Extending the lifetime of collector optics: advanced debris mitigation schemes and cleaning methods

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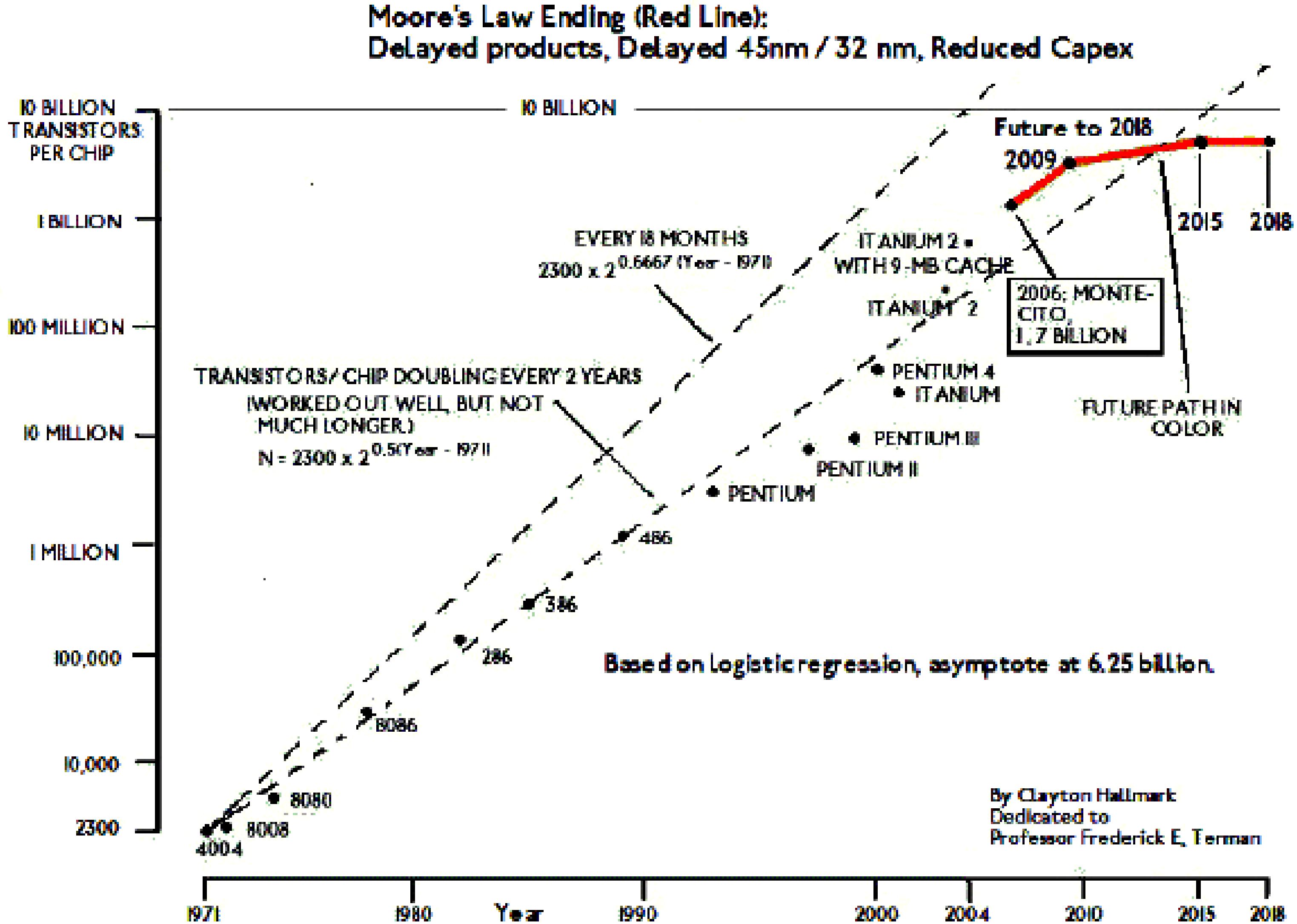
Outline

- Introduction
- Contributions from Illinois
- Ion Energy Analysis
  - INERT (Illinois Ion-Energy Reduction Technique)
  - E-Field ion mitigation
  - Plasma-based mitigation
  - Energetic neutral detection
- Collector Optics
  - Plasma cleaning techniques
  - Gibbsian alloy performance
  - Lithium cleaning
- Particle Removal
- Plasma Modeling
- Summary
- Acknowledgements

Why We are Here



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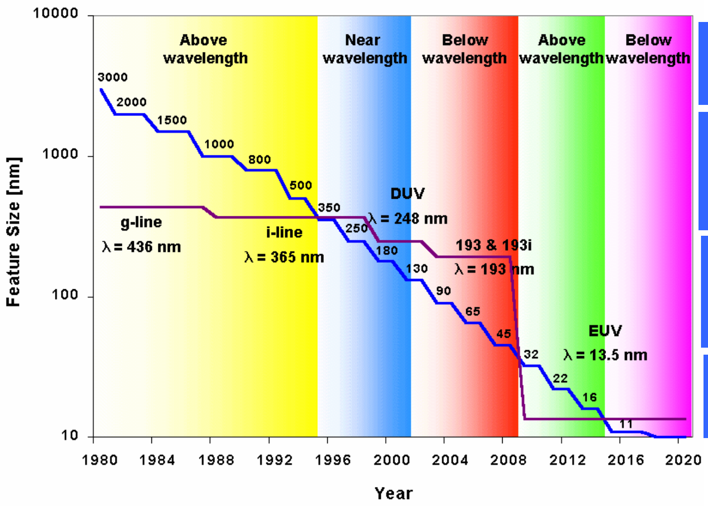
EUV can save Moore's Law

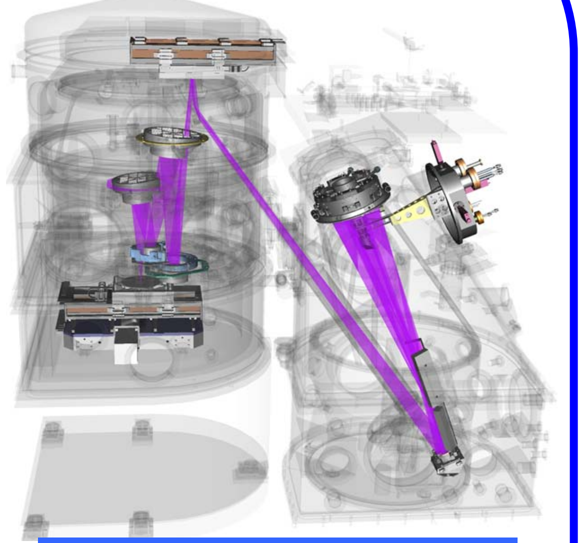


13.5nm wavelength for printable optical lithography through 2020.

Work on the ETS demonstrated full-field printing sub-65nm lines and spaces.

Active effort by over 100 companies, consortia and universities, including SEMATECH.

Moving forward but with significant challenges.



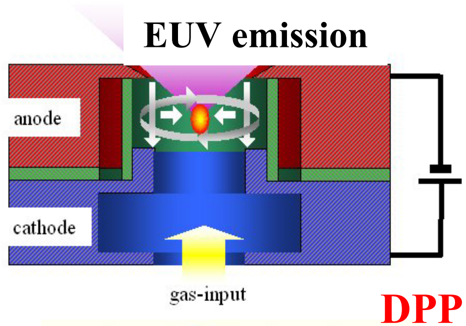
EUV is generated in a dense plasma generated by either:
- Gas Discharge Plasma (DPP)
- Laser Plasma Interaction (LPP)

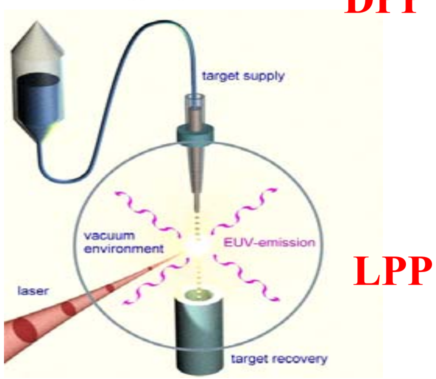
Xenon has traditionally been used as the plasma radiator, due to its inertness.

However its conversion efficiency is only about 1% of energy deposited into the plasma radiating at 13.5nm.

DPP is simpler but has plasma contacting electrode surfaces.

LPP is more complex with costly laser components, but yielding a cleaner, collectable EUV signal.





For 13.5nm systems, reflective mirrors are needed instead of refractory optic lenses.

Normal incidence optics use Si/Mo multilayer super lattices for Bragg reflection.

Grazing angle optics use shallow angles for near total external reflection.

The collector optic is plasma facing, meaning it is exposed to the harsh debris, photon and thermal environment.

Debris Characterization and Debris Mitigation is still a challenge

But only if…..

- The collectors will survive long enough to give EUV sources a reasonable COO

07-SO-38, Characterization of Debris Mitigation Techniques for Sn and Xe-fueled EUV Light Source, Keith Thompson et. al.

05-CC-36, Gibbsian Segregating Alloys Driven by Thermal and Ion Flux Gradients, Huatan Qiu, et. al.

06-CC-37, Selective Etching of Sn from Ru EUV Mirrors with Ar/CL_2 plasmas, HyungJoo Shin, et. al.

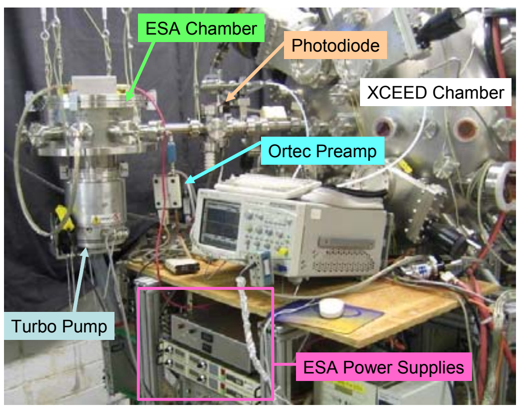
04-CC-35, Effect of Deposition, Sputtering and Evaporation of Lithium Debris Buiild-up on EUV Optics, Martin Neumann, et. al.

- The masks can be kept free of contamination

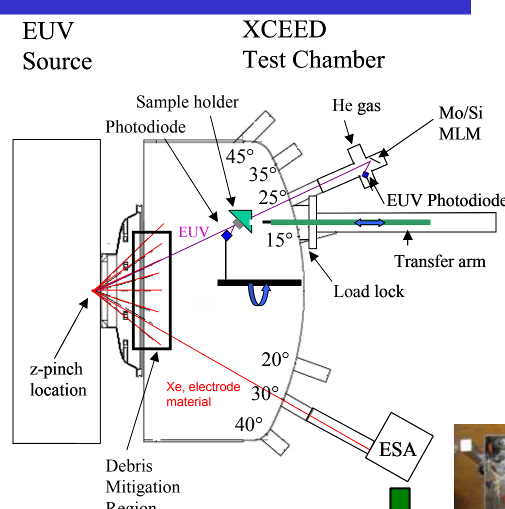
08-CC-85, Plasma-Assisted Electrostatic Cleaning of EUV Masks, (PACE), Wayne Lytle, et. al.

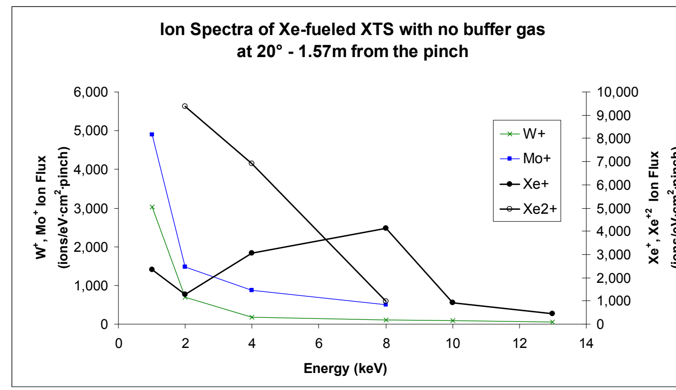
Debris Diagnostic (ICE devices)

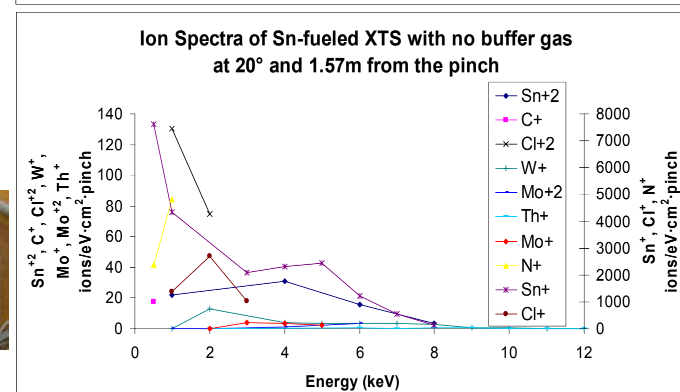
- Illinois Calibrated Electrostatic Analyzers (ICE) can reproducibly measure energetic ion spectra and neutral atom spectra.
- Our devices are being or will be used at a number of source suppliers.
- An ICE device llows for direct experimentation on ***Debris Mitigation Schemes*** and provides ***Accelerated Lifetime Testing*** for Collector Optics.

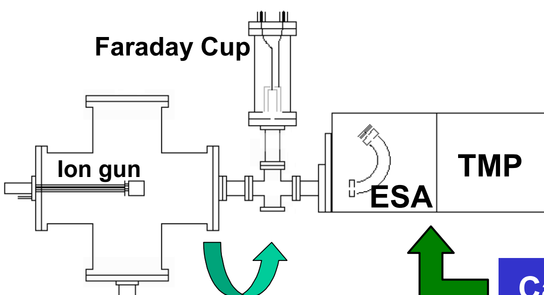


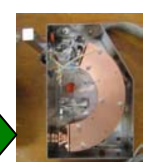
Ion energy spectra measured using ICE device for Xe and Sn EUV sources







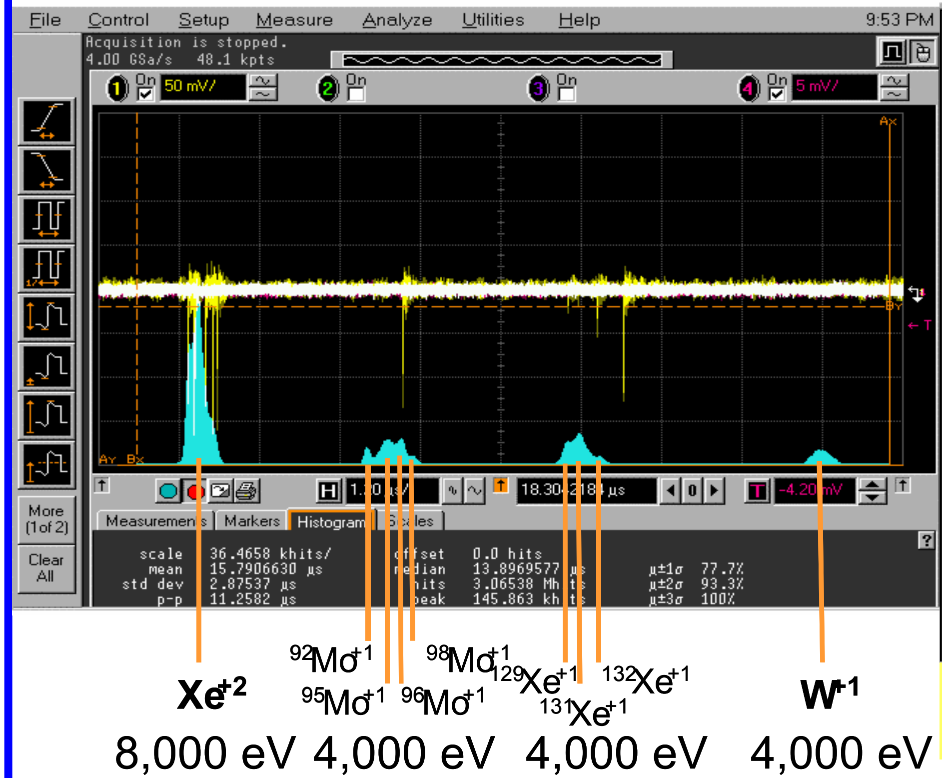




Calibration set-up for ESA

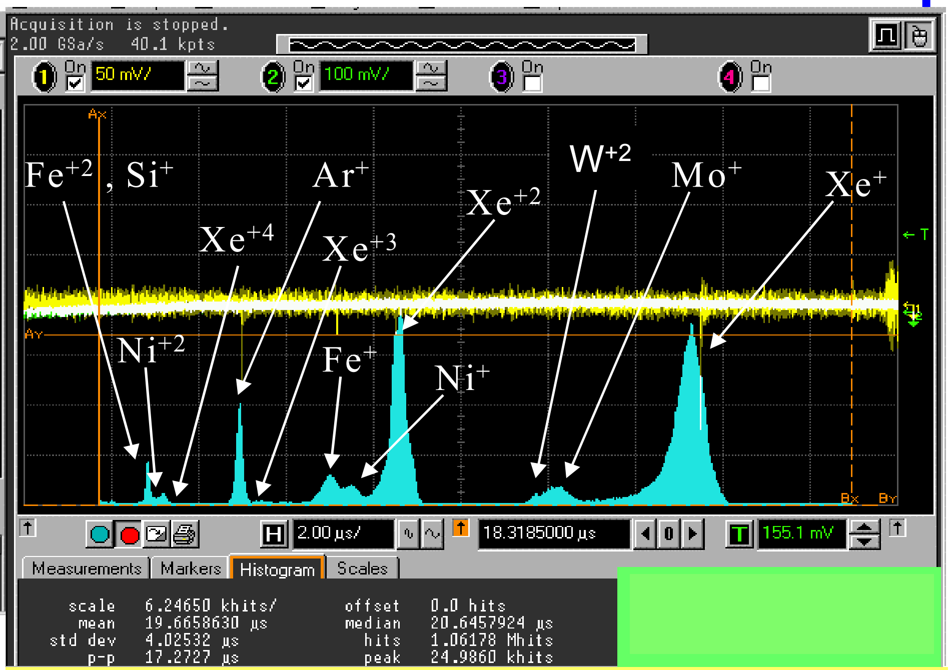
ICE machine capabilities

Isotope separation



TOF-ESA sensitivity is high enough to resolve isotopic abundance of Mo present in debris field.

Charge resolved measurement

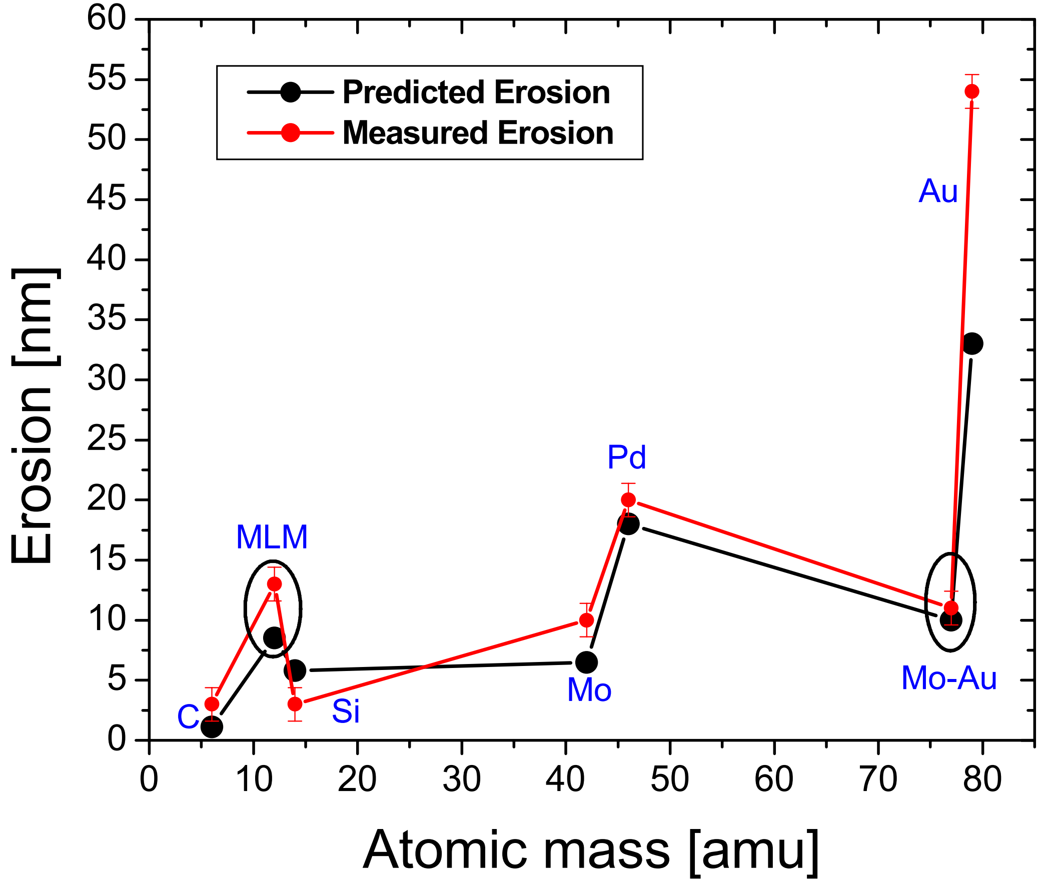


$$t = \frac{d\sqrt{m}}{\sqrt{2E}}$$

Distance to source = 150 cm

TOF-ESA shows high energy states and impact of mitigation schemes on the debris field for collector lifetime estimation.

Comparison between measured and predicted erosion



Good agreement means accelerated lifetime testing is accomplished simply by measuring the energetic ion flux

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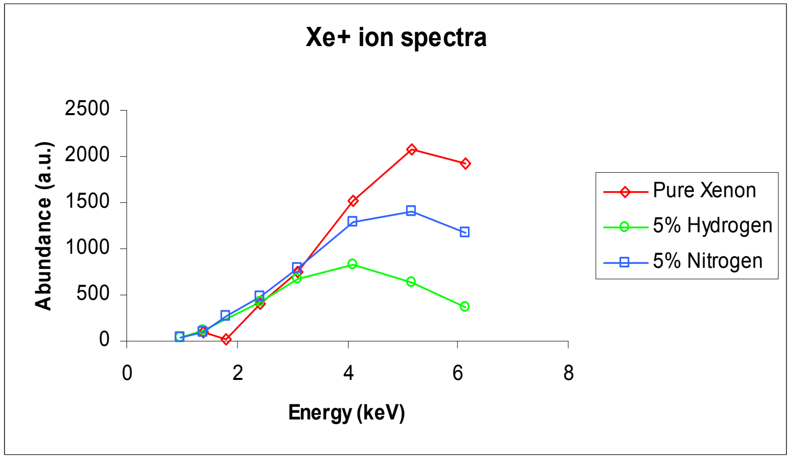
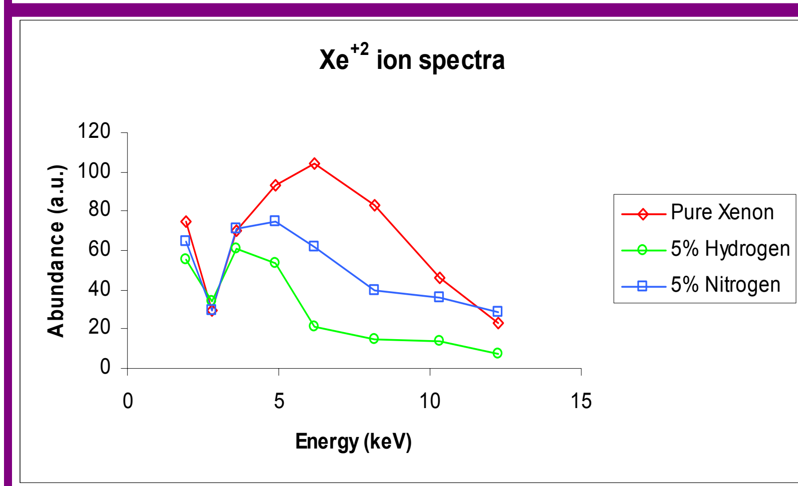
Illinois Ion-Energy Reduction Technique (INERT) could become industry standard





Ion energies reduced in half ! Number of Xe ions reduced four times!

Experiment done with N_2 instead of H_2 to check theory. Results fell in-between as expected.

EUV photon signal increased (marginally) with H_2 addition !

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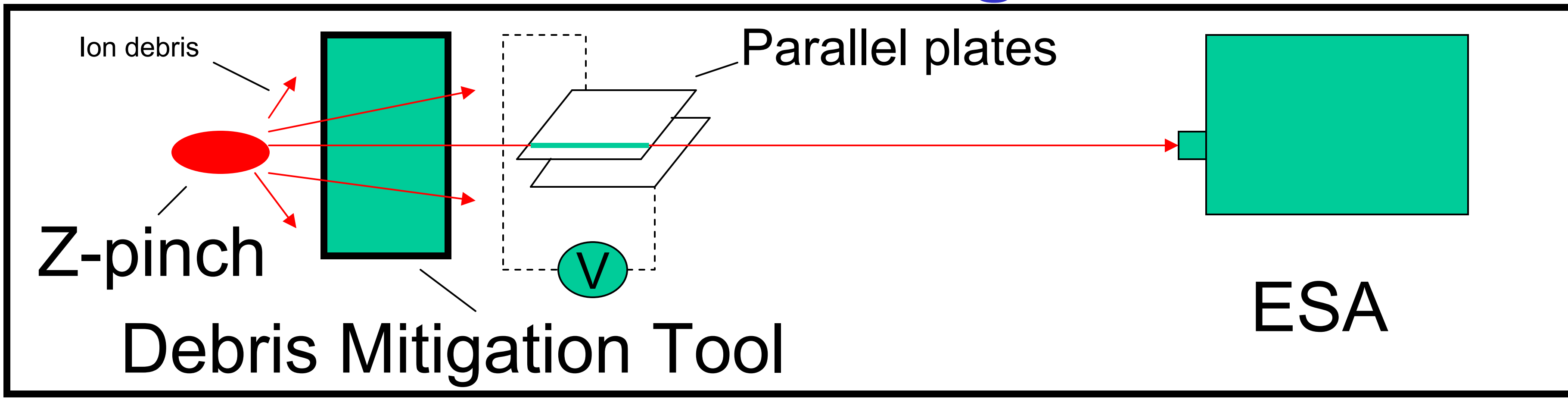
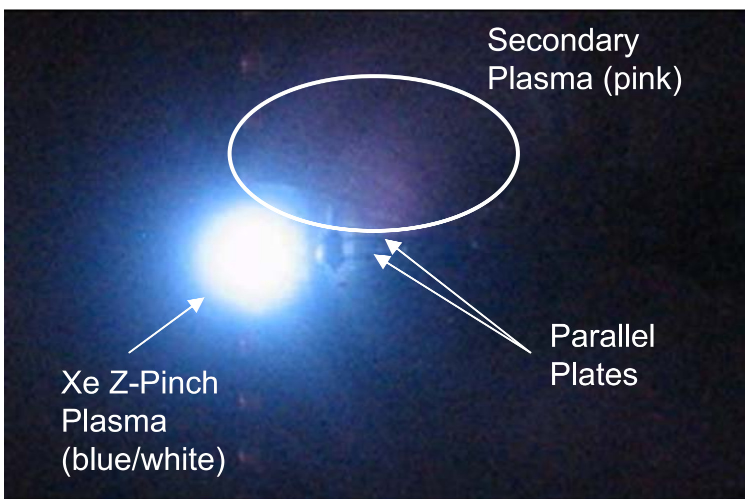
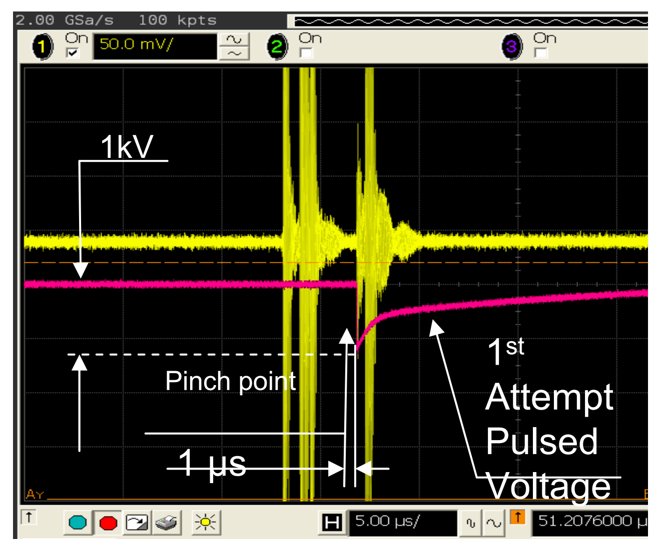
E-Field Ion Mitigation



07-SO-38, Characterization of Debris Mitigation Techniques for Sn and Xe-fueled EUV Light Source, Keith Thompson et. al.

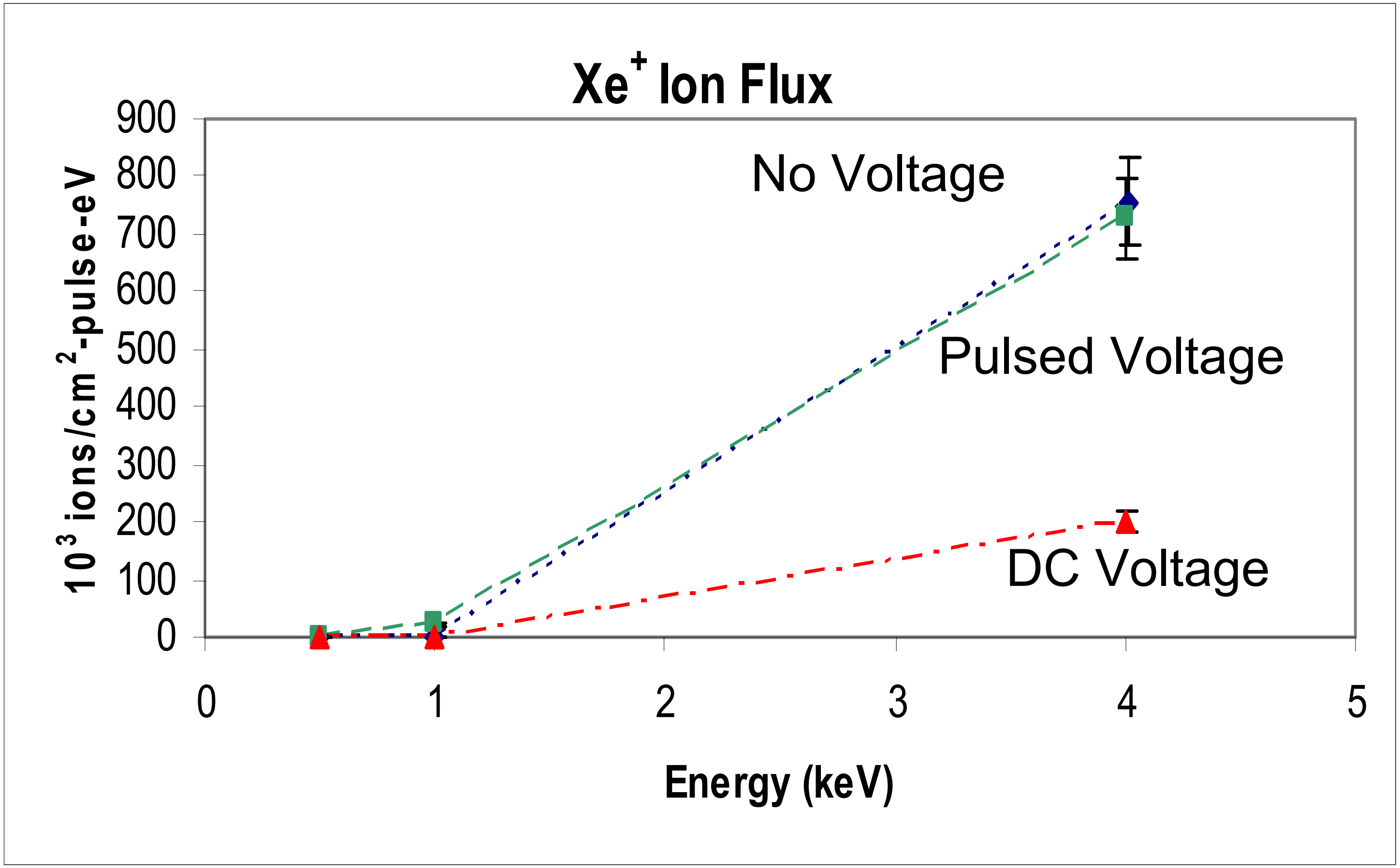


Parallel plates in front of the z-pinch with a dc voltage applied



Xe^+ ion flux with and without E-Field

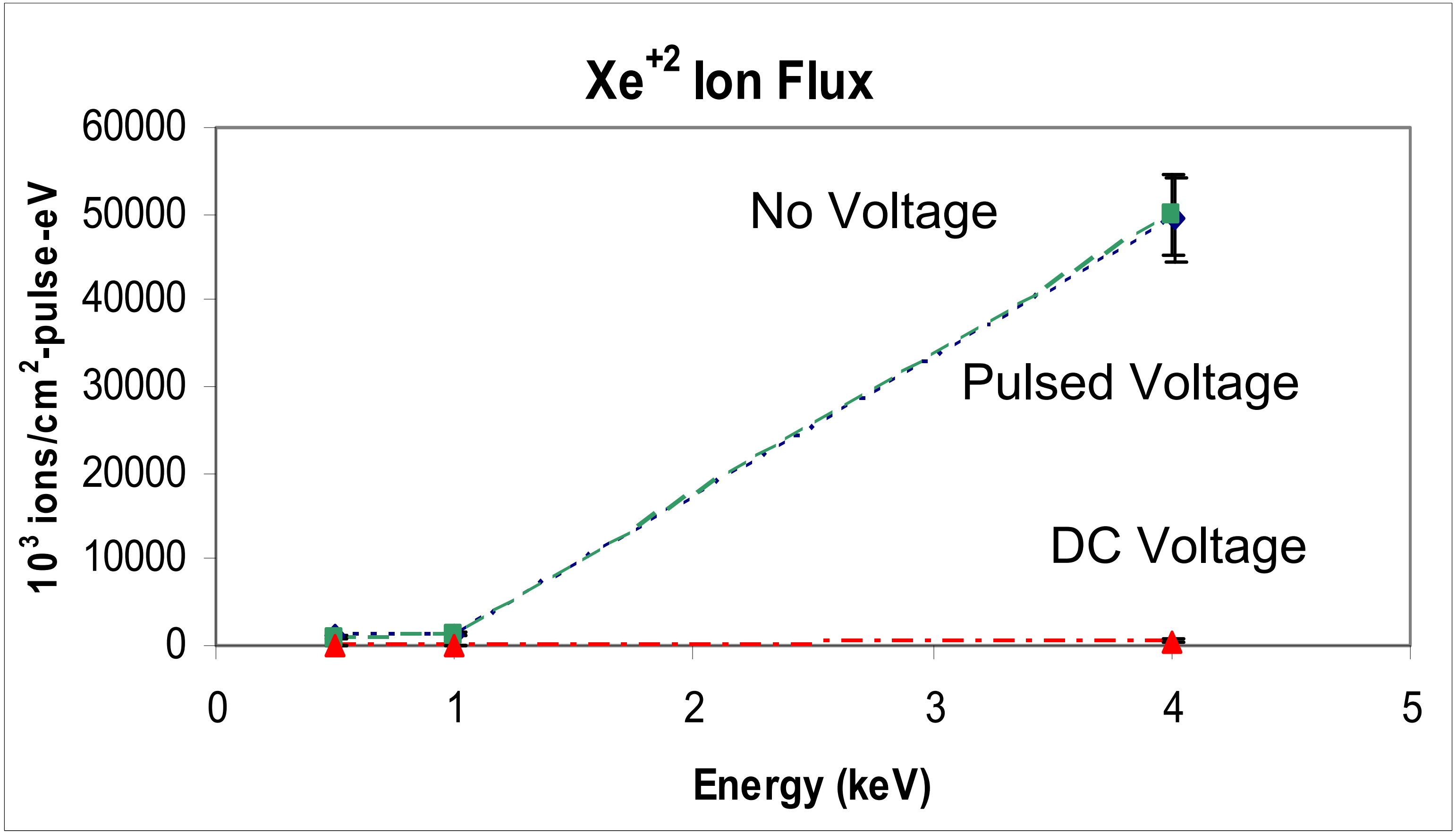
Xenon ion flux measured with and with pulsed and dc voltages applied to the E-field mitigation plates



Reduction of 3.75 times for 4 keV Xe^+ ions

Xe^{2+} ion flux with and without E-Field

Xenon ion flux measured with and with pulsed and dc voltages applied to the E-field mitigation plates



Dramatic reduction of 88.0 times for 4 keV Xe^{2+} ions

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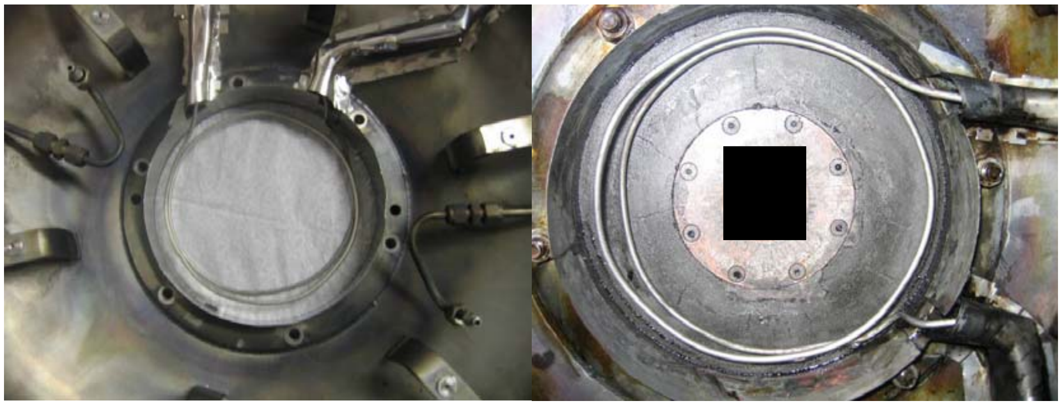
Plasma based mitigation

Pictures of RF coil installation in XCEED

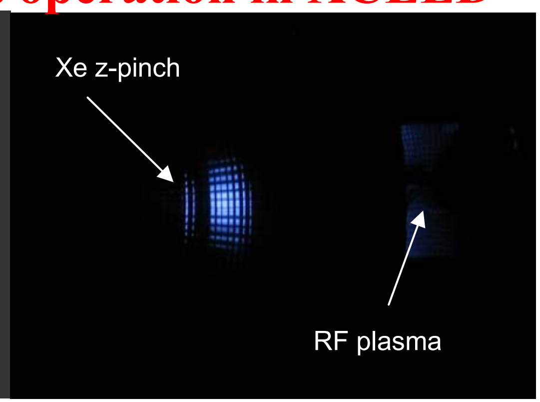


Pictures of RF plasma operation in XCEED

Mitigation tool occludes view

Pinch Plasma

RF Plasma diffusing out slightly

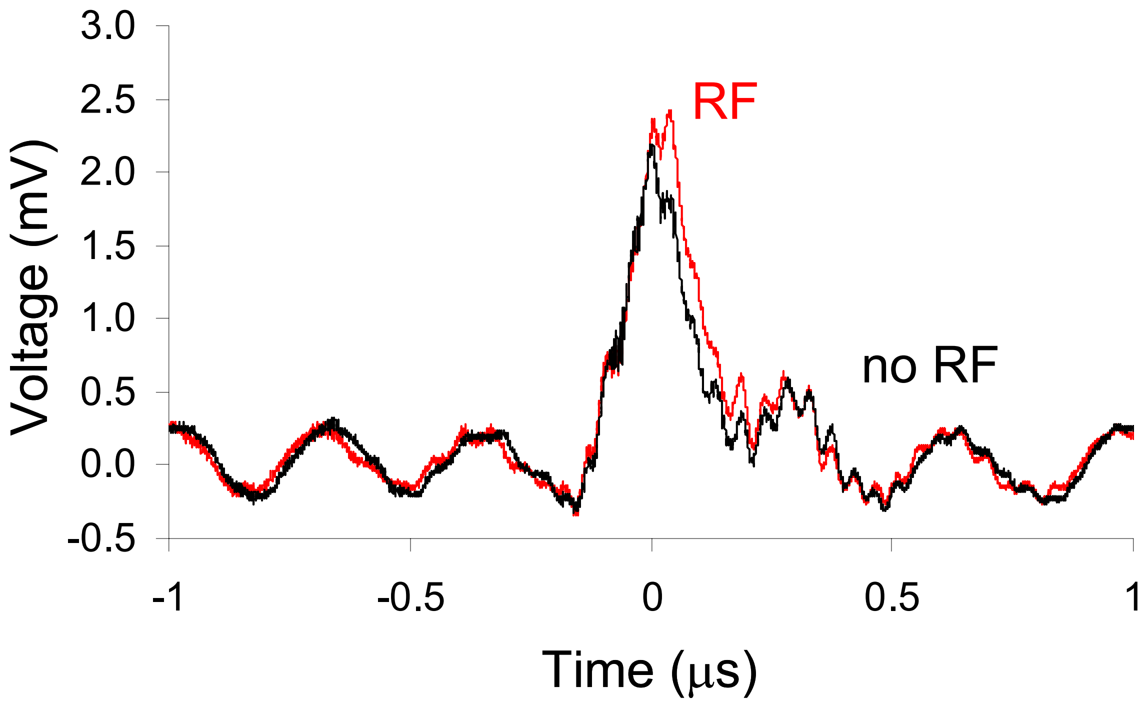


RF Plasma striking in the XCEED chamber, visible as glow from behind the foil trap

Secondary RF Plasma in Operation

- Steady RF plasma achieved
- Does not interfere with DPP operation (no change in I-V characteristics)
- Plasma contained to mitigation tool area

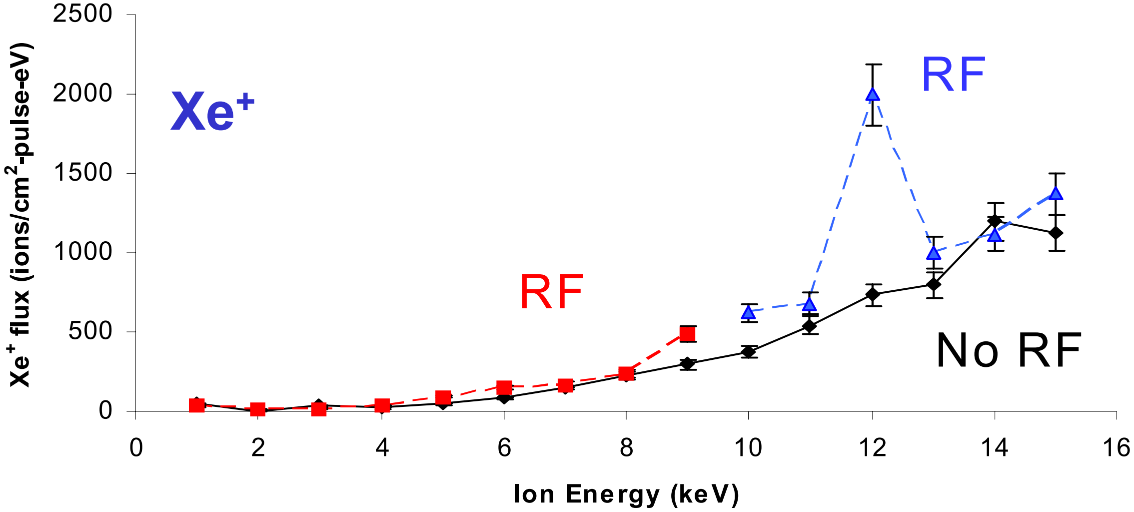
EUV reflectivity with and without RF plasma



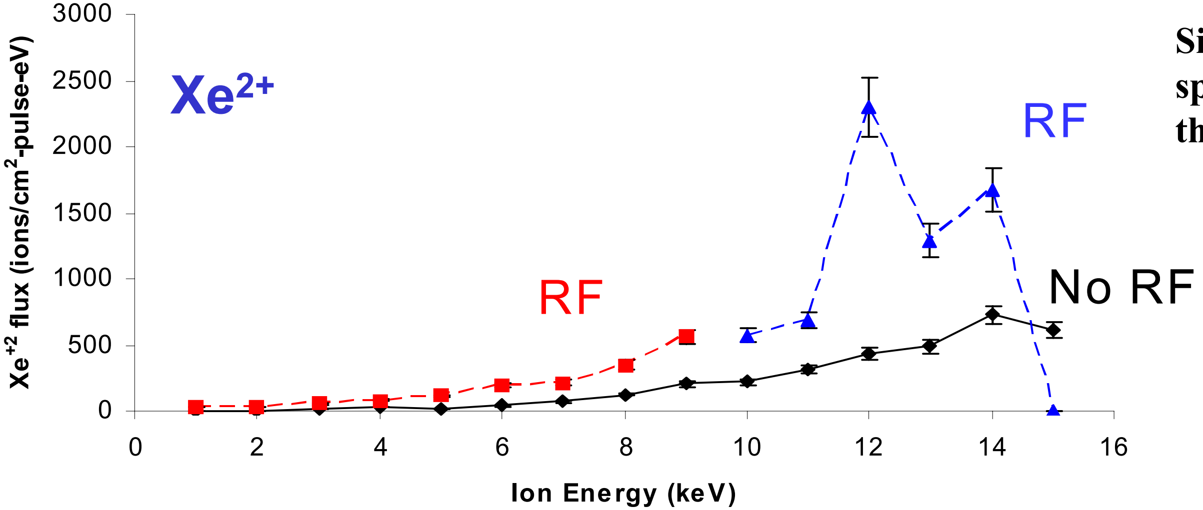
The RF plasma did not appreciably change the EUV photo diode signal. Slight rise may be due to enhanced pre-ionization

Xe Ion spectra with RF plasma

Ion energy spectra with and without RF plasma for Xe EUV source

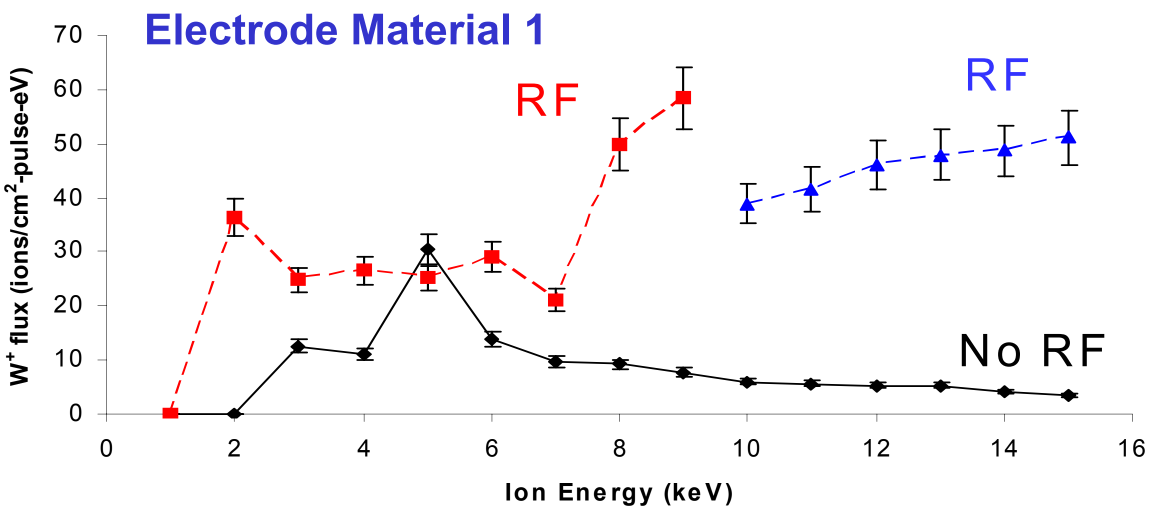


An RF plasma is created in the pinch area to increase the local ionization percentage in an effort To increase pinch efficiency and mitigate debris when combined with other techniques

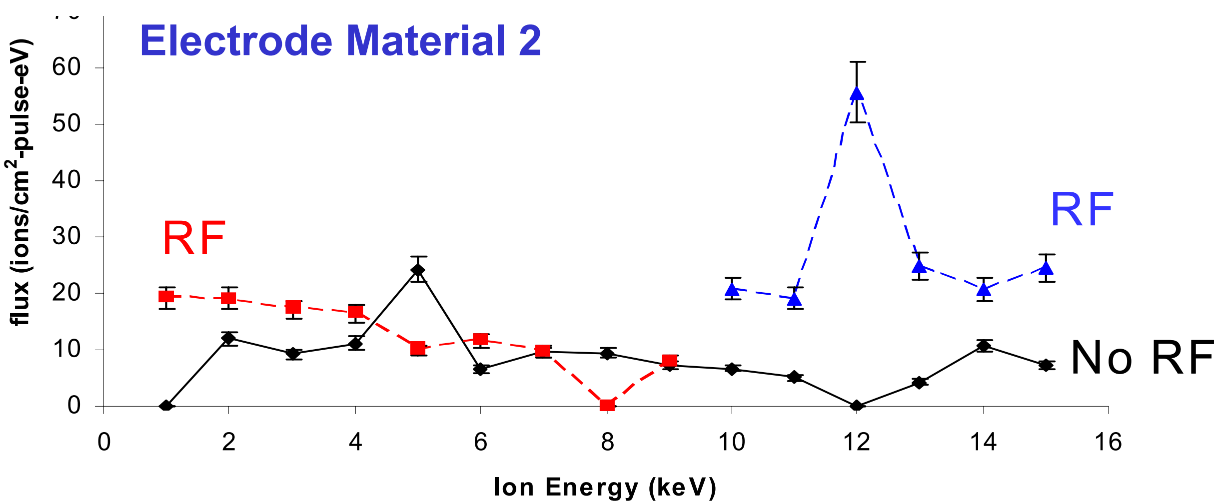


Singly and doubly charged Xe ion species were higher with RF plasma than without

Electrode material ion spectra with RF plasma



RF plasma caused a marked increase in electrode material ion flux



Could this be used to our advantage?

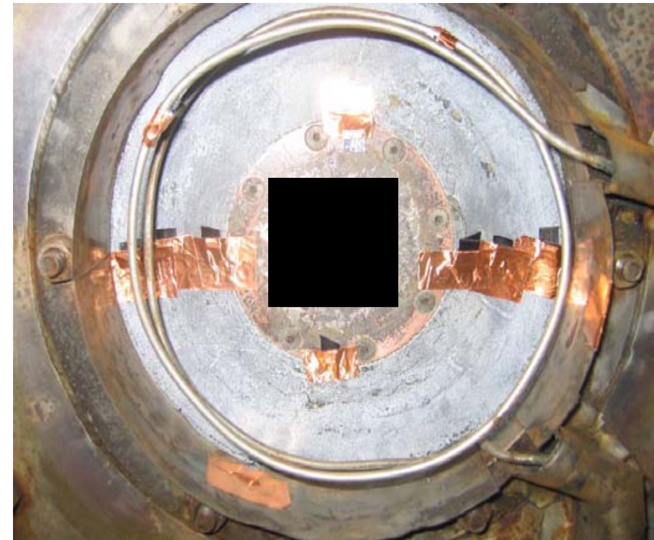
Reduction of Material Accumulation on Electrodes

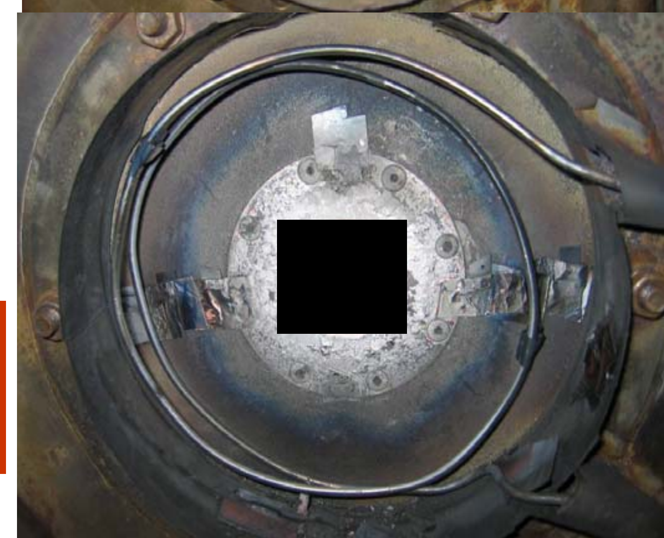
Si witness plates are placed on the forward facing surface of the XTS EUV source

A variety of surface treatments were tested on the samples with and without the secondary rf plasma

XTS forward facing surface with Si witness plates after exposure to 7M pulses of the Xe-fueled z-pinch

RF Plasma can aid in the elimination of material accumulation





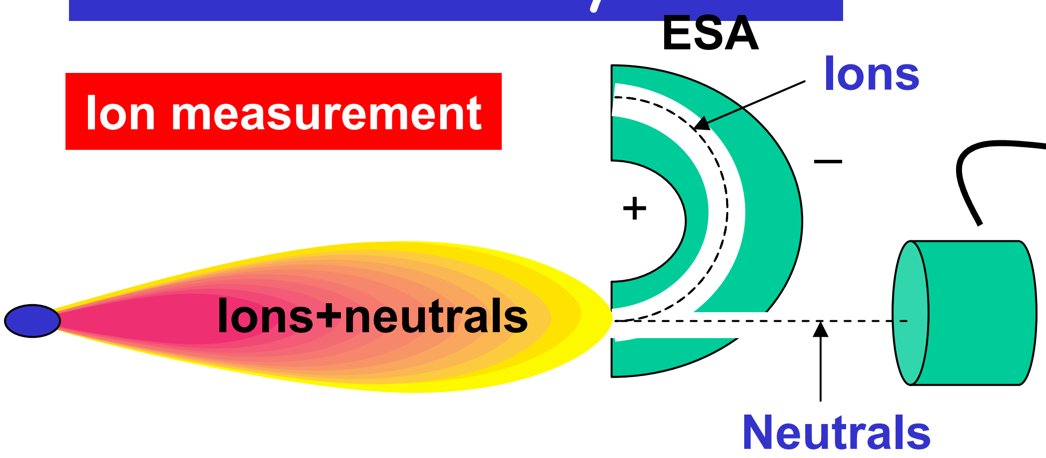
Neutral particle measurements

How many neutrals?
How energetic?
What damage they do?

Simultaneous measurements of ions and neutrals will help our understanding considerably

Neutral detector

Ion measurement



Neutral measurement

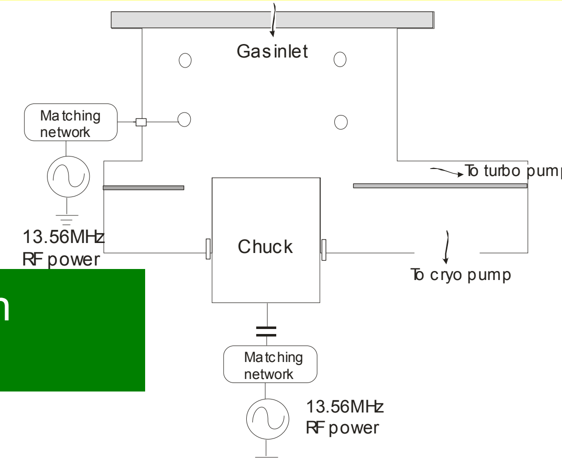
Should have results to show at 2007 SPIE conference

Cleaning techniques

Reactive Ion Etching (RIE) Experiment

Cleaning Sn debris on mirror using Ar/Cl2 plasma etching to extend mirror life time
Previous work showed high etch rate of Sn with halide ion etching

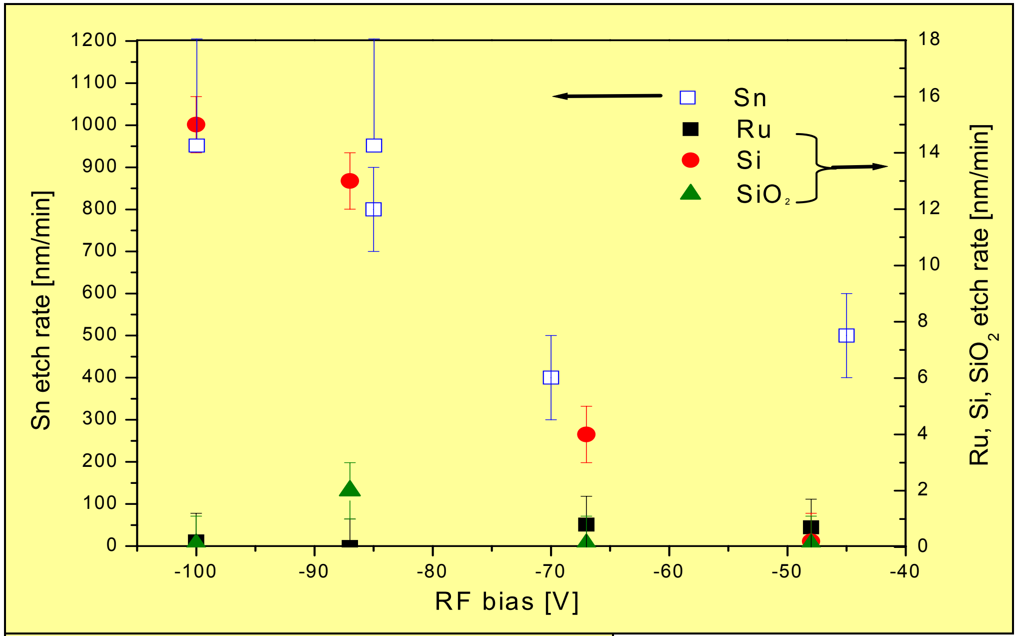
$Sn+4Cl \rightarrow SnCl_4$ Tb=114 C



06-CC-37, Selective Etching of Sn from Ru EUV Mirrors with Ar/CL_2 plasmas, HyungJoo Shin, et. al.

- 2-turn internal ICP coil insulated with glass cloth tape
- Independent RF power for the chuck bias to control the ion bombardment energy
- Pumping systems including turbo molecular pump, Cryogenic pump and Dry pump for using corrosive halogen gas-Cl_2
- Computer controlled Mass Flow Controllers for Cl_2 and Ar
- Heater and cooling water for the samples
- RGA mounted to monitor the water vapor pressure

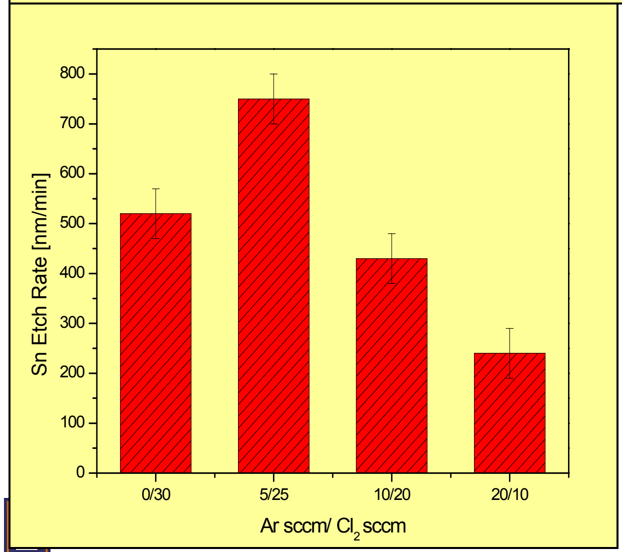
Etch rate measurement for Sn-Ru-Si-SiO_2



500W ICP power, 10mTorr

10 sccm Ar, 20 sccm Cl_2

The measured etch rates for Sn, Ru, Si and SiO_2 samples as a function of RF bias to the chuck. Left y-axis is used for Sn etch rate and right y-axis is for other materials since there is substantial difference between their etch rates. Standard error for these depth measurements with the profilometer was about ±100nm for Sn and ±10nm for other samples.



Sn etch rate is substantially higher than other materials

At around -80V bias, reactive ion etching enhances the etch reaction significantly.

- 1 min. of cleaning etched all the Sn (~1μm thickness)
- Whereas Ru and SiO_2 show almost no etching even for 10 min.
- For the case of Si, Ar/Cl_2 plasma reacts to form volatile silicon chloride($SiCl_4$). Note though that there is some native oxide layer which lowers the initial etch rate for Si.

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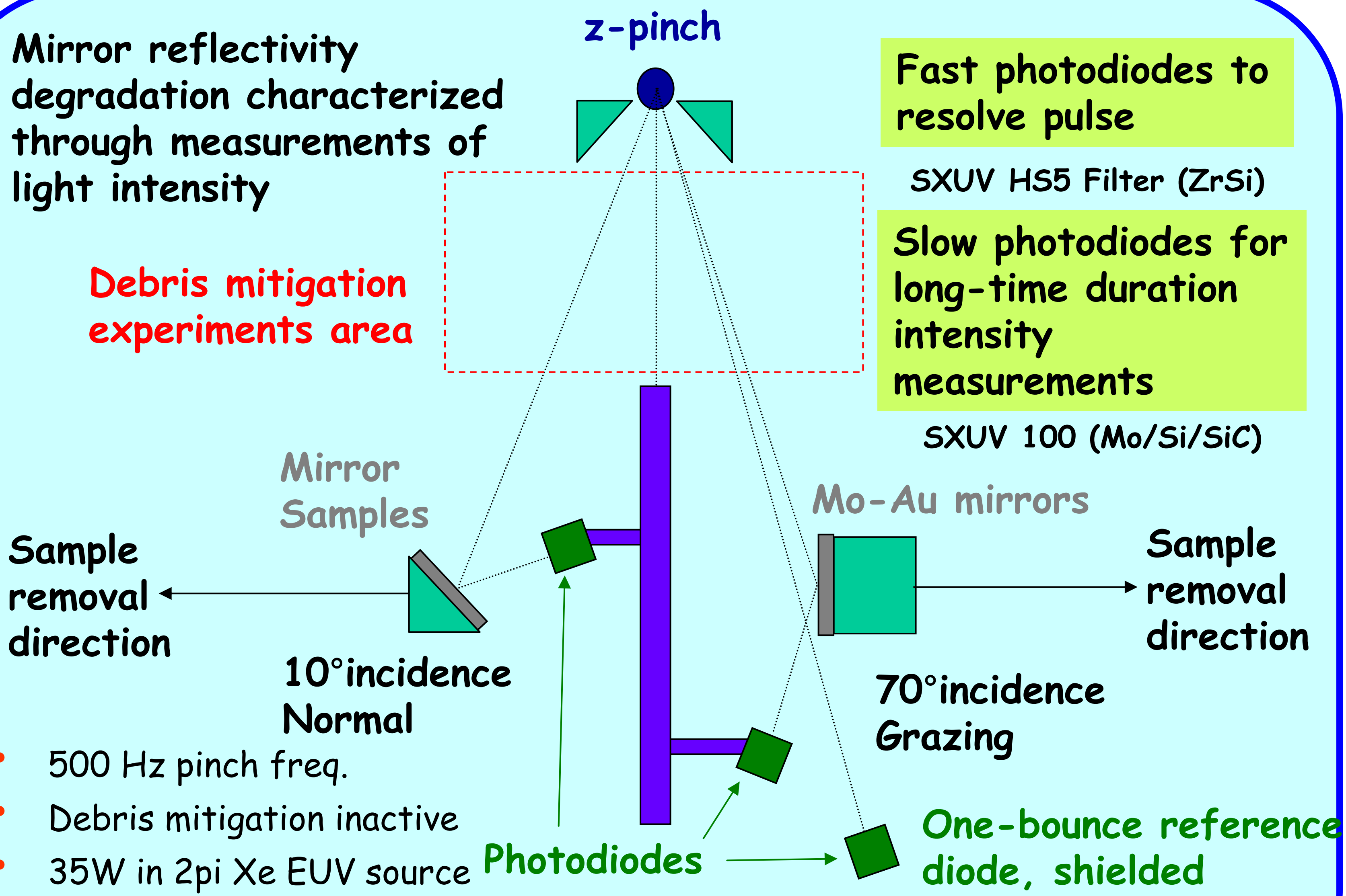
Reflectivity Measurements in XCEED

Mirror reflectivity degradation characterized through measurements of light intensity



- 500 Hz pinch freq.
- Debris mitigation inactive
- 35W in 2pi Xe EUV source
- Up to 3 million shots with 200 minute exposure
- 2 mTorr operation with Xe feed gas and no carrier and buffer gas

Cleaning Restores Reflectivity

Sn is coated on Ru samples using a bell jar vaporizer

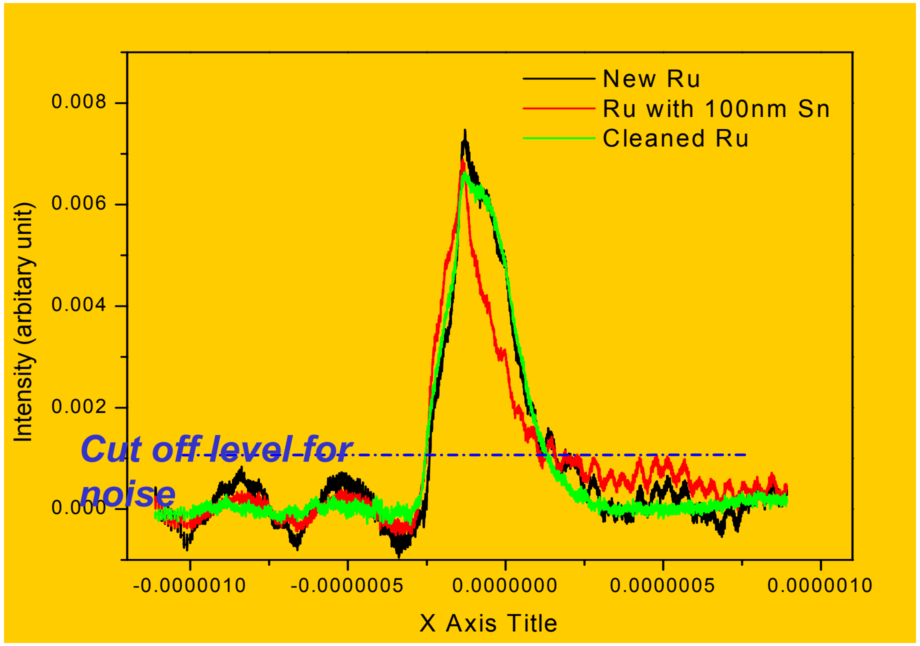
Sn is cleaned using our plasma-based cleaning method

Reflectivity measured on
- **Ru samples**
- **Sn coated Ru samples**
- **Ru samples after cleaning Sn**

Bell jar vaporizer

Reflectivity is the same or even higher after removing the Sn

	Total counts (arbitrary unit)	Normalized reflectivity
New Ru	*3.4*	*100%*
Ru with100nm Sn	*2.9*	*85.3%*
Cleaned Ru	*3.5*	*103%*



Reflectivity measurement

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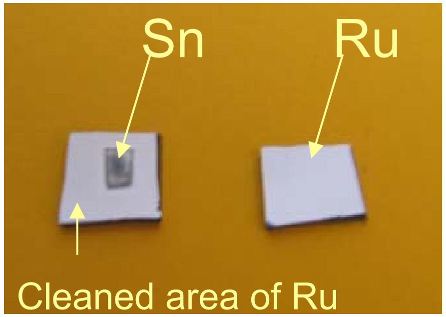
Cleaned sample characterization



Cleaned Sn on Ru (left) vs. new Ru sample (right)

We applied one of the best recipes (-77V, 5sccm Ar, 25 sccm Cl_2, 500W power, 10mTorr) for 5min. to clean off 100nm Sn on Ru.

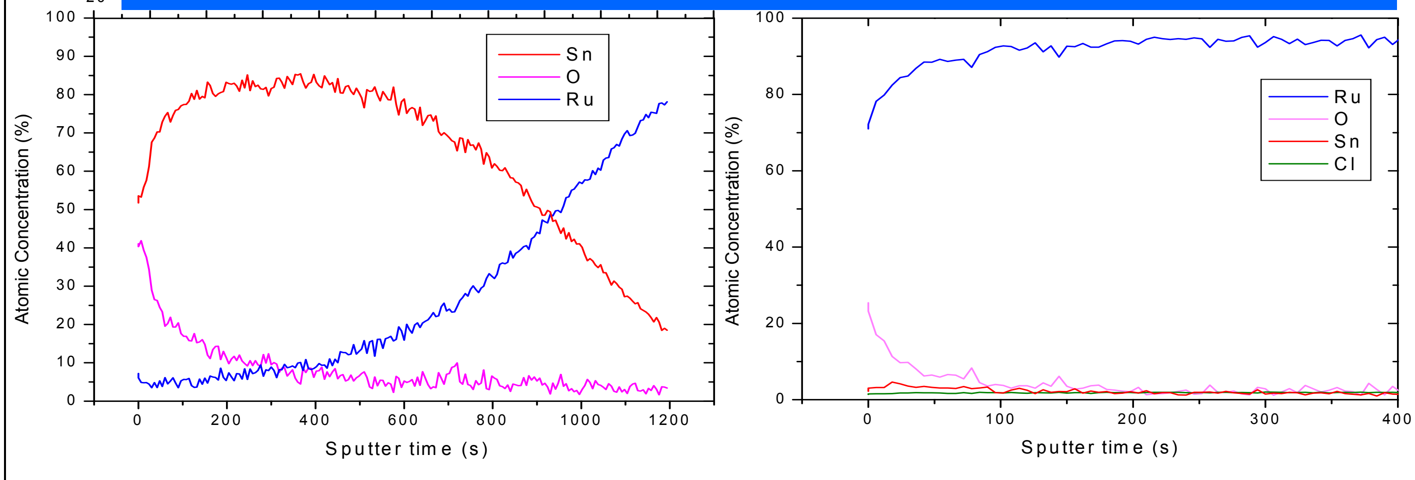
Top figure shows the cleaned Sn on Ru sample and the pure Ru sample

Small square part is the area covered by a piece of SiO_2.

We did a Auger Electron Spectroscopy measurement to see if Sn remains after cleaning or if there is ion implantation.

AES result confirm the cleaning

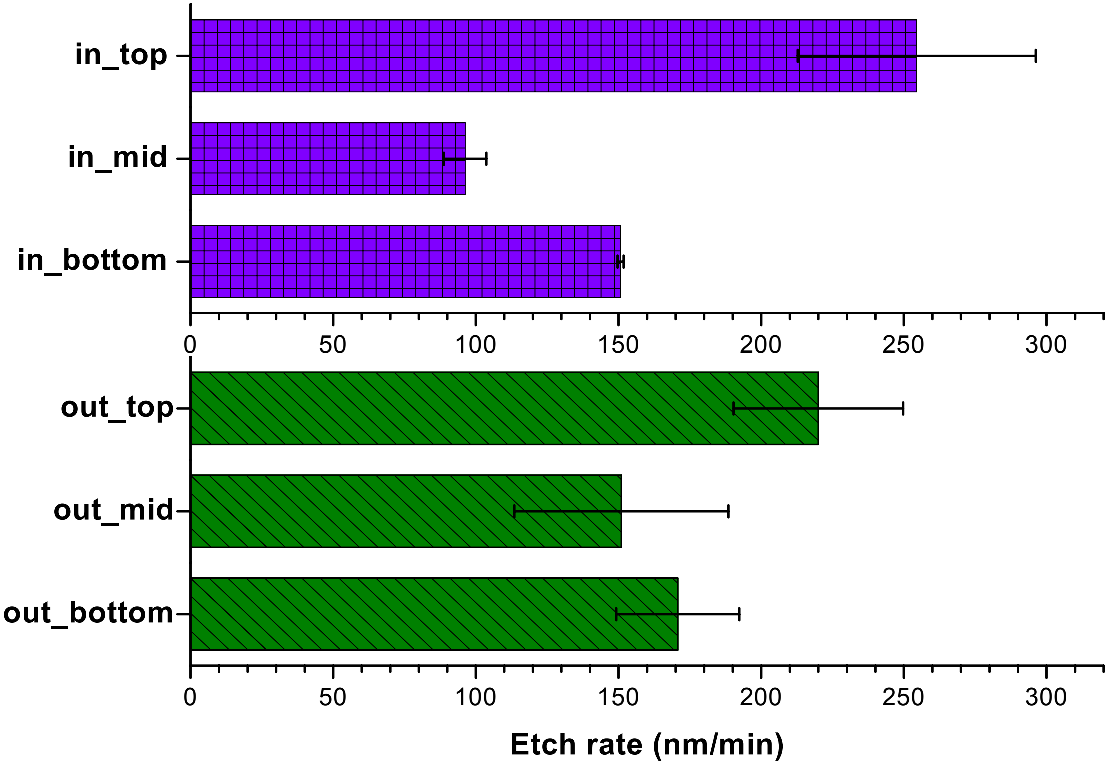
AES depth profile of Ru sample before and after 5-min. cleaning

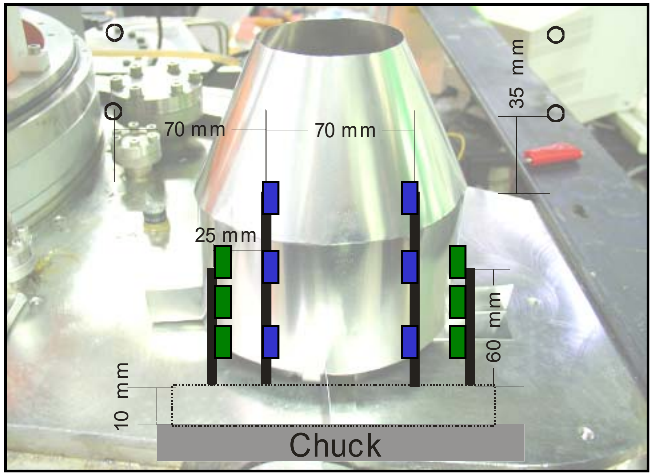


After cleaning, a depth measurement by a profilometer showed that we etched Sn all the way down to the Ru surface as we intended. In order to check Sn cleaning, AES depth profile was used. Before cleaning, we had about 100nm Sn but after cleaning, Sn Auger electron signal was not detected on the surface. This confirms that we cleaned all the Sn off Ru.

Earlier Etching Results

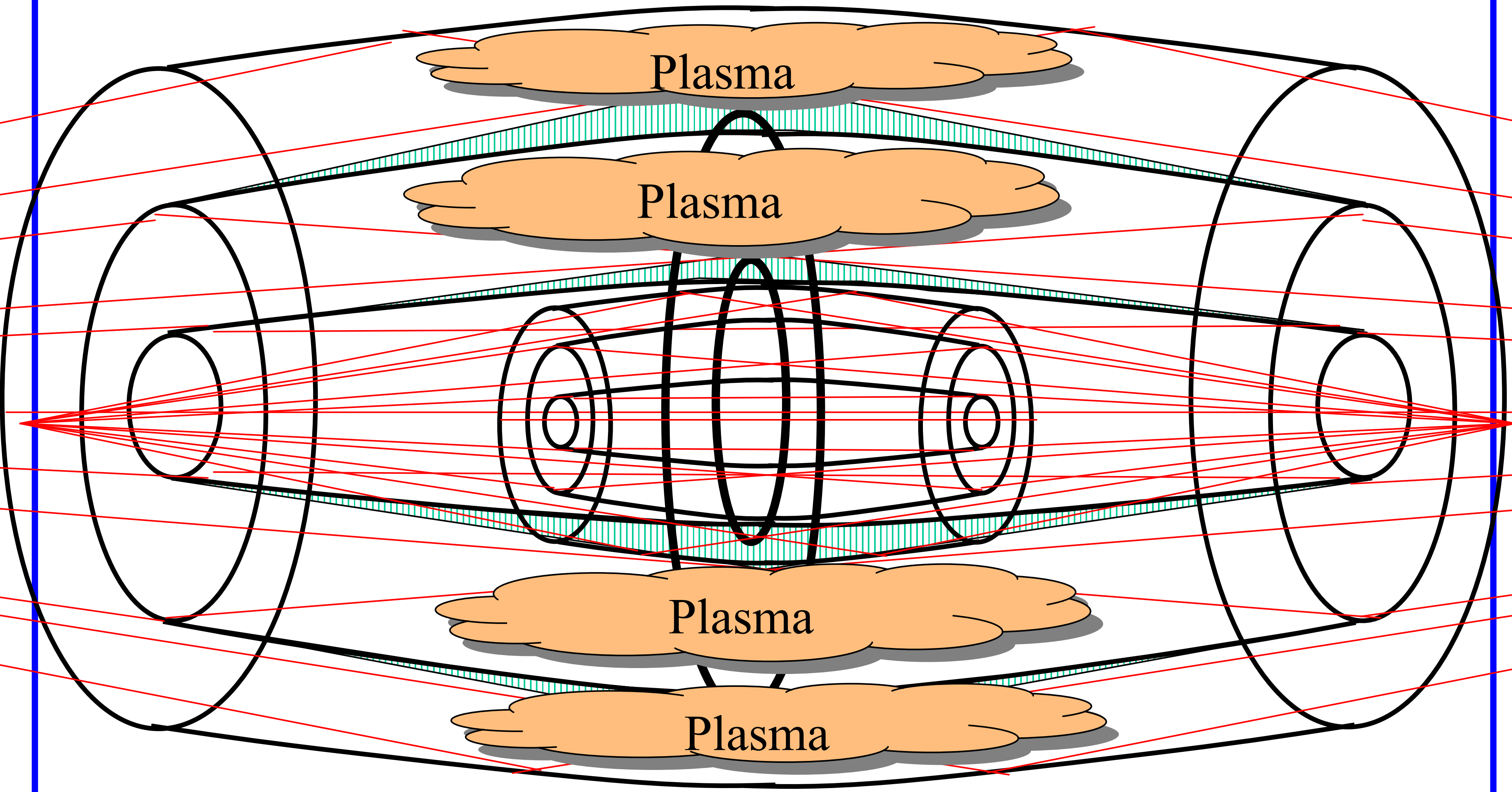
Etch rate at different positions on mock-up collector



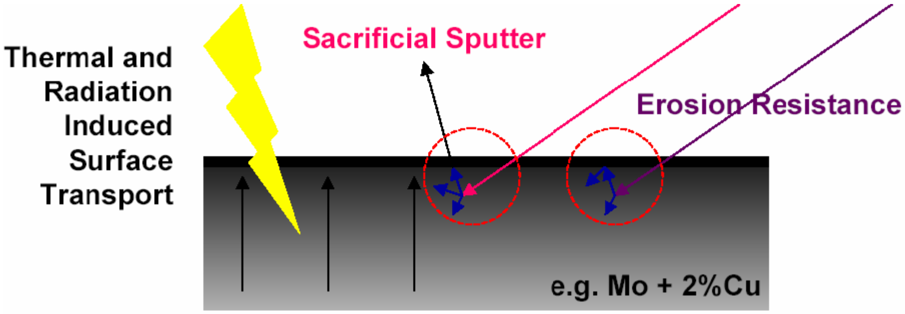


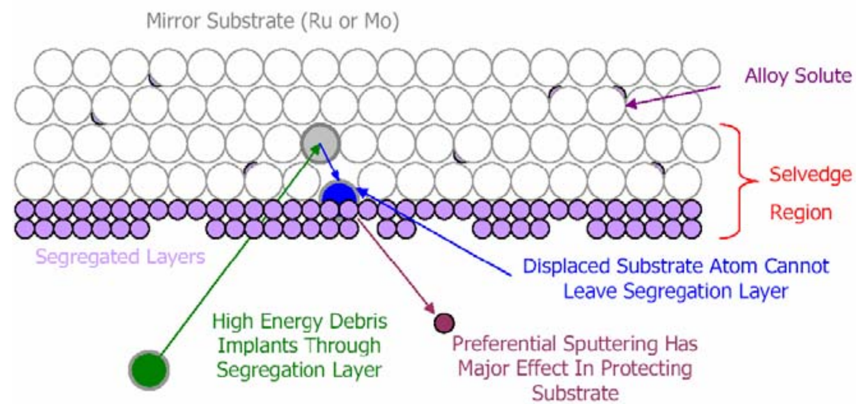
We put the samples at the top, mid, and bottom of each shell of two-shell mirror mock-up. Generally the outer shell samples' etch rate was higher than inner shell samples' etch rate except for top one. That is because the plasma density is larger when closer to the plasma source. The reason for bottom sample's etch rate increased although it is placed further from source than the mid sample is because of the 1cm gap at the bottom so boht plasma can enter and etch products can exit.

Integrating cleaning technique in collector mirrors



Gibbsian Alloy Mirrors





05-CC-36, Gibbsian Segregating Alloys Driven by Thermal and Ion Flux Gradients, Huatan Qiu, et. al.

Sample exposure in XCEED

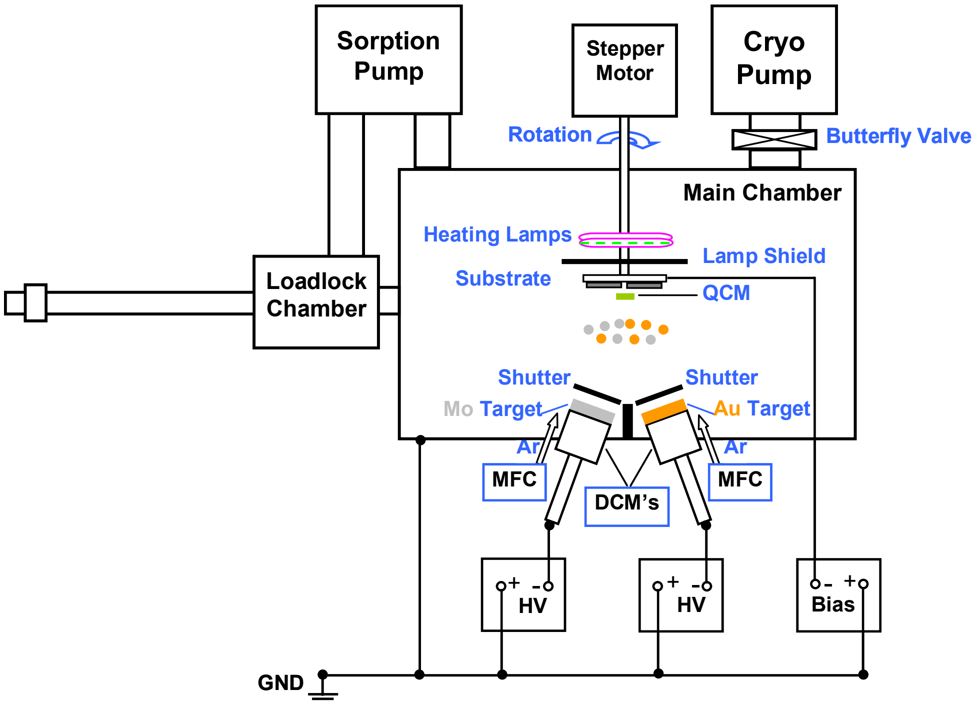
2 Mo-Au samples were exposed to Xe EUV source

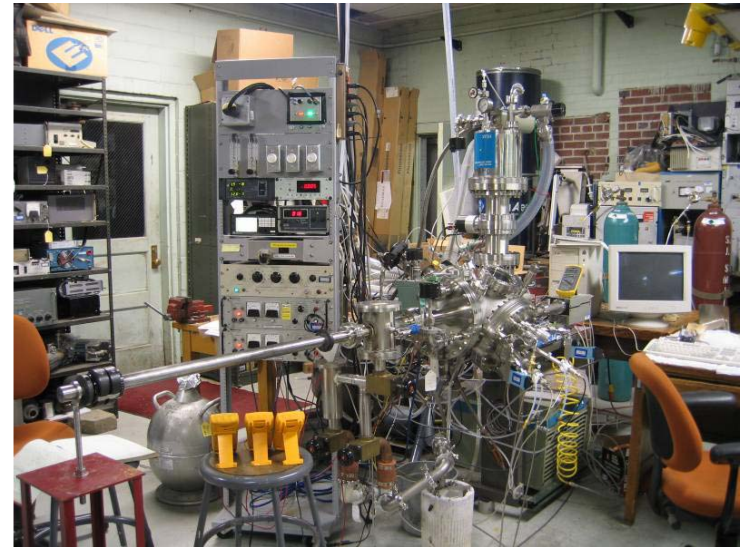
Reflectivity is measured as a function of number of shots`

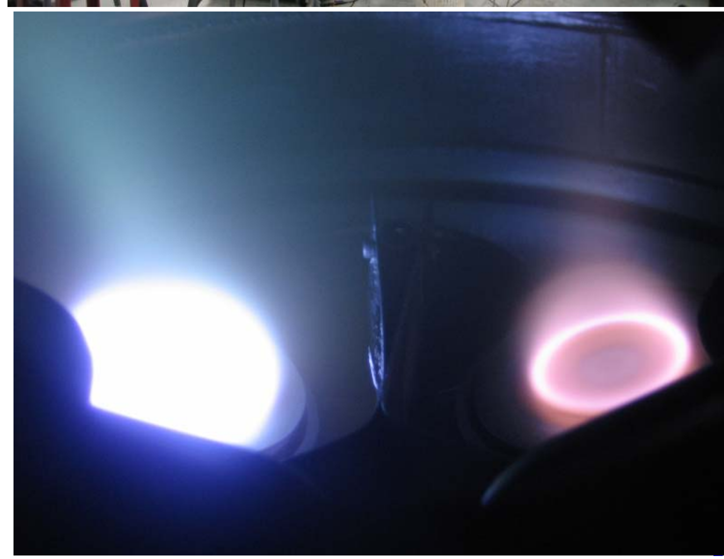
Reflectivity is compared for two samples at different temperatures

Material characterization is performed (AFM, SEM and AES)

Dual Magnetron System at UIUC



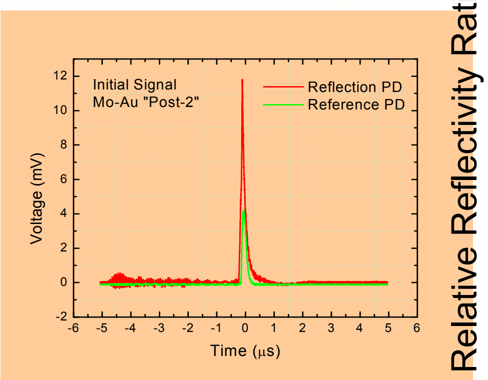


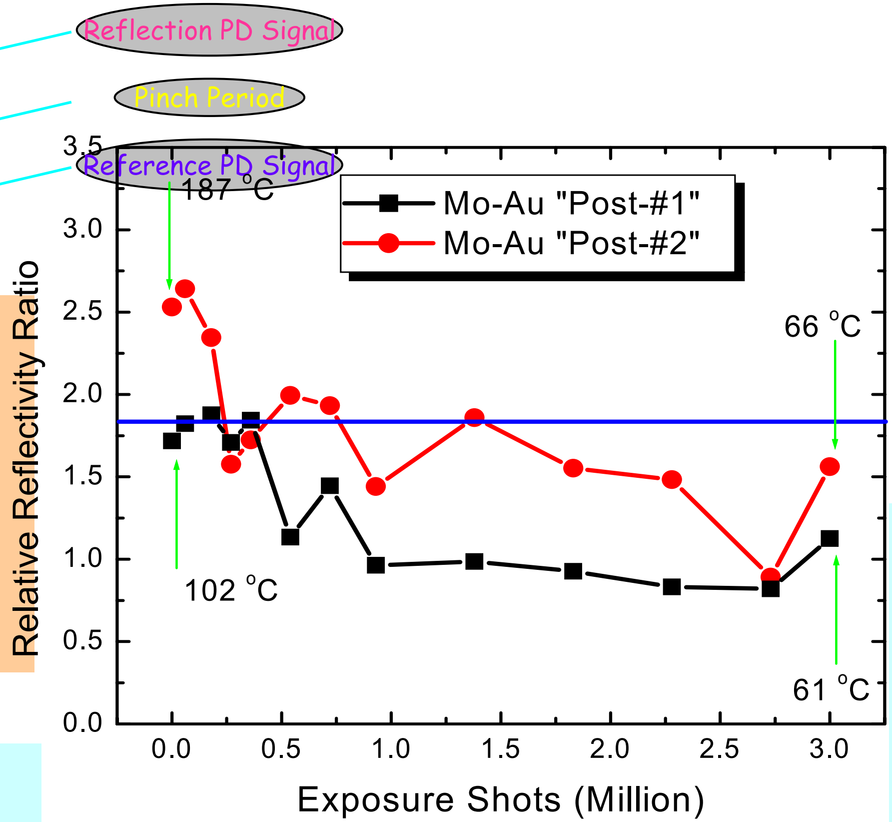


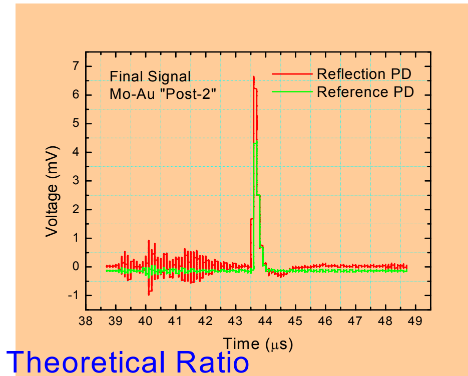
- Rotatable substrate: uniform deposition
- Biasable substrate: minimize columnar structure, improve film quality
- Pre-heat substrate: ~ 150 °C, get rid of H_2O
- Pre-sputter targets: minimize O composition
- Base pressure: < 10^{-8} Torr minimize impurities
- Operation conditions:
  2 mTorr Ar, 150 C, DC power @ 65 W (Mo)/1.7 W (Au)

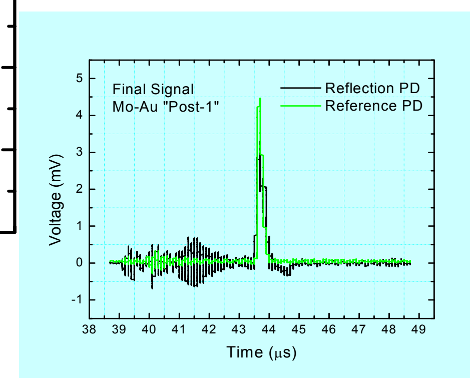
In-situ Reflectivity Evolution *vs.* Time (Exposure Shots)

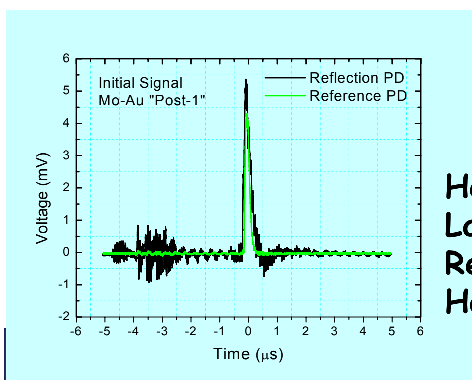
Typical Signals











Heated sample has higher initial reflectivity due to smoothing effect of segregation Layer. If sample temperature had not dropped, reflectivity may have remain higher Reflectivity degrades with exposure time due to roughening from ion bombardment. However, this drop is small compared to pure Ru. Segregate keeps mirror smooth.

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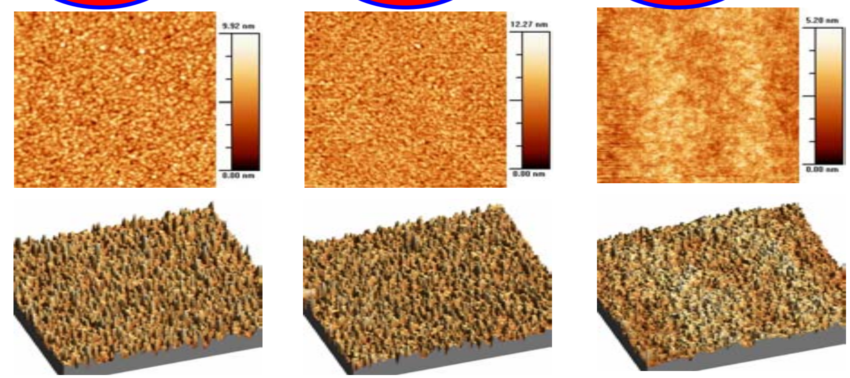
Roughness -- Au kept it smooth

AFM

- Post - #1 got a x1.1 increase of its RMS roughness, while Post - #2 became even smoother than its original RMS roughness, after 3 million shots (200 minutes) of Xe exposure without any debris mitigation
- GS Mo-Au has impressively small roughness change, due to the segregation effect
    - ✓ protects the mirror material (Mo) underneath the surface Au layer by sacrificial sputtering
    - ✓ repairs the surface damage due to the bombardments by ion debris, especially under higher temperature conditions
- It's quite useful for EUV optics, in particular for grazing incidence since roughness reduction is critical to maintain their reflectivities

PRE-#0 | POST #1 | POST #2



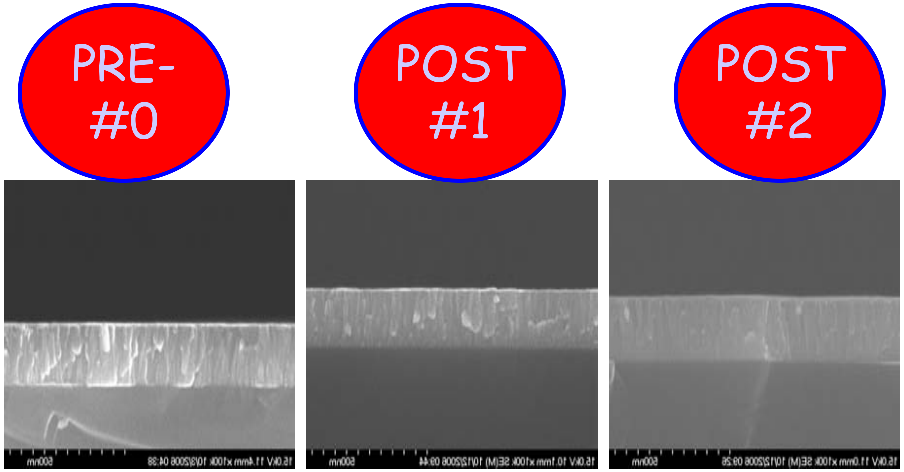
AFM RMS Roughness (nm)

Mo-1.08%Au	RMS Roughness [nm]	Change (Post / Pre)
Pre - #0	1.10	-
Post- #1	1.23	1.1
Post- #2	0.54	0.5

Erosion – Au saved the day

SEM

- Post - #2 was eroded only 1 nm which is hard to accurately measure, However, its RMS roughness did lessen which could be due to the contribution of the GS mechanism for self-repair.
  - The contribution of the segregation effect seems to reduce roughness.
  - Au may indeed act as a sacrificial layer protecting the active mirror component !



SEM Thickness and Erosion (nm)

Mo-1.08%Au	Thickness [nm]	Erosion [nm]
Pre - #0	201.	-
Post- #1	185.	16.
Post- #2	200.	1.

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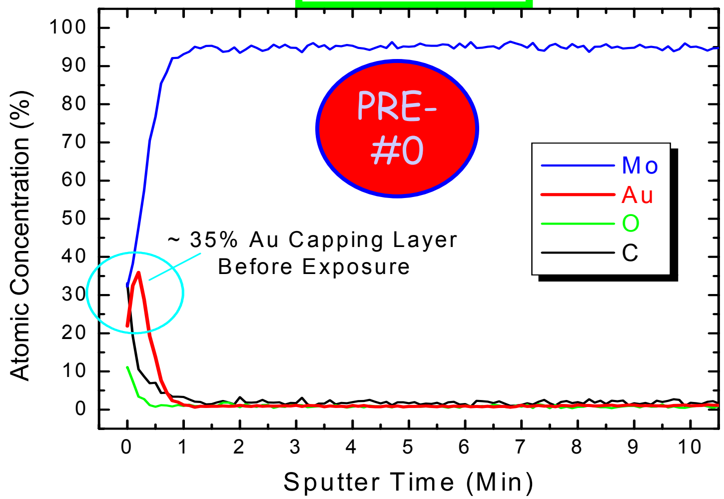
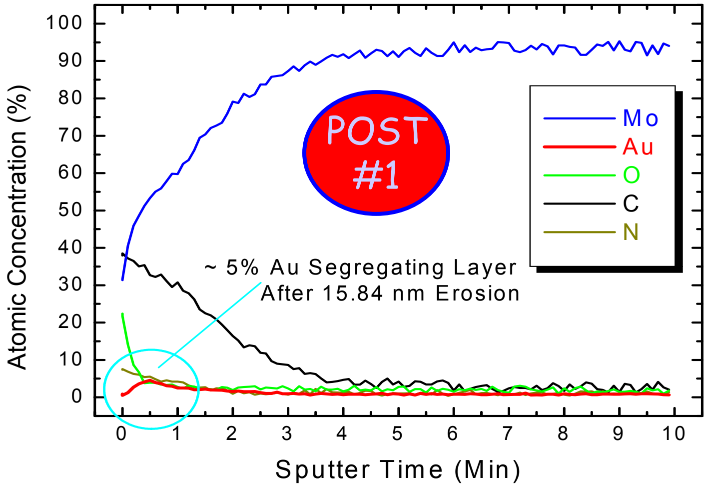
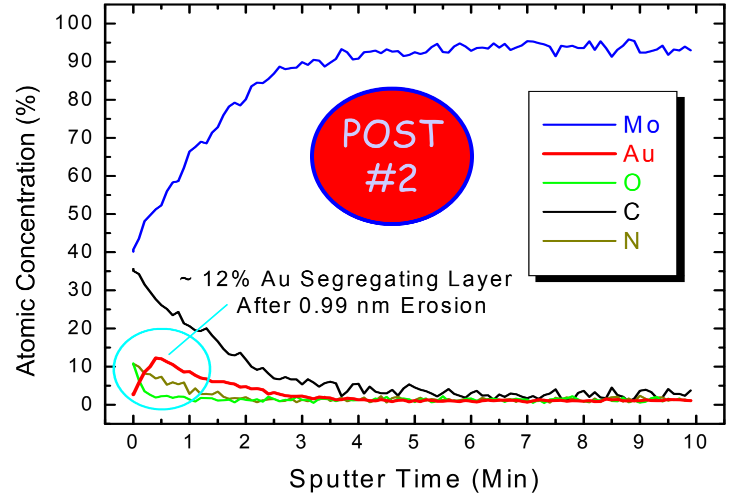
Film Composition and Segregation Evidence

AES



- Au component is higher than the bulk atomic concentration in the initial w nm of the eroded Mo-Au film
  - ✓ Bulk concentration of Au: ~ 1.08 ± 0.16%
  - ✓ Surface concentration of Au: ~ 5-12% (or higher if a smaller sputtering interval was used) even after eroded by ~ 16 nm
  - ✓ Proved our Gibbsian segregation idea !
- Note that the Au component should segregate and enrich on the surface more strongly than measured here. More segregation is possible to obtain through increased heating and encouraging diffusion along grain boundaries, in order to obtain better GS performance

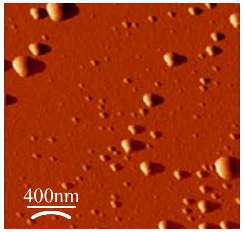


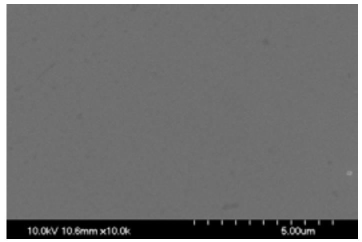


Li Cleaning can also be done

Surface comparison of EUV mirror optic samples

As received

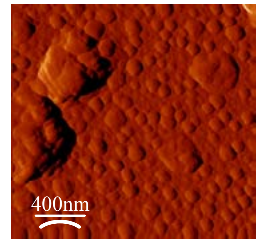


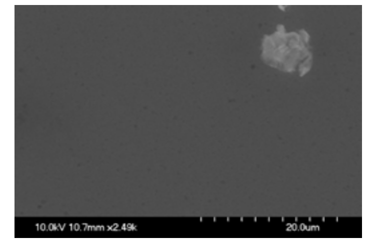


RMS Roughness of 2.94

10.0k magnification

More He$^+$ Flux: More Li Debris Removal

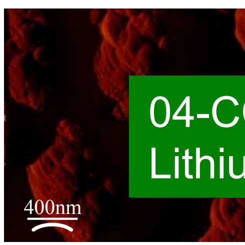


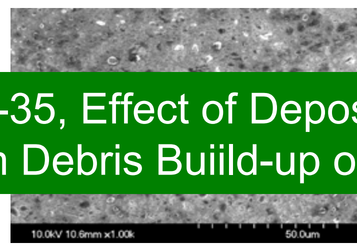


RMS Roughness of 27.4

2.49k magnification

Baseline Deposition

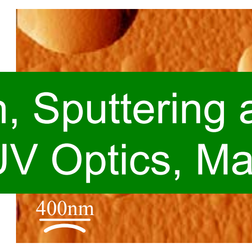


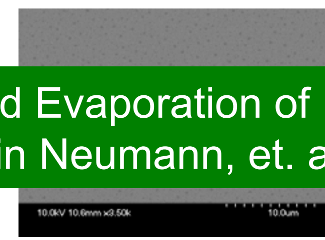


RMS Roughness of 56.9

1.0k magnification

MLM to 400^o C: Li Debris Removal



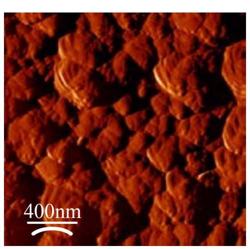


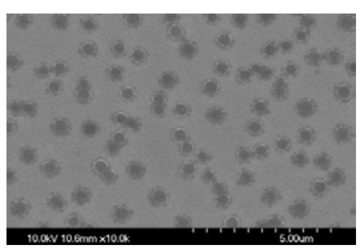
RMS Roughness of 26.4

3.5k magnification

04-CC-35, Effect of Deposition, Sputtering and Evaporation of Lithium Debris Buiild-up on EUV Optics, Martin Neumann, et. al.

Addition of He$^+$ Flux: Initial Li Debris Removal

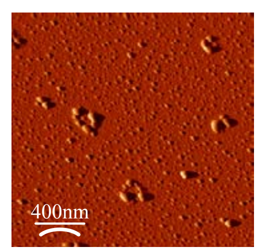


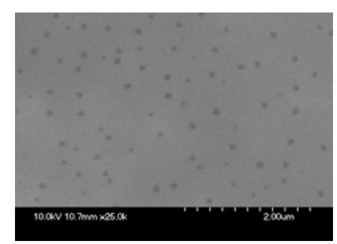


RMS Roughness of 30.5

10.0k magnification

400^o C and He+ Flux: Near as received condition





RMS Roughness of 1.03

25k magnification

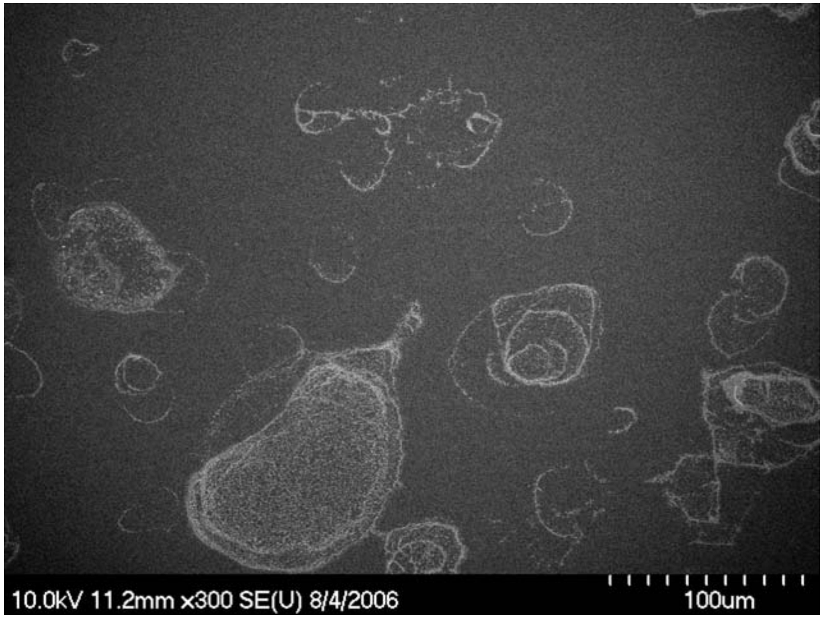
Mask Cleaning / Particle Removal

- Contamination on the Mask will print defects on every wafer
- Current cleaning technology (wet cleaning) may not be 100% effective in particle removal
- A new process (PACE) was developed that is a **P**lasma-**A**ssisted **C**leaning by **E**lectrostatics

08-CC-85, Plasma-Assisted Electrostatic Cleaning of EUV Masks, (PACE), Wayne Lytle, et. al.

- Apply a pulsed DC bias to the substrate
- Use a plasma to charge the particle up more negative
- Use the modification of the sheath potential to create a larger electric field
- Particles are removed by $\vec{F}_{repulsive} = q_p \vec{E}_{sheath}$

Particle Removal Results of PSL from Ruthenium Capped Quartz



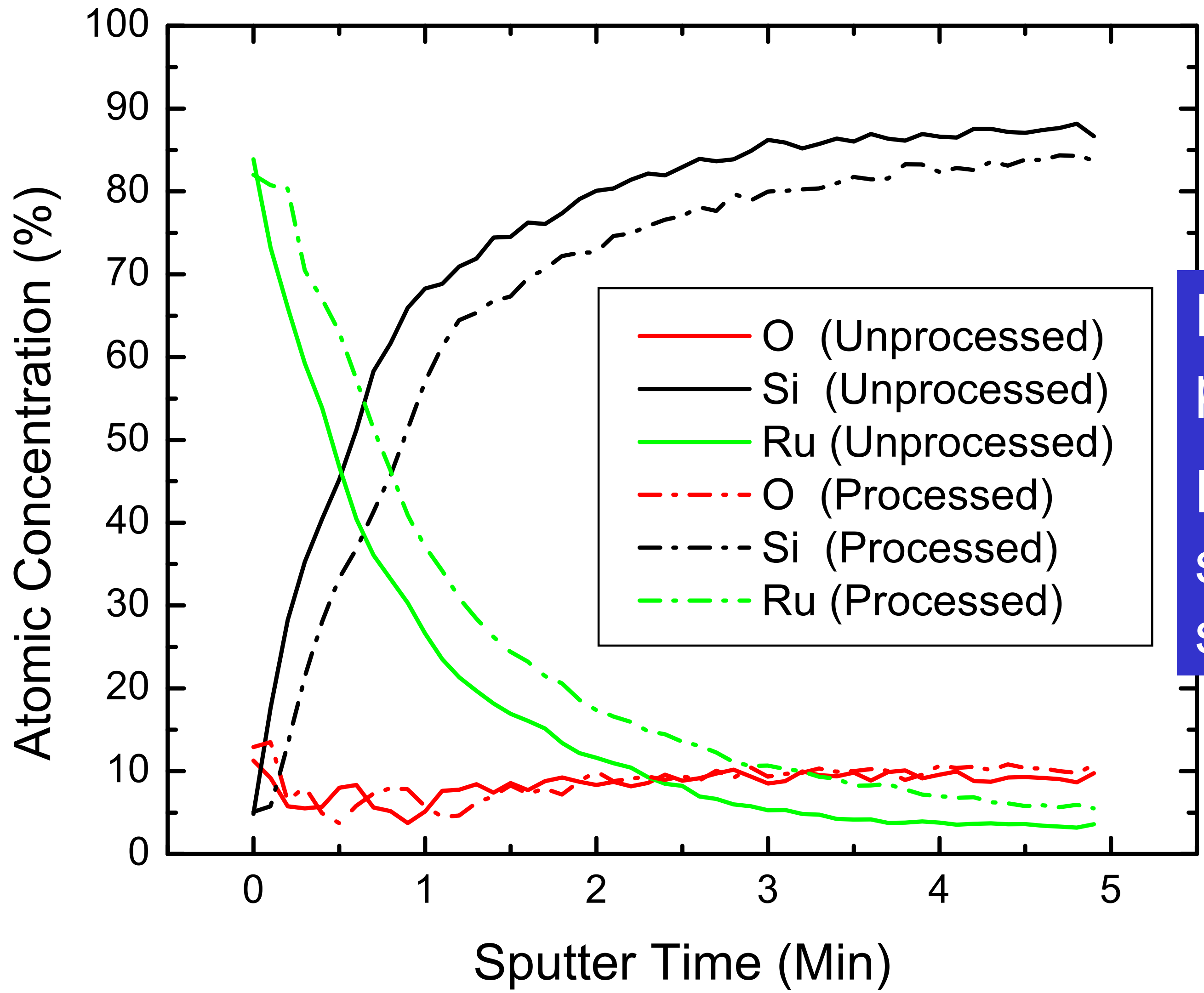
Control Sample 1.5 % ± 0.8 % covered

Processed Sample 0. 16 % ± 0.007 % covered

After 10 minutes of cleaning, we have a particle coverage **reduction of 90 %**

Cleaning is probably even better since experiments are not in a clean room and stray dust is counted on the processed sample

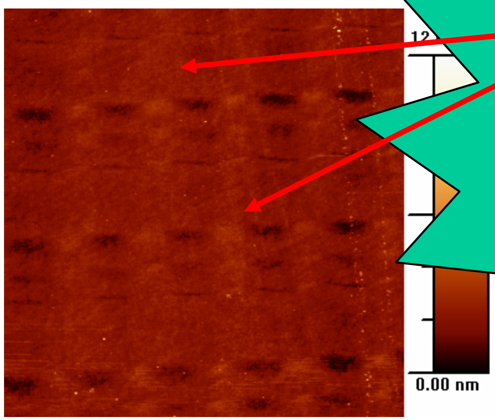
Ruthenium Erosion Data



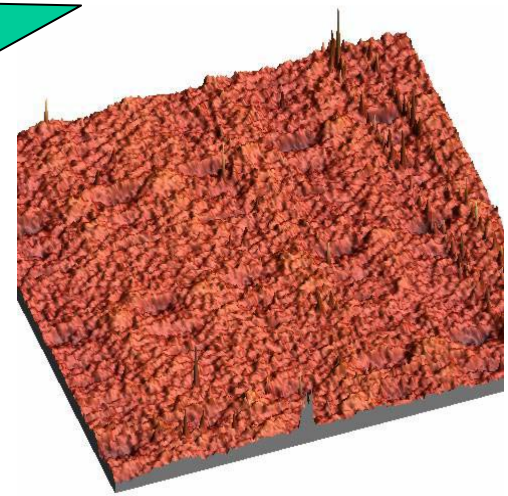
Ru still present !

No sputtering seen !

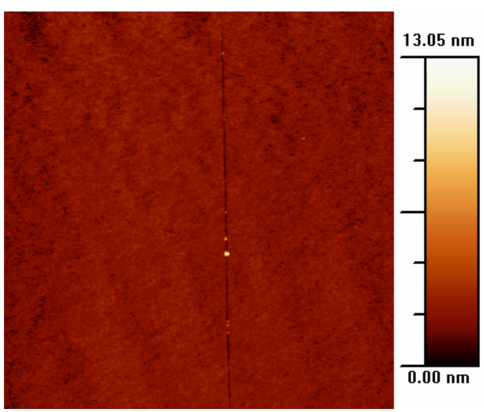
Surface Roughness Scans (same sample, before and after processing)



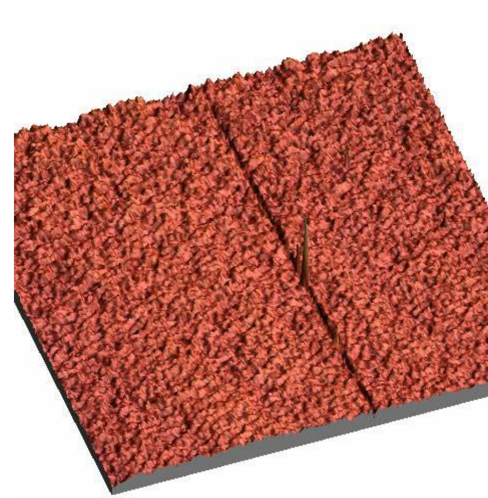
Artifacts from our AFM tip: the computer smoothed the data to account for these.



Surface did not get rougher !



Processed



Surface Roughness Results

Measured Position	RMS Roughness [nm]	
	Unprocessed	Processed
0	0.490	0.521
1	0.525	0.536
2	0.528	0.435
3	1.272	0.436
4	0.897	0.379
Average	**0.742**	**0.461**

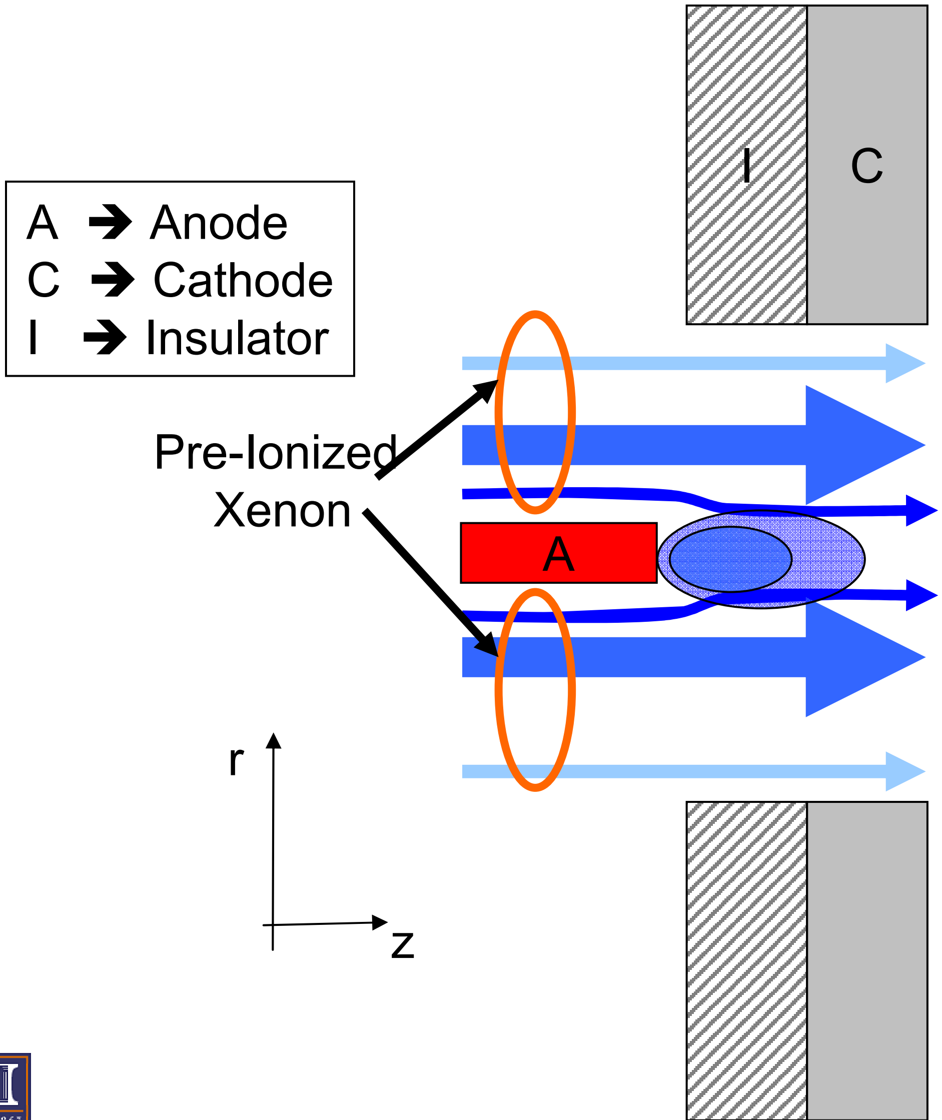
The RMS roughness (5u by 5u) of the processed sample is clearly smaller than the unprocessed sample. However, there are a few islands on the surface as seen in 3-D pictures, which might possibly be the dust of the unprocessed sample. The actual film surface of the processed sample became smoother than the unprocessed sample, which indicates that we cleaned the dust off of the surface while preparing these samples using the PACE technique.

Comments on PACE

- The PACE technique can remove contamination.
- Results are very encouraging.
  - Ru is not removed
  - Surface is not roughened
- Real world contamination is not spherical and will fall into the lower range of Van der Waals forces due to particle roughness which makes this technique even more promising

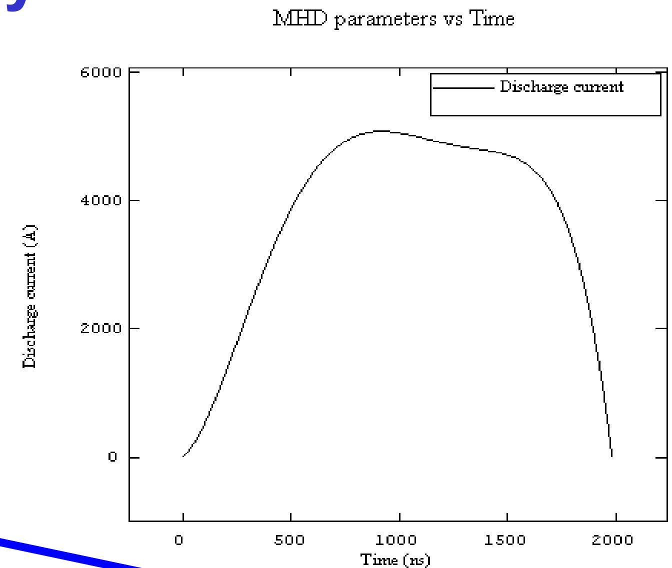
MHD Simulation of the XTREME XTS-13-35 Z-pinch EUV source using HELIOS-CR*

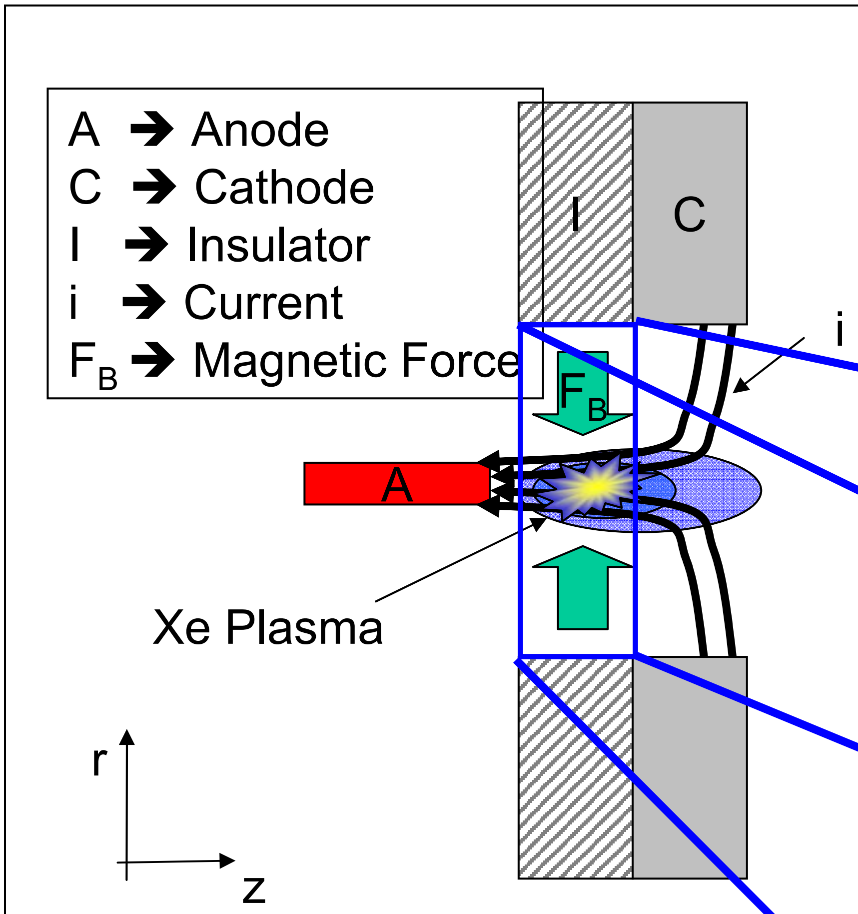
*Prism-Spec, J. MacFarlane

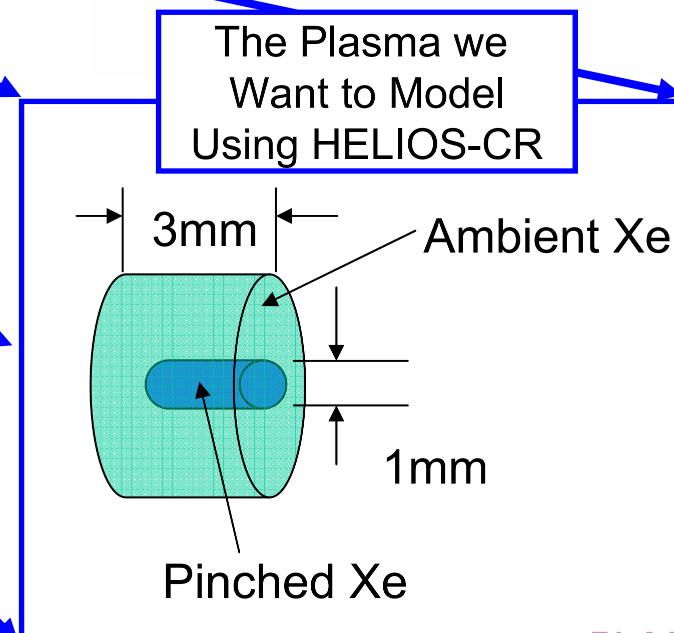


Current modeling efforts for the EXCEED project at the University of Illinois, have involved using the fully collisional-radiative magneto-hydrodynamic simulation package produced by Prism Computational Sciences, HELIOS-CR. This work is focused on developing a detailed radial and temporal resolved model of the plasma during the pinch. In addition to adding to the understanding of the complex plasma dynamics of the pinch, this model is intended to be give initial conditions for a long-range electro-dynamic simulation, PlasmaEX, that is being developed to study the transport of a multi-species plasma that is being expanded due to columbic interaction of differing ion types and electrons.

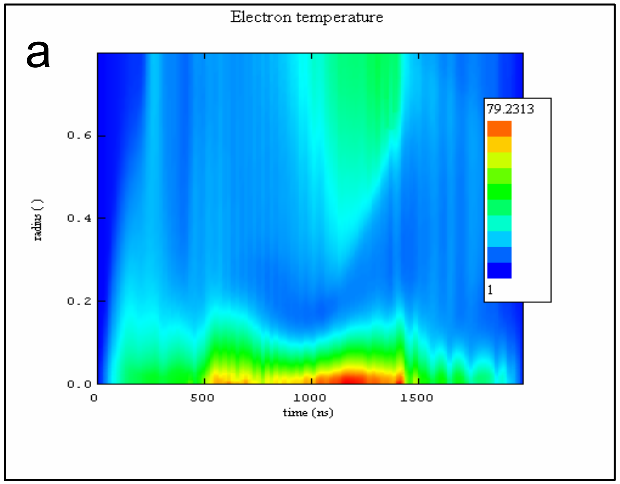
Cartoon of our EUV Z-pinch System

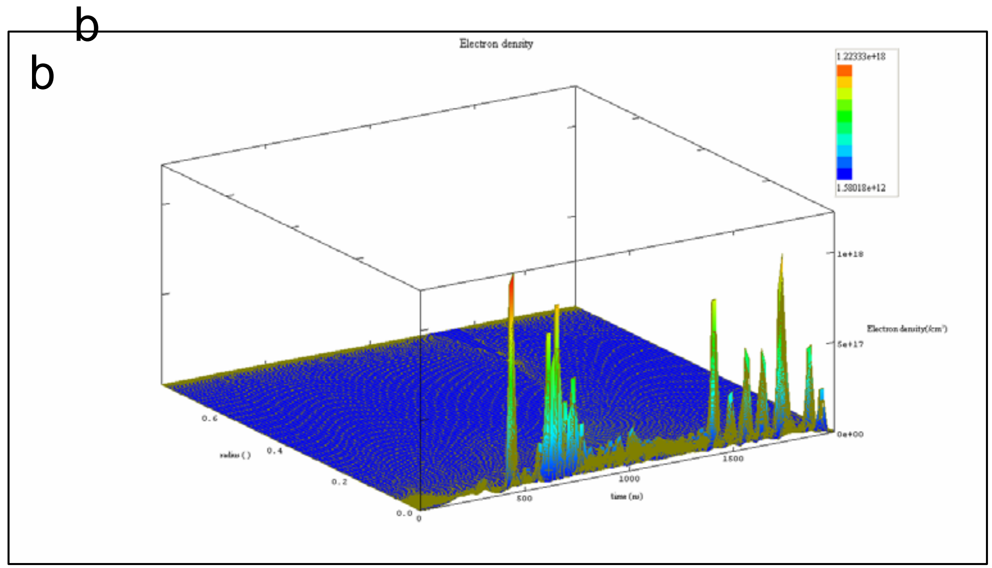


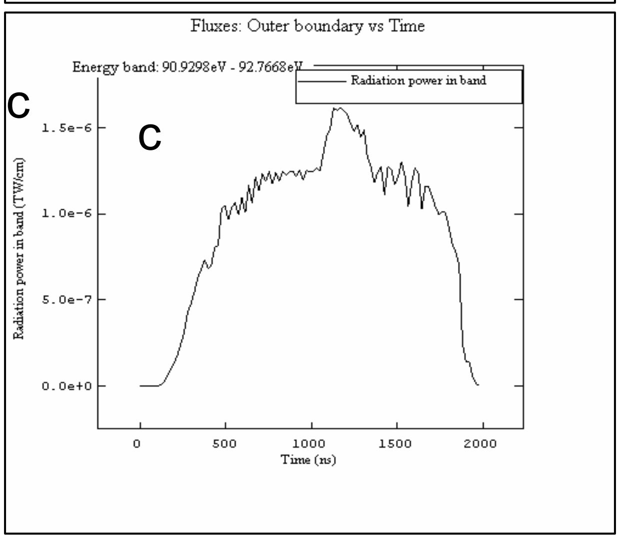




Current MHD Results







a. This shows the electron temperature in eV as a function of time and space (cm). b. This 3D figure shows the electron number density as a function of space (cm) and time. Figures a. and b. demonstrate that the pinch is hot and dense on the radial axis as expected. c. This figure shows the temporally resolved EUV output of the pinch into 2π.

Goals of the Modeling Project

- Refine our HELIOS-CR MHD model of the pinch to match observed EUV output
- Compare results of simulation to analytical pinch instability study
- Use results of MHD and analytical studies of the pinch as initial conditions for long range transport simulations to predict ion spectra
- Post-process results for spectral analysis of the pinch using SPECT-3D

Summary

- Illinois Calibrated ESA
  - Allows innovative debris mitigation schemes to be tested (INERT, E-Field, Secondary Plasma)
  - Enables accelerated lifetime testing
- Mirror Cleaning
  - Restores reflectivity
- Adding a Gibbsian Solute to Mirrors
  - “Prevents” erosion
  - Keeps mirrors smooth

Acknowledgements

- Robert Bristol, INTEL
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