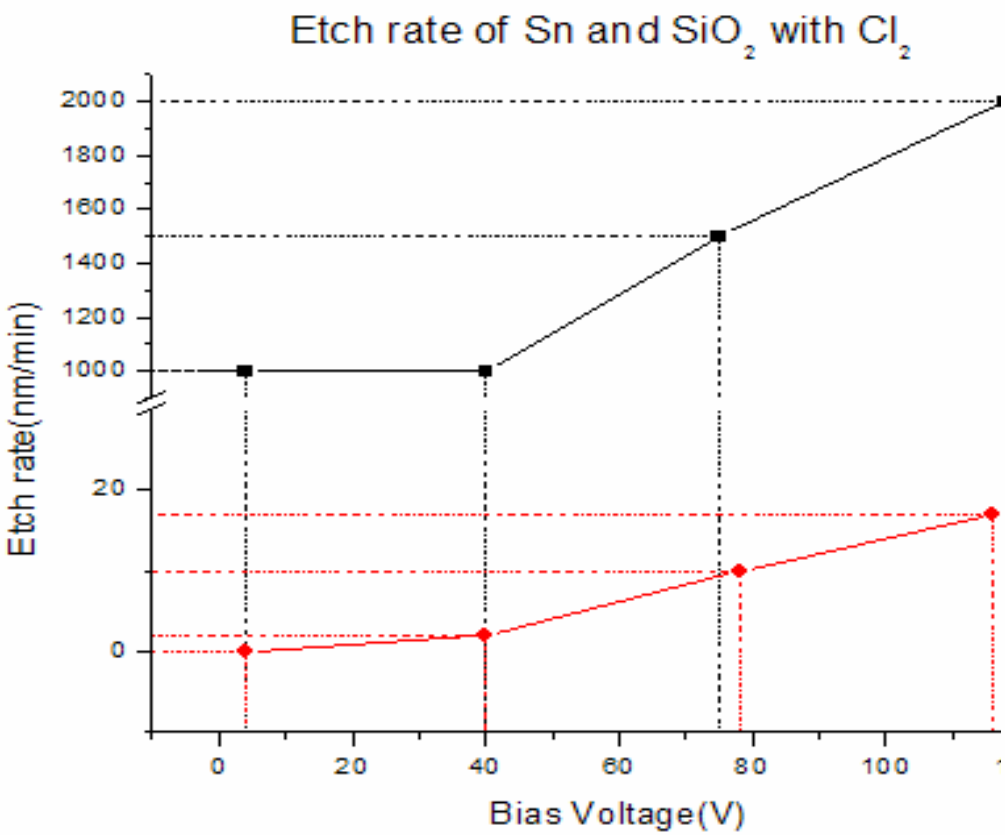
- Tested several reactive etch process recipes in a commercial reactor.
- Best results were achieved using standard etching in Cl_2, Ar plasma.
- Measured step change across a covered area.

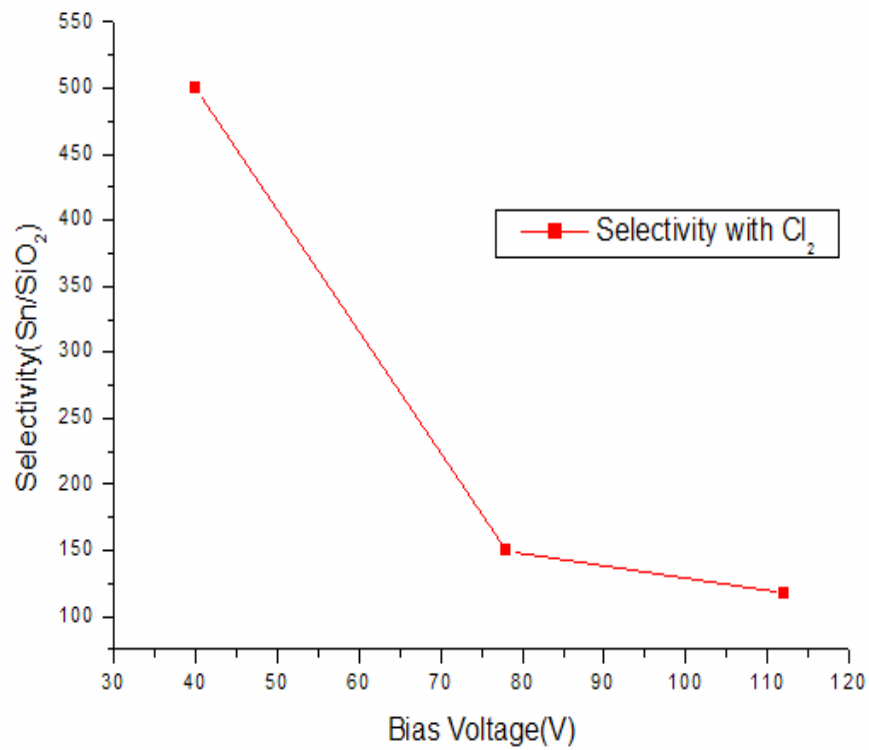


CoP 10

Sn, 33nm / 10 s

Etching rates and Selectivity for Sn over SiO_2





Best selectivity was 500 to 1, at a 1000 nm/min etch rate for Sn

Illinois Debris mitigation for EUV Applications Laboratory (IDEAL)

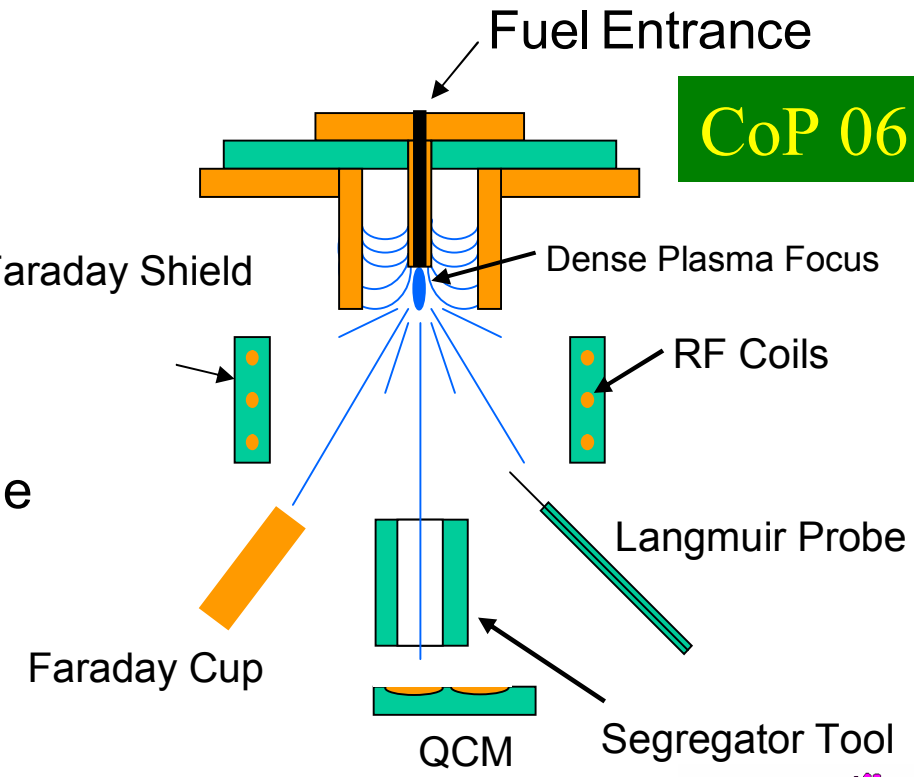
Stop Sn before it gets to the condenser optics !

Components

- Differential pressure gas manifold scheme
- 3 turn RF antenna for secondary plasma (1-500W @ 10-35 MHz)
- Tin injection and waste retention system

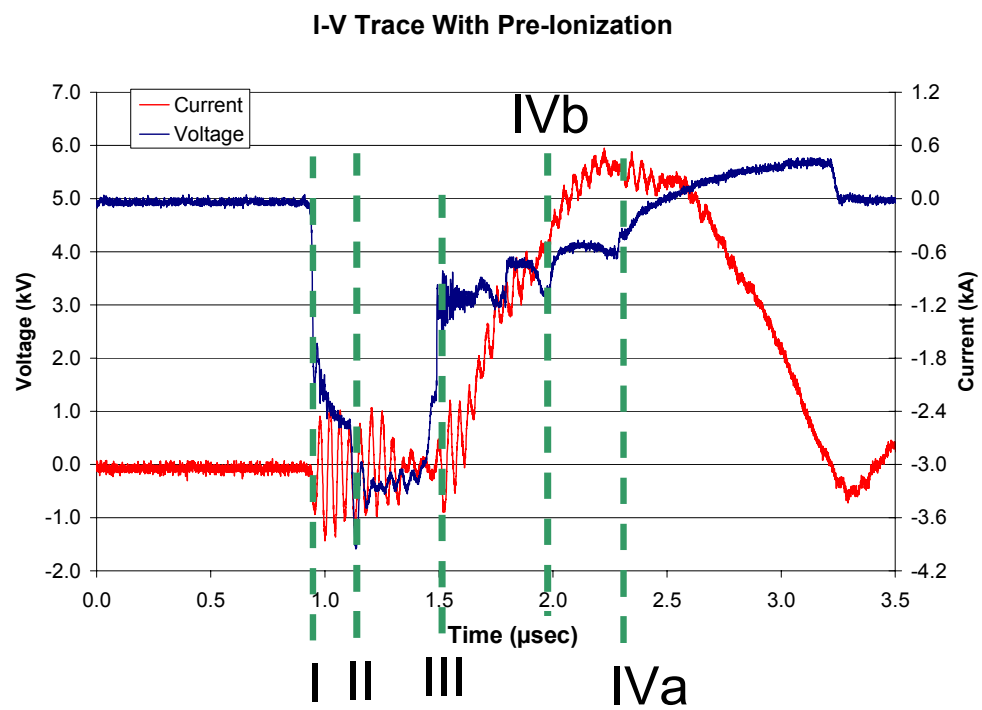
- **IDEAL facility is capable of collecting and analyzing data relevant to EUVL sources**
- ENI A-500 Tunable RF Amplifier
- DPF Pulsing System (50 Hz)
- Tetramethyl Tin Bubbler System

CoP 06

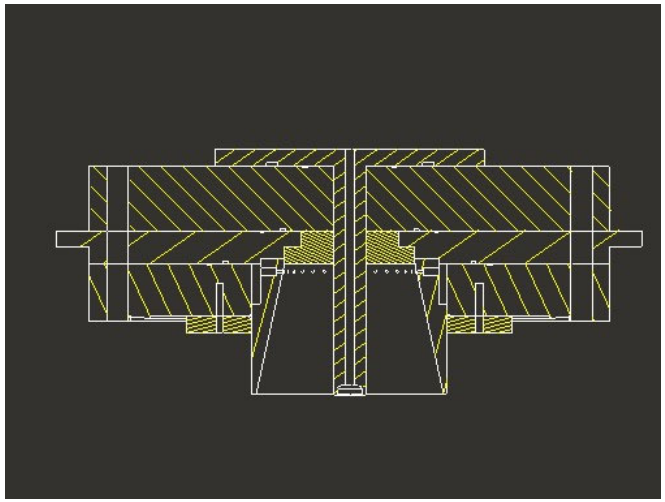


IV Traces of DPF Discharge

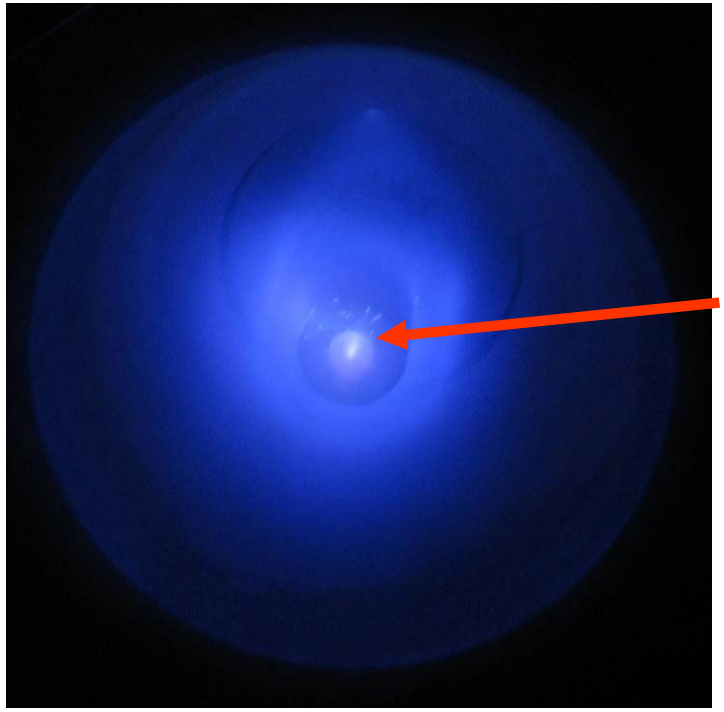
- I: Potential Applied to Anode
- II: Breakdown
- III: Rundown Initiates
- IVa,b: Pinches



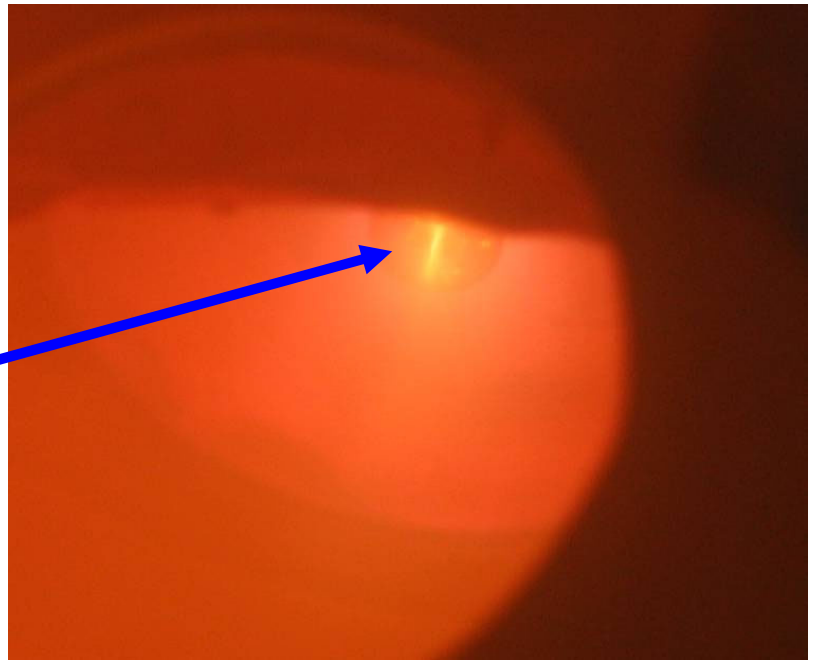
Examples of Pinch in $Sn(CH_3)_4$



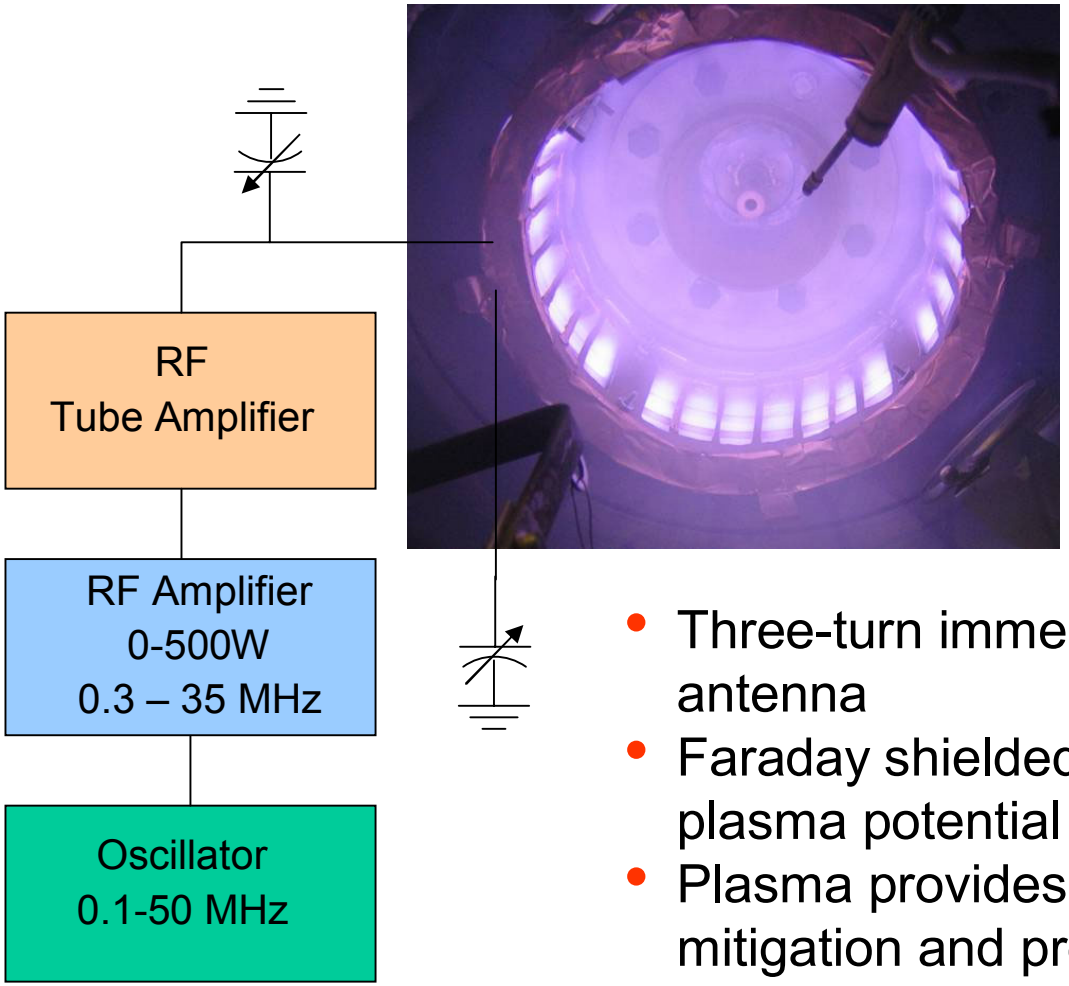
- Pulsing system utilizes a fast hydrogen thyratron switch:
  - 690 nanosecond current rise time
  - L = 89 nH
  - C=3.33 μF
  - Repeatable DPF firing at 0-40 Hz
  - Well defined pinches



Pinch visible at electrode tip



Secondary Plasma

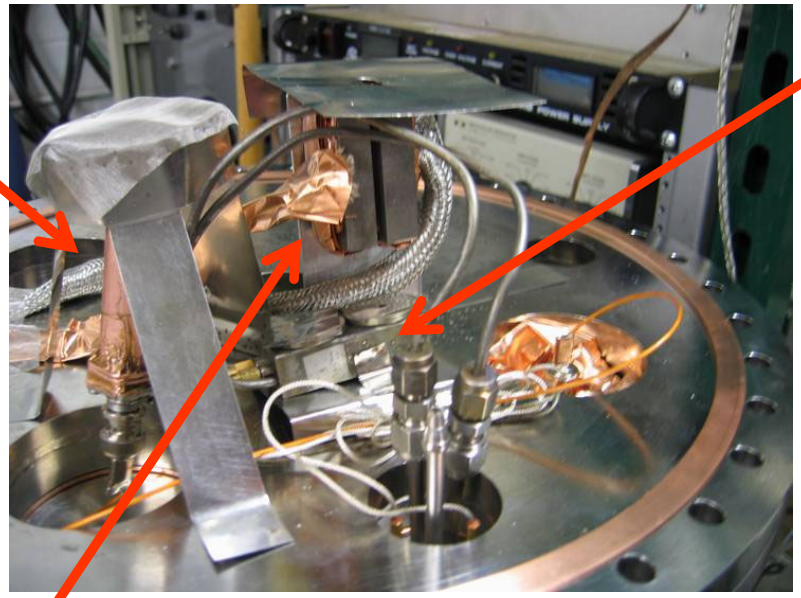


- Three-turn immersed antenna
- Faraday shielded to reduce plasma potential
- Plasma provides debris mitigation and pre-ionization

Diagnostics

Faraday Cup

- Collects charged particles
- L/D ratio prevents secondary electron emission



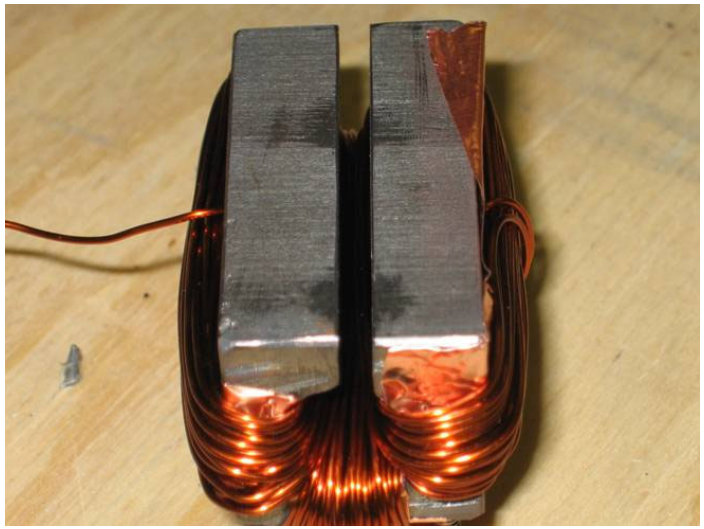
Dual QCM

Dual In-Situ Crystal

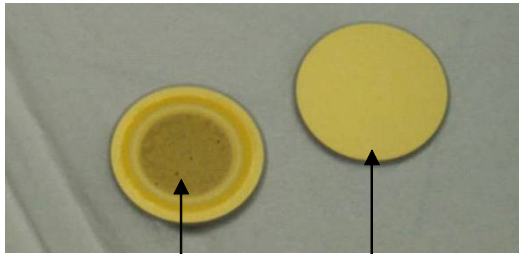
- Filters Noise
- Extremely Sensetive

Segregator

- Deflects fast ions away from QCM aperture
- Deflects up to 10 keV Ar



QCM Crystals

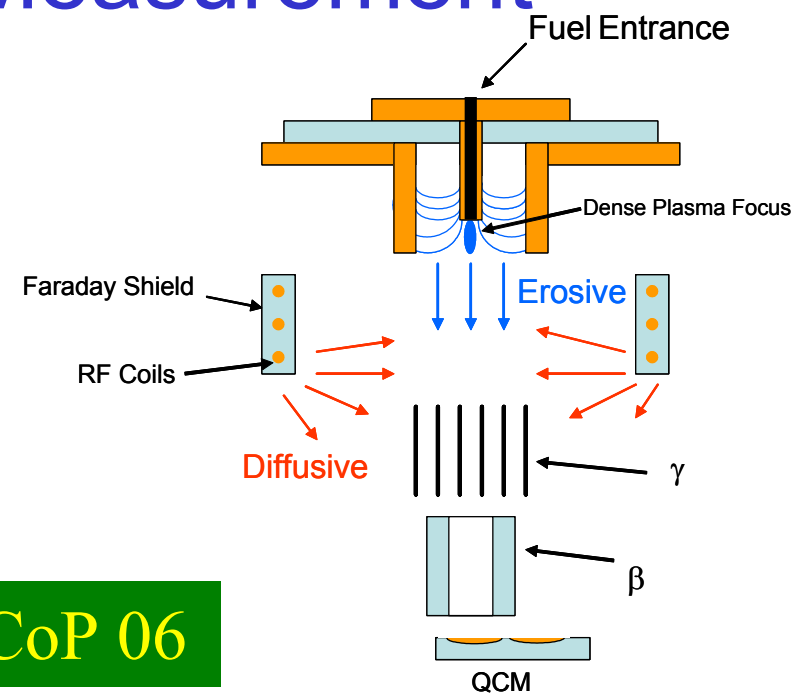


Debris on Surface **Clean Surface**

Ionization Fraction Measurement

Problem Statement

- Different components of debris must be separated
- Intense magnetic field in **segregator** deflects much of the erosive fast ions from the pinch region
- **Foil trap** also attenuates some fast ions
- Used in conjunction, a table of variables can be built to study the effect of the RF plasma



CoP 06

Pulse	RF	Foil Trap	Segregator	Gas	Deposition Terms	Erosion Terms	Measurement (+/- 0.05)
X	LOW			Sn	A	B	.373
X	LOW		X	Sn	A	βB	.744
X	LOW	X	X	Sn	A	$\gamma \beta B$	.825
X	LOW	X		Sn	A	γB	.606
X	X			Sn	δA	αB	.359
X	X		X	Sn	δA	$\beta \alpha B$	.565
X	X	X	X	Sn	$j \delta A$	$\gamma \beta \alpha B$	.516
X	X	X		Sn	$i \delta A$	$\gamma \alpha B$	.309

Conclusions – Xe operation

- First measurements of ion energy spectra and absolute flux from a commercial DPP with and without debris mitigation.
- Extensive pre-exposure and post-exposure analysis of candidate mirror materials (after 10M shots).
- Measured erosion consistent with measured ion flux due to physical sputtering.

Conclusions – Advanced Fuels

- Made first measurements of diffusion, evaporation and plasma cleaning of Li.
- Demonstrated successful plasma cleaning and etching of Sn for advanced fuel EUV sources.
- Operation of a DPF with Sn fuel.
- Mitigation of Sn by RF plasma.

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