Secondary-Plasma-Based Debris Mitigation for Next Generation EUVL Sources

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IDEAL Vision

Illinois Debris mitigation for EUV Applications Laboratory

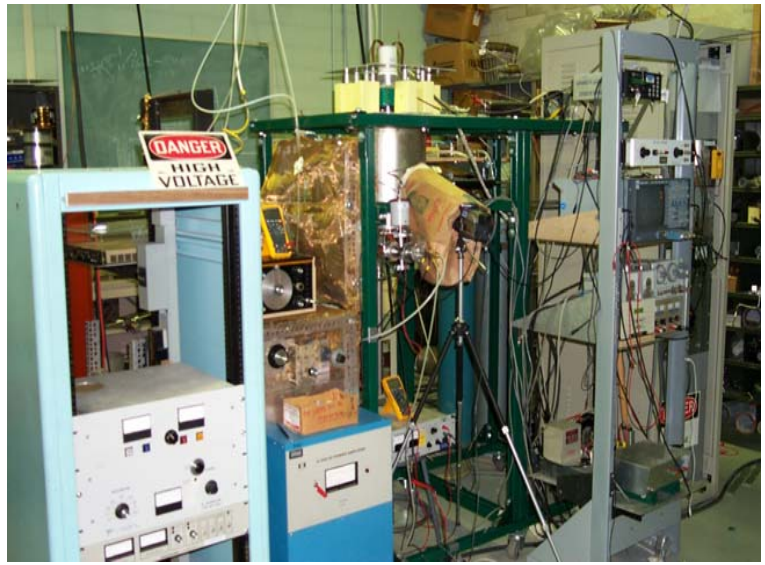
- **Construct EUV experimental applications laboratory to study debris**
  - Understand and quantify debris generation mechanisms
  - Test debris mitigation schemes
  - Generate ideas and intellectual property related to debris mitigation and effects that could broadly be used in industry
- **Examine RF-plasma based debris mitigation**
  - Ionize the sputtered material as in iPVD
  - Accomplish this without sputtering coil or other parts
- **Work with suppliers**
  - Test bed or prototype development facility
  - Add tools to your toolbox

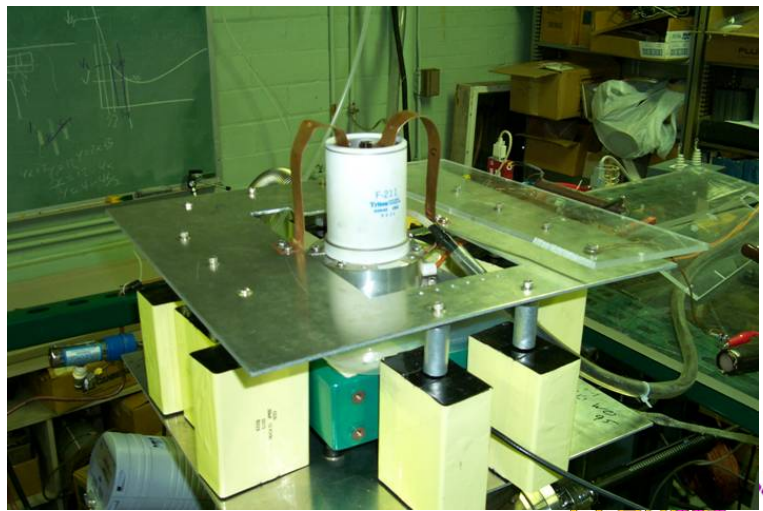
Presentation Overview

- **IDEAL Experimental**
  - DPF Pulsing System
- **A Brief Tutorial on Debris**
  - What is Debris
  - How do you measure it
  - How do you mitigate it
- **Diagnostics and Mitigation Schemes**
  - QCM Diagnostic
  - Foil Trap Collimator
  - Secondary Plasma Source with magnetic shielding
  - Gridded Energy Analyzer
  - Witness plate depth profiles
- **Results and Model**
  - Off-Axis, On-Axis, and Rep Rate Analysis
  - Material Characterization (Auger)
  - Pre-Ionization and Pressure Effects
- **Next Steps and Summary**

IDEAL Facility

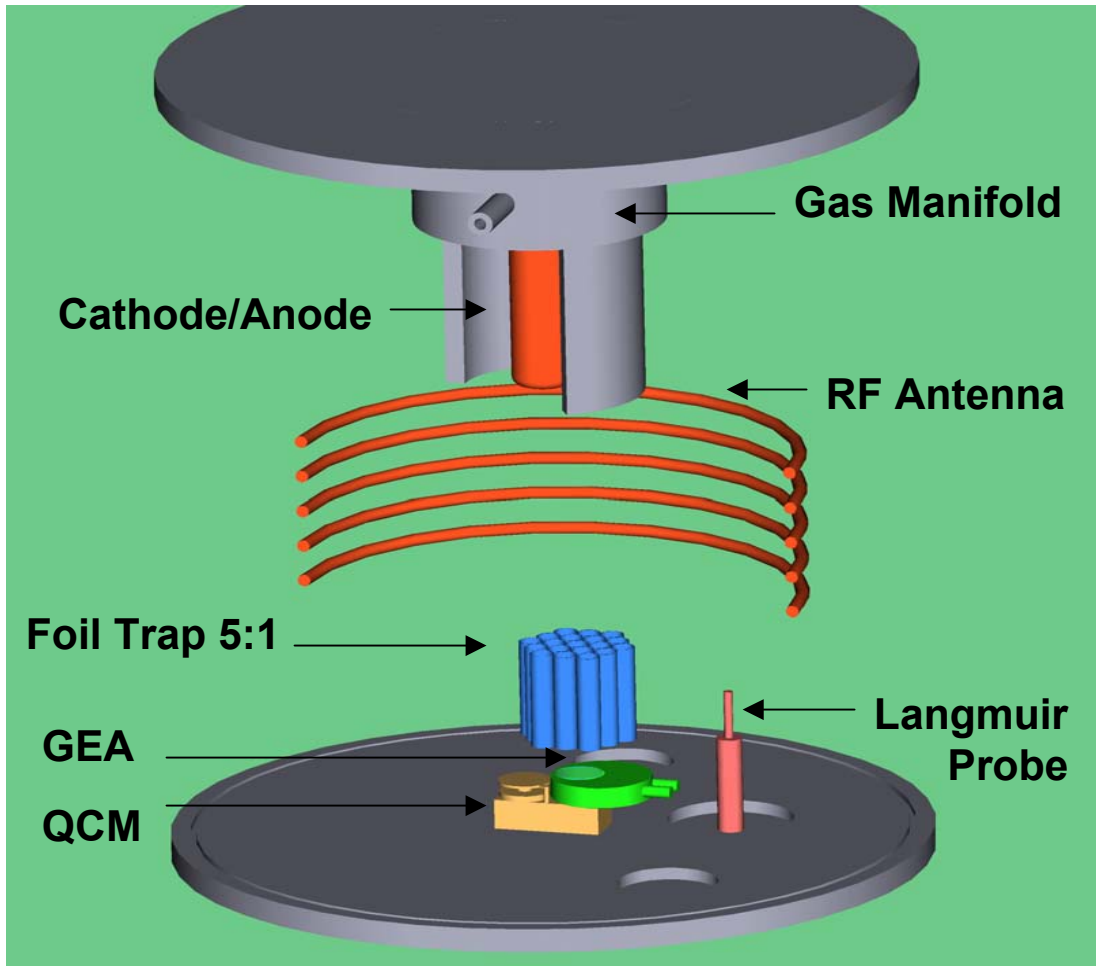
- **IDEAL facility is capable of collecting and analyzing data relevant to EUVL sources**
  - 300 l/s Varian Turbo Pump
  - Ebara High-Throughput Dry Roughing Pump
  - BK Precision RF Signal Generator
  - ENI A-500 Tunable RF Amplifier
  - LeCroy Digital Oscilloscope
  - DPF Charging Supply (18 kW max)
  - DPF Pulsing System
  - Pressure Control System
  - LabVIEW Computer Interface
  - ENI Low Voltage, High Current DC Supply (130 A max)
  - Various In-Situ Diagnostics
- **Housed at world-class institution: University of Illinois Urbana-Champaign**
  - Center for Microanalysis of Materials: Auger, SEM, ITOF, SIMS, XPS, RBS facilities readily accessible



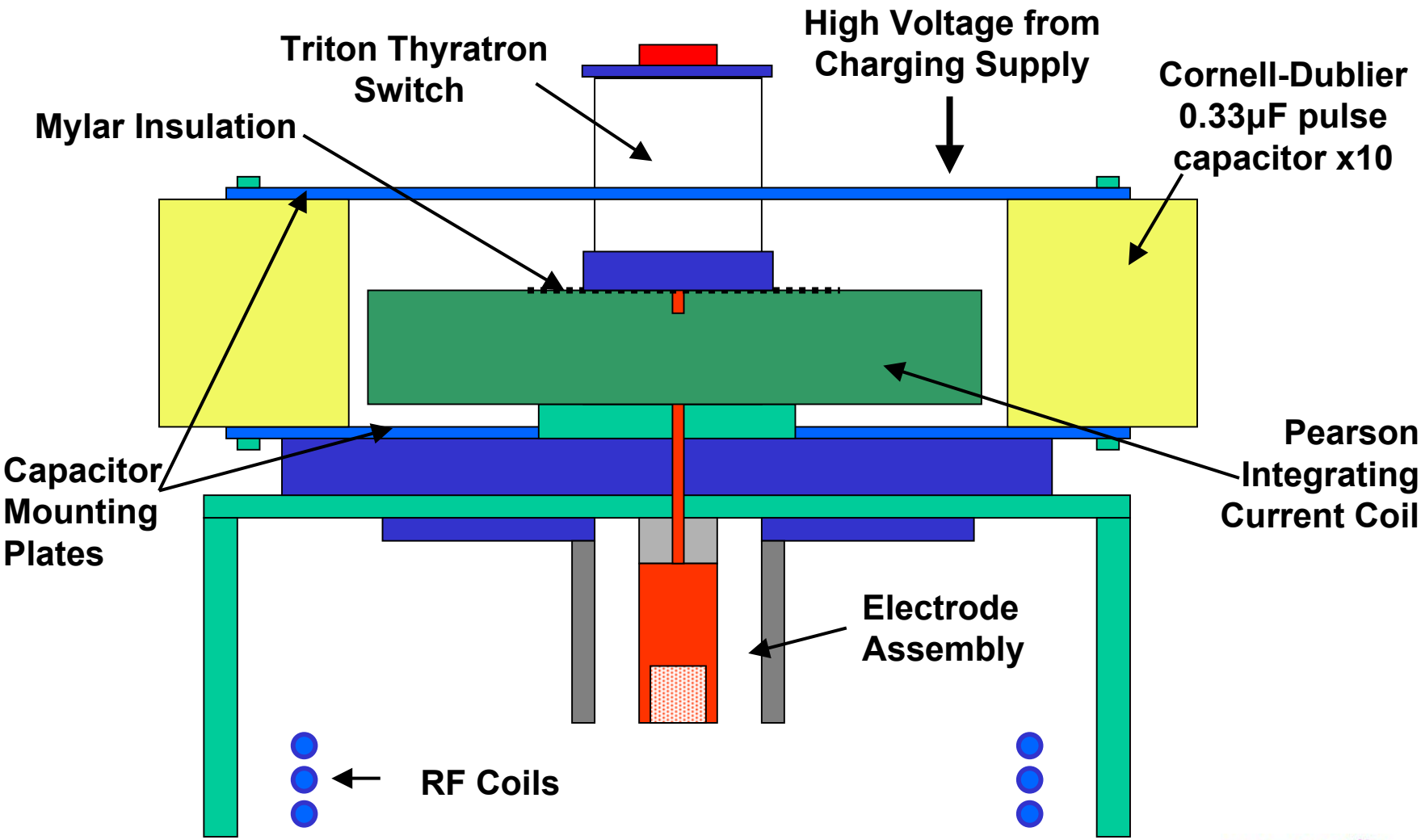


Chamber Cross Section

- **Components**
  - Differential-pressure gas manifold scheme
  - 5 turn RF antenna for secondary plasma (1-500W @ 10-35MHz)
- **Dimensions**
  - 3.16 cm OD Cu anode
  - 8.25 cm ID Al cathode
  - 12.0 cm overall length
  - 18.1 cm anode to QCM
- **Diagnostics:**
  - Inficon Quartz Crystal Monitor (QCM)
  - Gridded Energy Analyzer (GEA)
  - Langmuir probe
  - Witness plates



Current DPF Pulsing Setup



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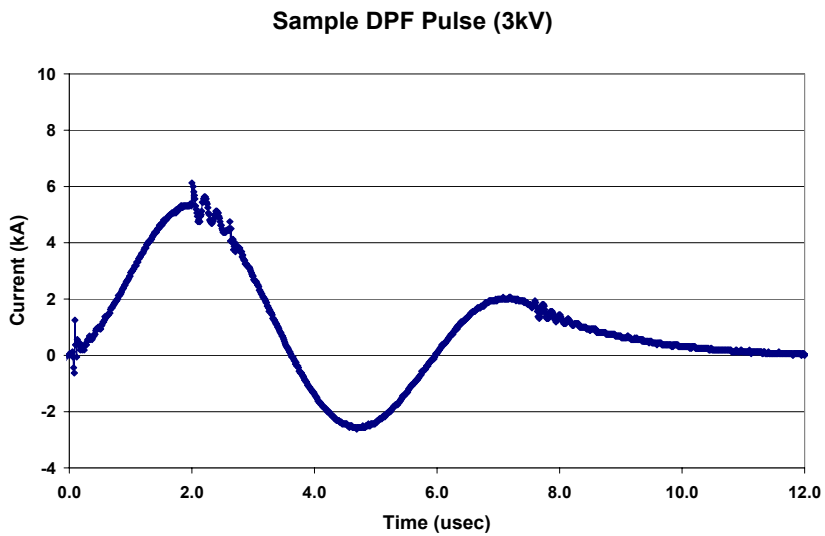
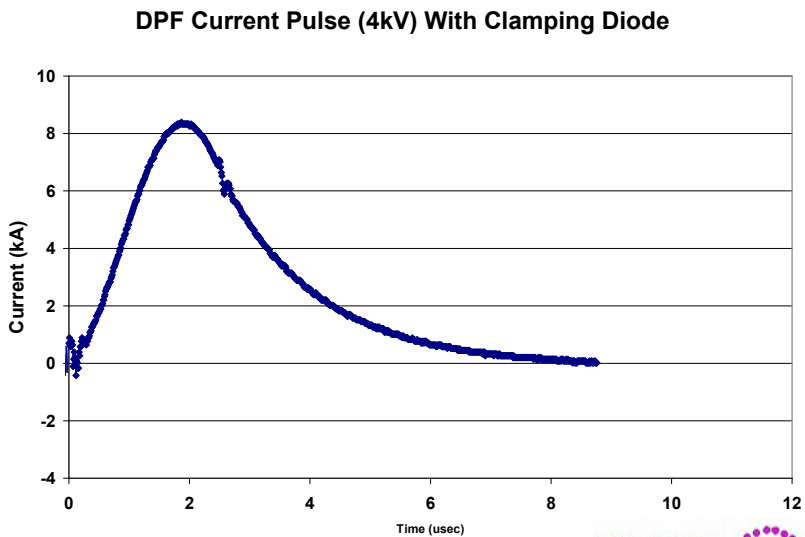
Electrical Circuit Information

- **Characteristic pinch waveforms are observed**
- **Pulsing system now uses a hydrogen thyratron. It will soon use a low-inductance, high-current SCR switch assembly:**
  - 2000 nsec (will be 750 nsec) peak current pulse
  - L = 350 nH (will be 80 nH)
  - C = 3.33 μF
  - V = 4 kV
  - Power = 10 to 30 J
  - Rep-rate = 1 – 20 Hz (will go up)
  - Current = 8kA (will be 20 kA)





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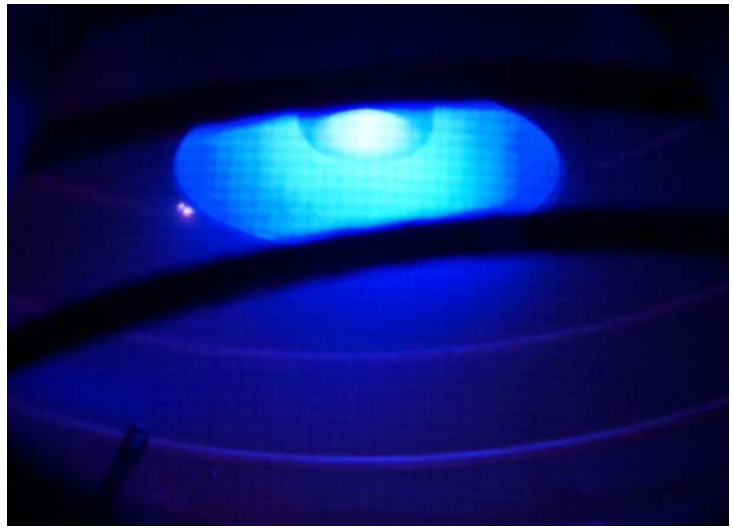
DPF Plasma Description

- **Extended time exposure camera shows typical DPF pulse**
  - Hard DPF shot – no pre-ionization
  - 4 kV single shot
- **Electrode is visible with bright source at tip with RF coils in foreground and background**
- **Foil trap collimator is mounted on a linear motion feedthrough to position on-axis or off-axis of the DPF pinch region**



DPF Pulsing At 20 Hz

Note: Camera Flicker Due To Electrical Interference

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What is Source "Debris"?

How do you measure it?
How do you mitigate it?

A. Sputtered atoms (electrode material) or condensable vapors (like Sn)

- Measure by …
  - QCM deposition monitor
  - Witness plates
- Mitigate by …
  - Foil trap collimator
  - Plasma-based ionizer

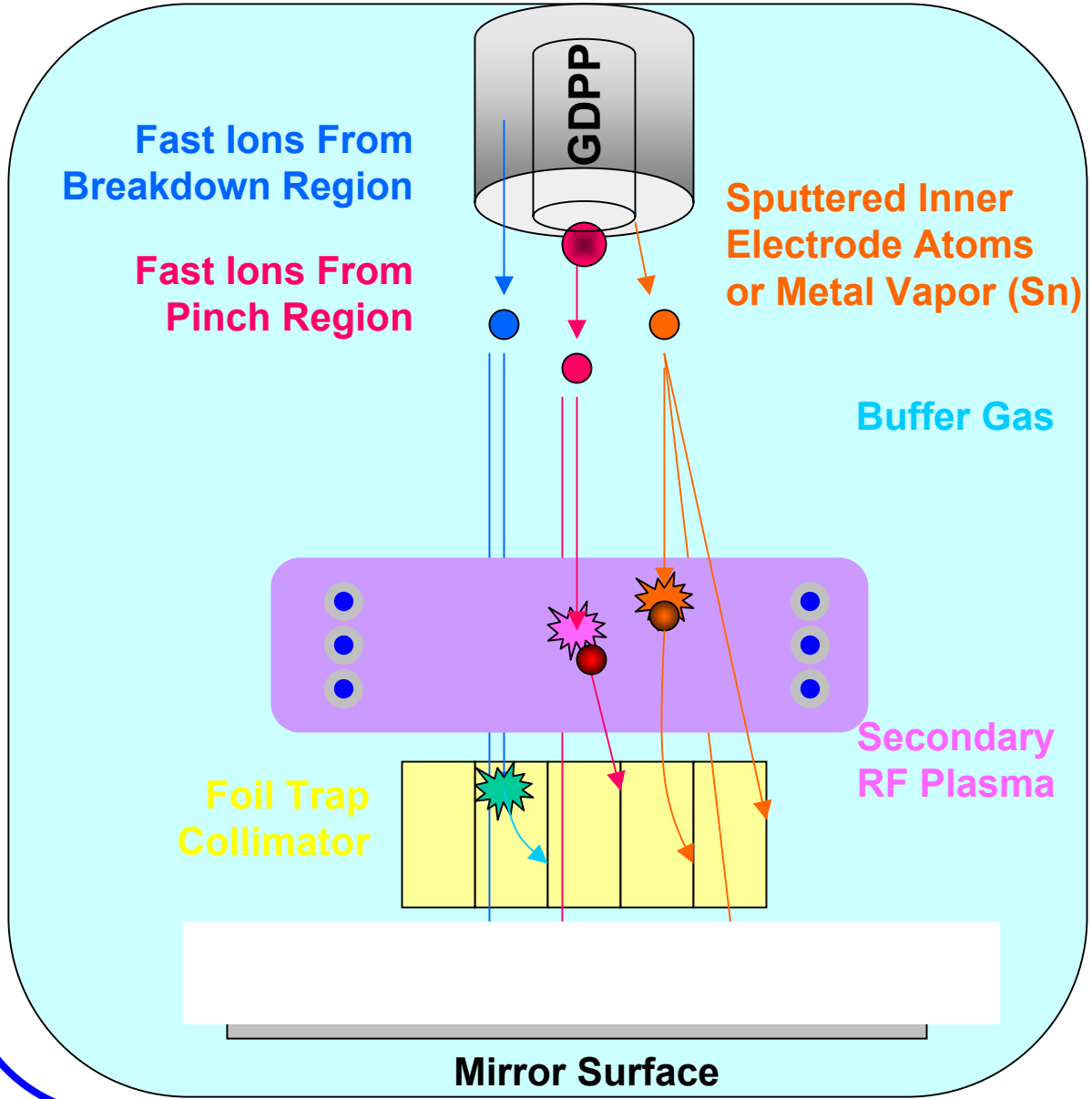
B. Fast Ions

- Measure by …
  - Gridded energy analyzer
  - Time-of-Flight
  - Depth distribution in witness plate
- Mitigate by …
  - Gas curtain
  - Biased grids or foil trap
  - Plasma-interactions

C. Fast Neutrals

- Measure by …
  - Gridded energy analyzer / QCM combination
  - GEA / Depth distribution in witness plate
- Mitigate by …
  - Gas curtain
  - Plasma-ionization
  - Plasma-interactions

Debris Components & Mitigation



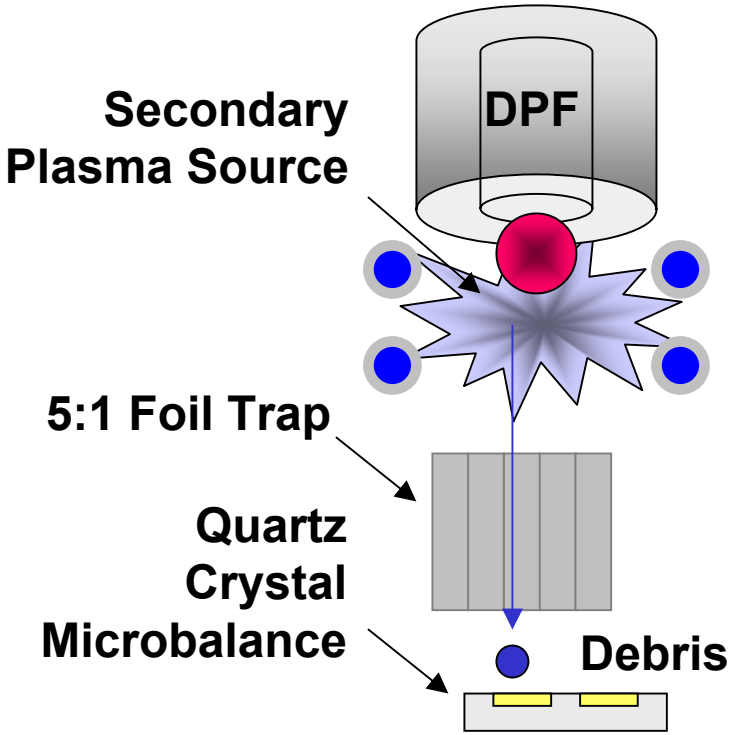
1. Debris is generated in the GDPP

2. A foil trap collimator removes a fraction of particle trajectories

3. A buffer gas increases scattering

4. A secondary plasma ionizes sputtered electrode material, tin vapor and charge-exchanged fast ions for removal

Dual QCM Diagnostic



Dual In-Situ Crystal

- Filters Noise
- Extremely Sensitive

$$T_{depositiojn} = K_{Z\text{-}ratio}\, \Delta F_{xtal2\text{-}xtal1} / \rho_{debris}$$

$$K_{Z\text{-}ratio} = N_{naturalF}\, \rho_{quartz} / F_{xtal1}^{2}$$

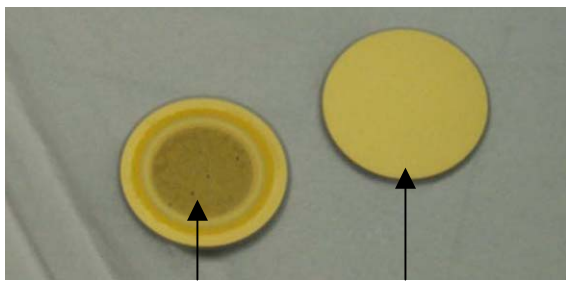
$$\rho_{quartz} = 2.65\ g/cm^3$$

$$\rho_{debris} = 6.06\ g/cm^3$$

$$N_{natural} = 166\ kHz$$

$$F_{xtal1} = 5.97\ MHz$$

QCM Crystals



Debris on Surface Clean Surface

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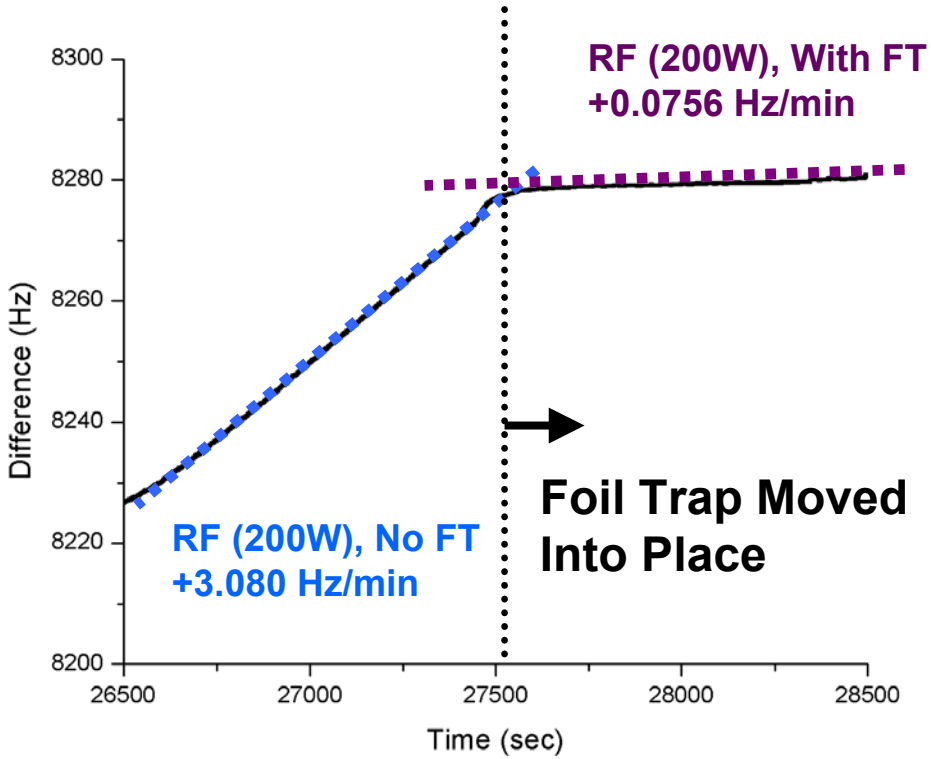
Foil Trap Collimator

- **Stainless steel tube collimator**
  - 5:1 aspect ratio
  - With high optical transmission
- **Tested with high power RF plasma**
  - 200 W
- **Factor 97.5% efficient at removing sputtered Cu**



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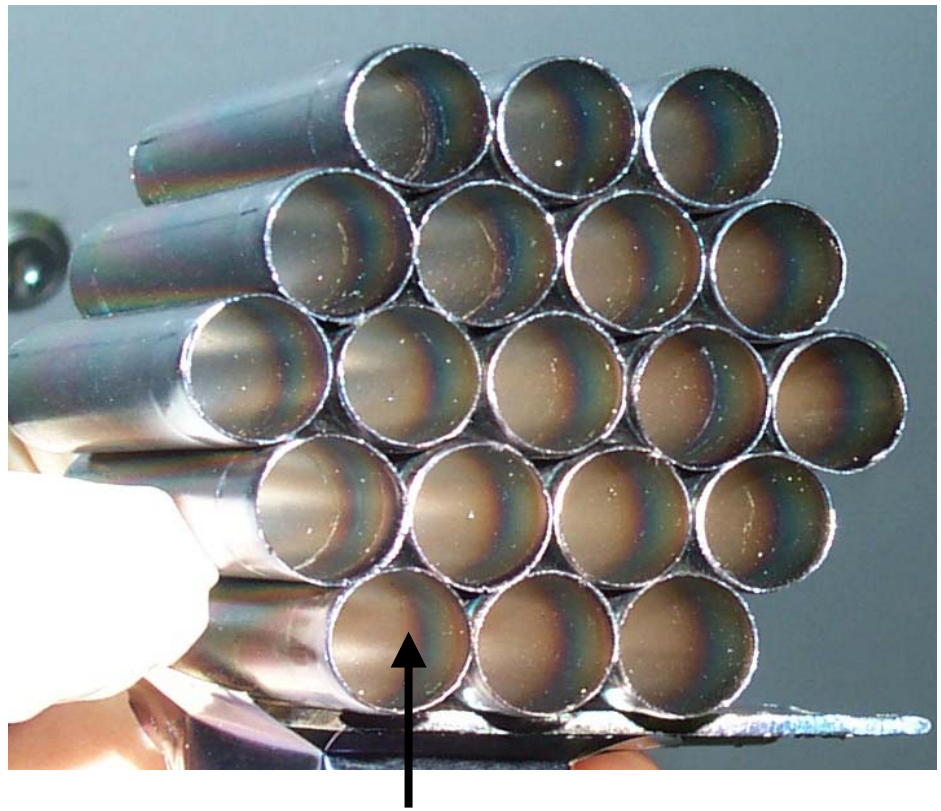
Deposition Pattern Confirms Diffusive Nature of Flux

- **Mean Free Path of Cu in Ar is ~9.2 mTorr cm**
  - For IDEAL DPF conditions:

  ~ 0.71 cm at 13.5 mTorr

- **Fringes show ~1 radii penetration into the foil trap collimator**

- **Fringes correspond to mean free path of Cu in Ar**



Deposition Fringe Depth

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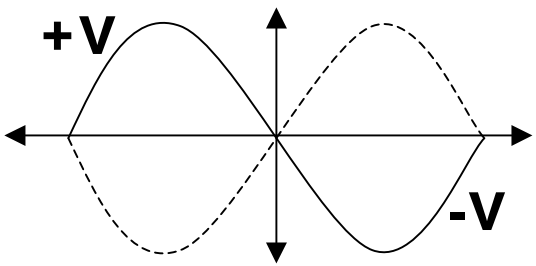
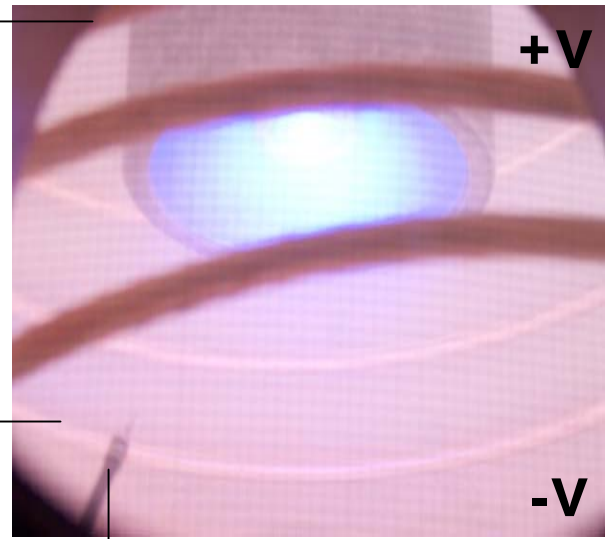
Secondary Plasma Source Circuit



Helical Resonator Configuration Minimizes $V_{DC\ BIAS}$

~5 turn immersed antenna



L_1

C_1

C_2

$C_{blocking}$

Matching Network

RF Amplifier

0-500W

0.3-35MHz

Oscillator

.1-50 MHz

$V_{DC\ BIAS}$

n_e

T_e

I_{plasma}

V_{plasma}

Scope

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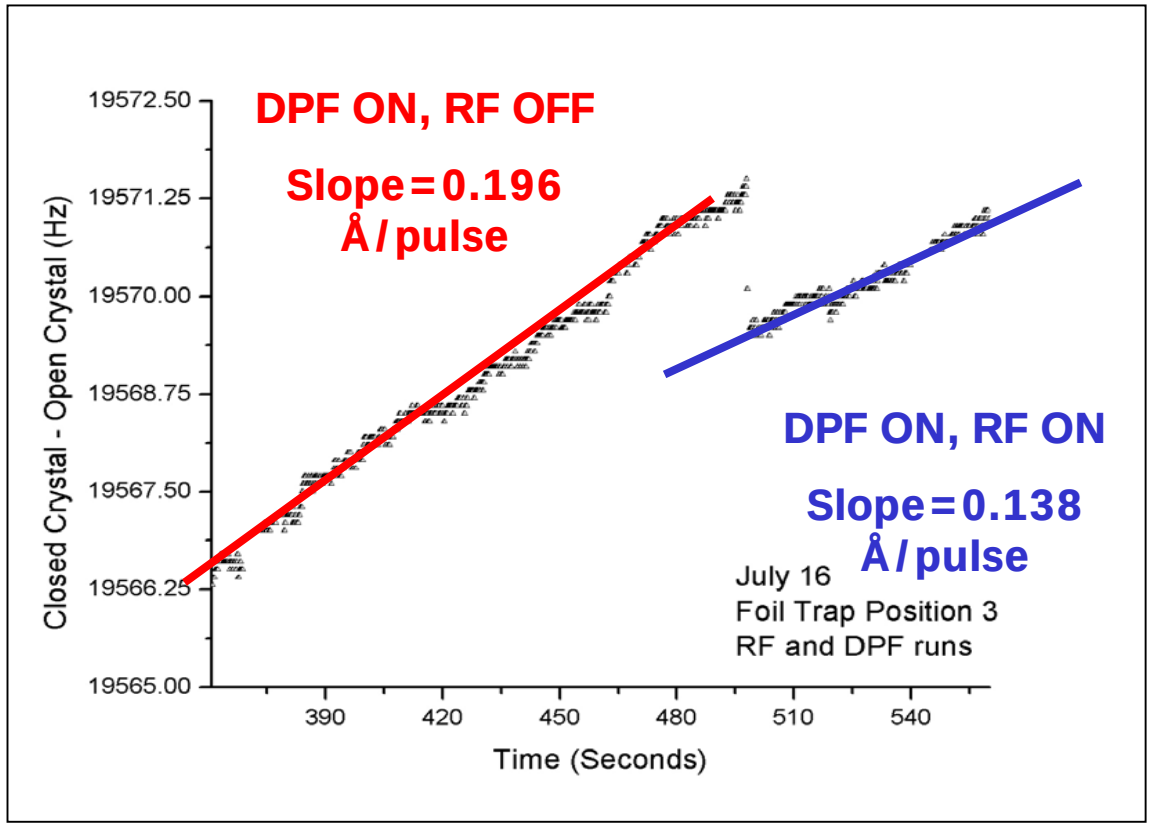
Secondary Plasma Ionizes Debris

- **An inductively coupled secondary RF plasma ionizes the diffusive flux component of the debris for removal at the foil trap collimator.**

- **Initial results were limited to low power RF due to coil sputtering**
  - $N_e = 6 \times 10^9\ cm^{-3}$
  - $T_e = 5.2$ eV
  - ~ 30% ionization achieved



The inductive plasma operates at low plasma potential minimizing plasma sputtering of chamber components, such as the foil trap. RF generated debris, is localized at the coil.

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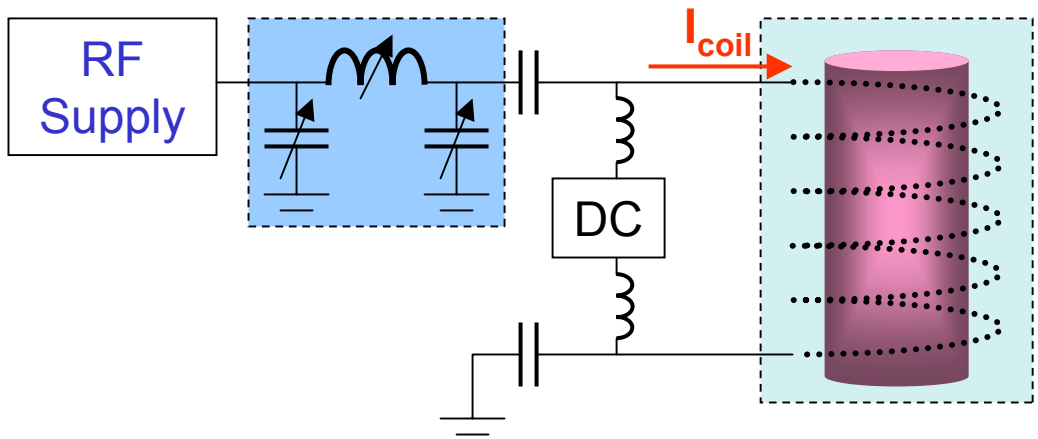
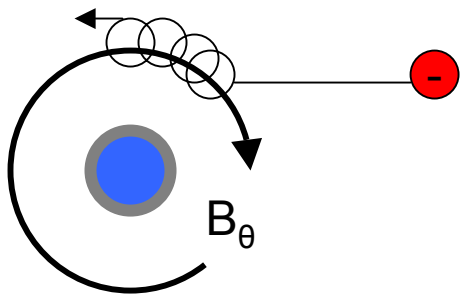
Challenges Overcome

- **Plasma Sources tend to sputter all adjacent surfaces and create much more "debris"**
- **Our plasma is <u>not</u> a net debris producer because**
  - Helical resonator design
  - Inductive vs capacitive coupling
  - Magnetic shielding of coil

Magnetic Shielding Current

- Magnetic shielding of the RF antenna can reduce the coil self-bias (sputtered source of debris) while maintaining high plasma density and temperature,
- A high current supply feeds 0-120A through the RF coil producing a weak magnetic field.
- During the RF cycle electrons are inhibited from reaching the RF antenna, minimizing coil charging and maintaining characteristic inductive discharge densities and high temperature.
- Coil voltages and sputtering can be significantly decreased.





$\Gamma_{electron} = \Gamma_{ions}$

Lowers $V_{RF\ Bias}$

Coil Current Produces Magnetic Field To Repel and Confine Electrons

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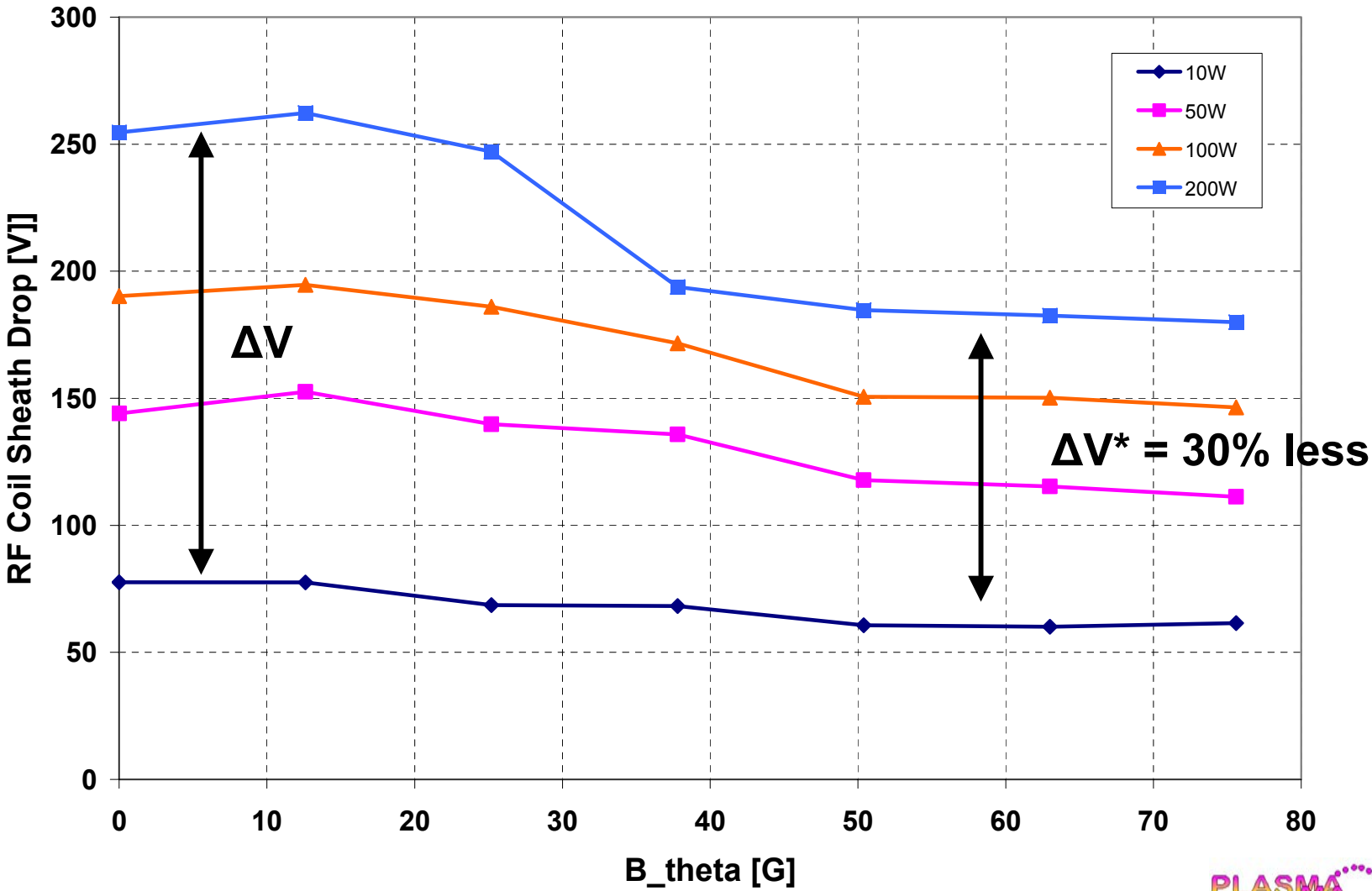
Power Level vs. Magnetic Field

Resultant Coil ΔV For Sputtering



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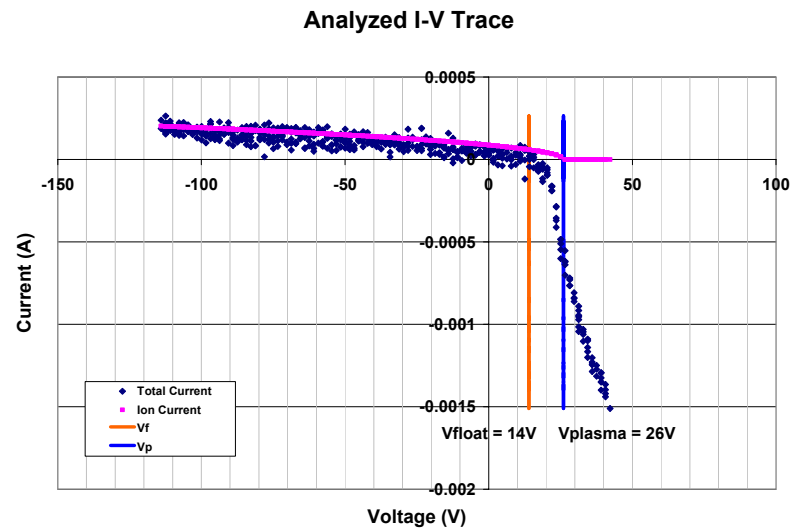
Movie Of Magnetic Shielding

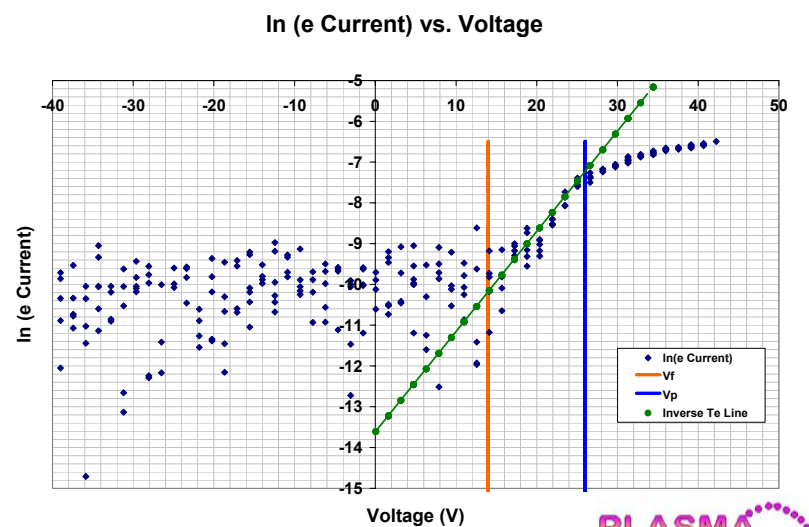
Optimal Condition is Low Power RF with 60 A Shielding

- **The magnetic shielding enhances plasma confinement**
  - $N_e = 2.1 \times 10^{11}\ cm^{-3}$
  - $T_e = 4.1\ eV$

- **Approximately 90% ionization fraction for sputtered electrode debris***

D. Juliano, D. Ruzic, et al., J. Appl. Phys., 91 (2002), p. 605





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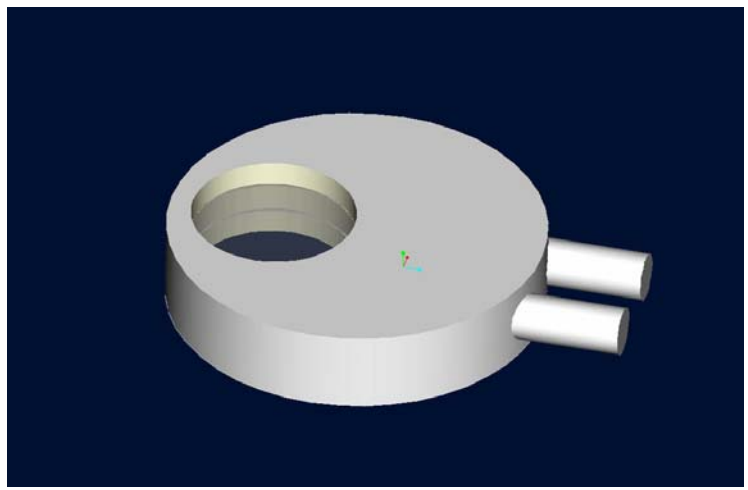
New Diagnostic: Gridded Energy Analyzer

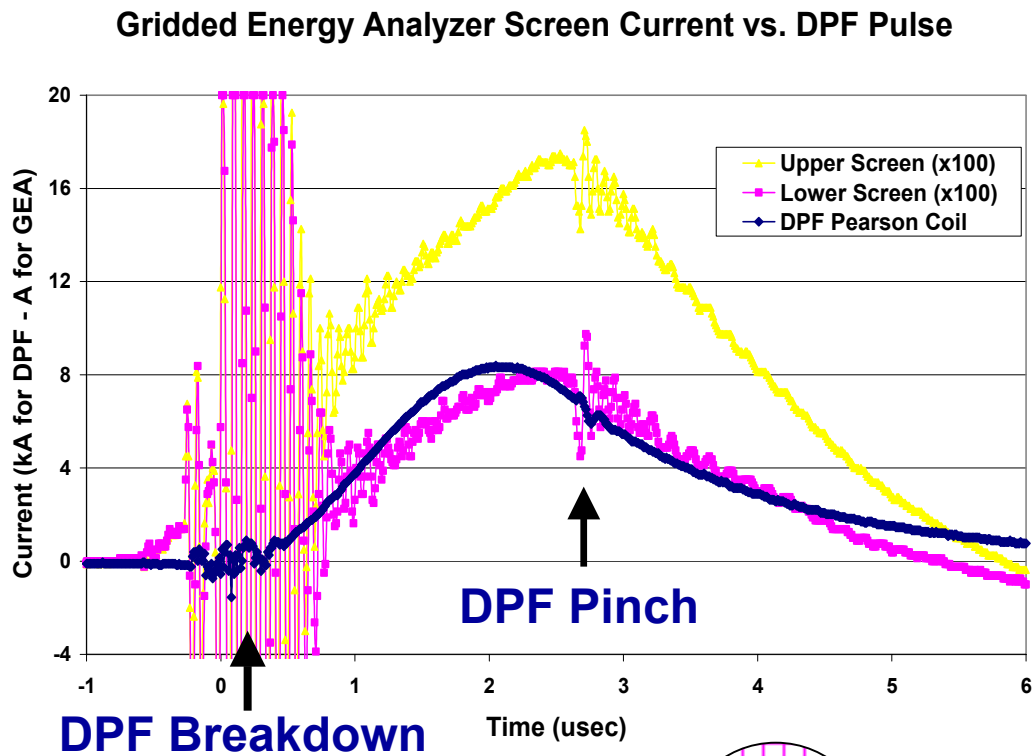
- **GEA allows:**
  - Measurement of ion and electron currents
  - Estimation of ion energy distribution
  - Capability to repel fast ions above QCM deposition monitor

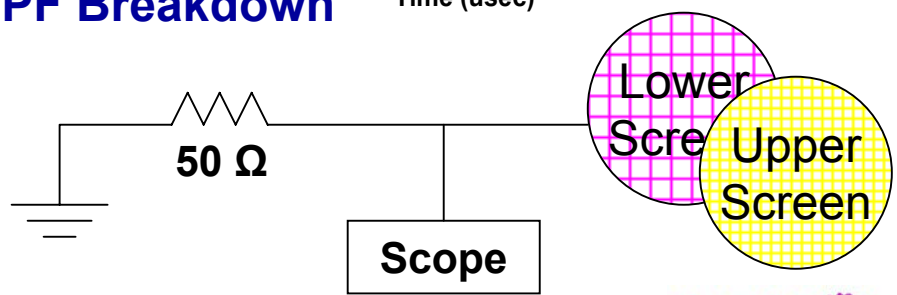
- **The GEA consists of:**
  - Two or three stainless steel wire mesh screens
  - 52% transparency
  - 3 mm gap spacing
  - Shielded
  - 0-1000 V Kepco power supply at 100 mA



GEA Signal Results During Pulse

- **Analysis of GEA screens during DPF pulse show measurable currents.**
- **The noise on left occurs during the breakdown phase of the pulse; the noise on the right during the pinch transient.**
- **There appear to be two components of the grid current:**
  - A group from the discharge initiation
  - A group from the pinch





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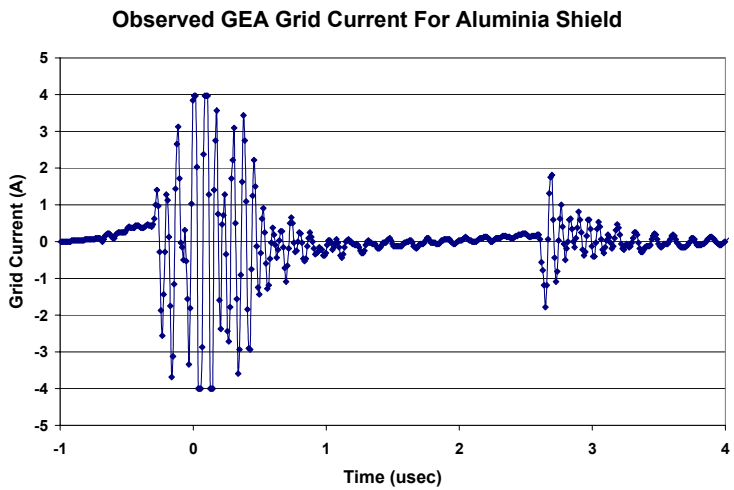
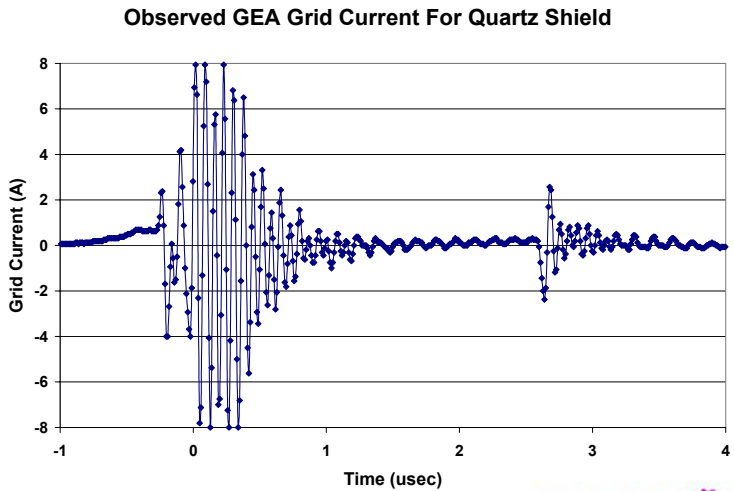
Is It Noise?

Cover With Ceramic and then Quartz

- Placing an alumina disc over the entrance to the GEA, particles and photons are blocked. The ceramic does not shield out EM noise.
- Placing a quartz plate over the entrance to the GEA, only particles are blocked allowing UV photons to pass. The quartz does not shield out EM noise.
- In both cases, the EM transients from the breakdown and pinch phases are evident, however no real current is observed.
- Thus, the current is due to particles (ions and electrons).





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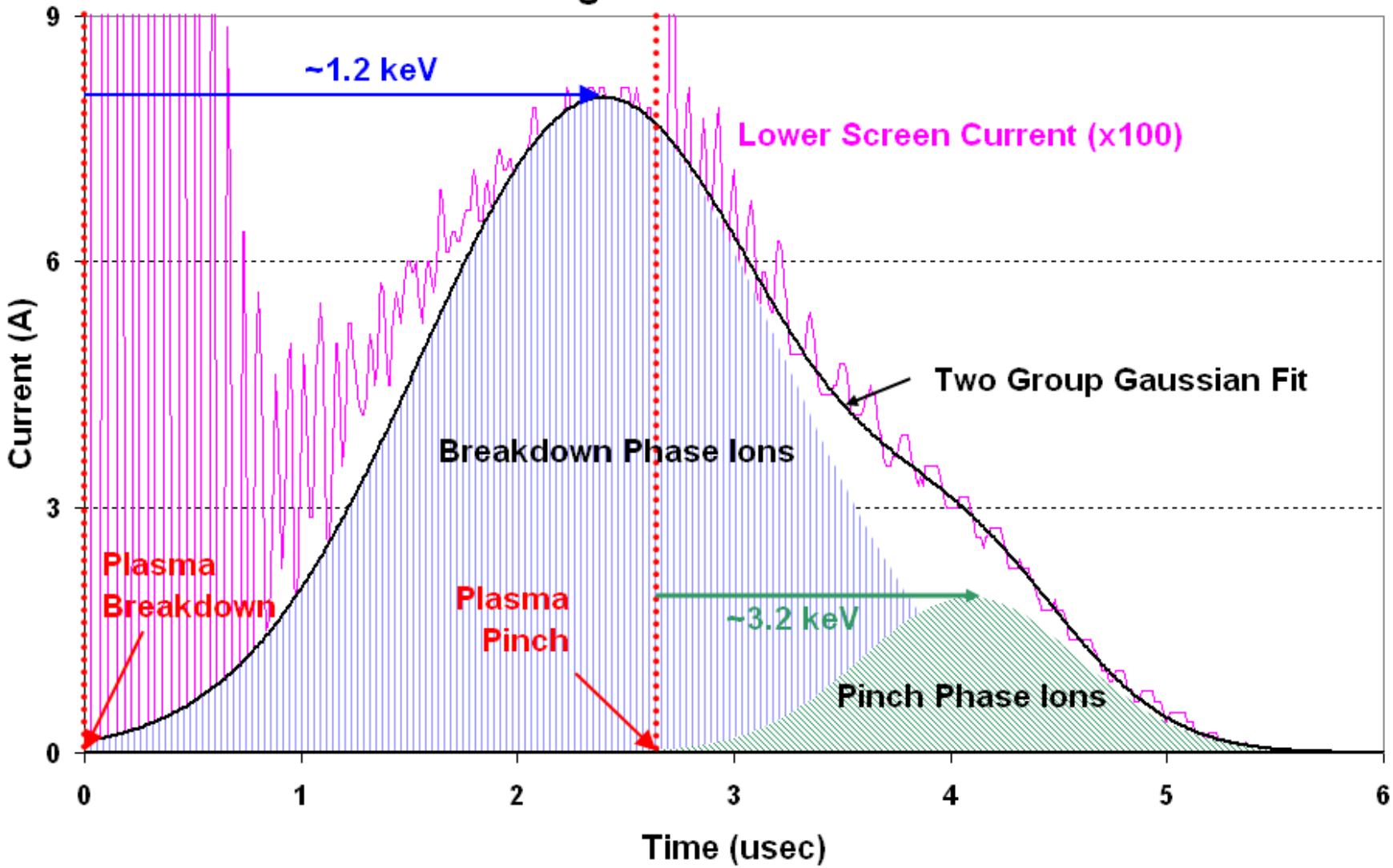
Ion Energy Distribution On Lower Screen For DPF Pulsing Without Pre-Ionization



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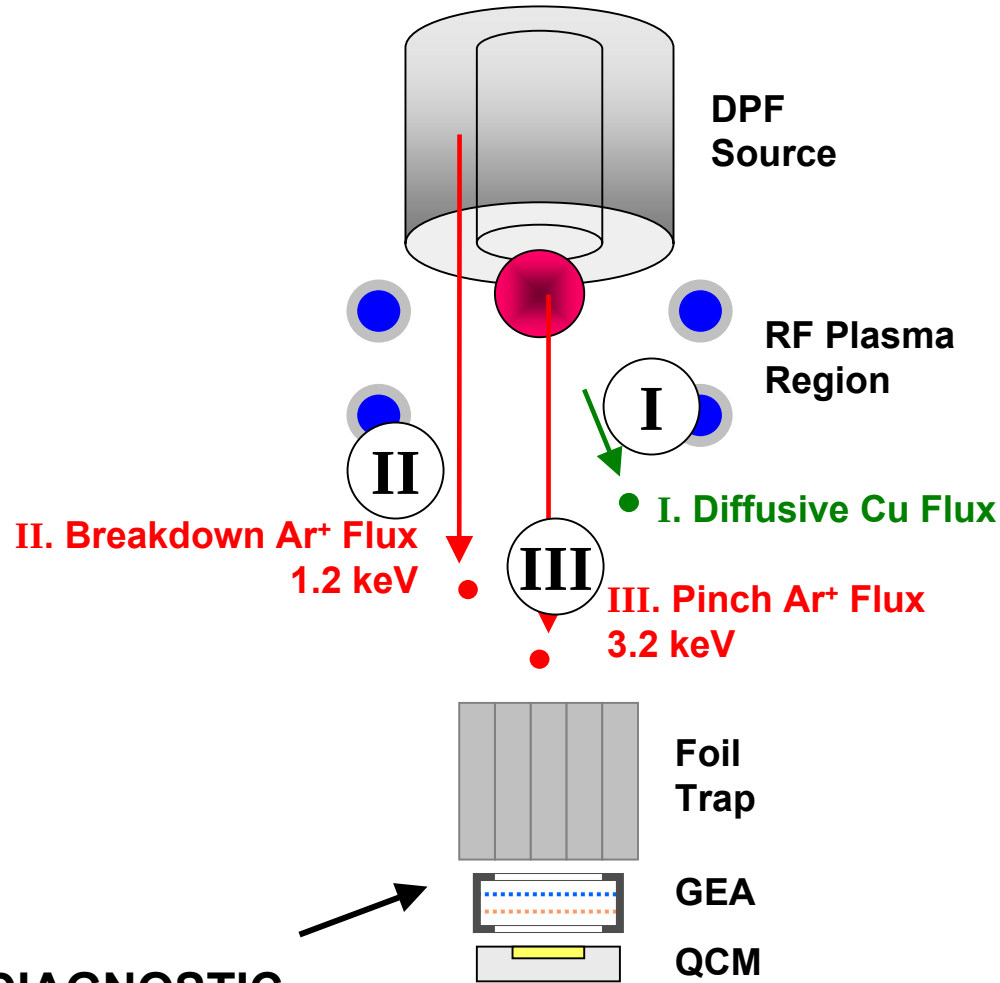
Results:
Three Debris Components

I **Diffusive Sputtered Cu Atoms**
- **DEPOSITS** on QCM
- Low Energy

II **Ar Ions From Breakdown Phase**
- **ERODES** the QCM
- High Energy ~ 1.2 keV

III **Ar Ions From Pinch Phase**
- **ERODES** the QCM
- Equals Pinch Energy ~ 3.2 keV



COMBINATION IN-SITU DIAGNOSTIC

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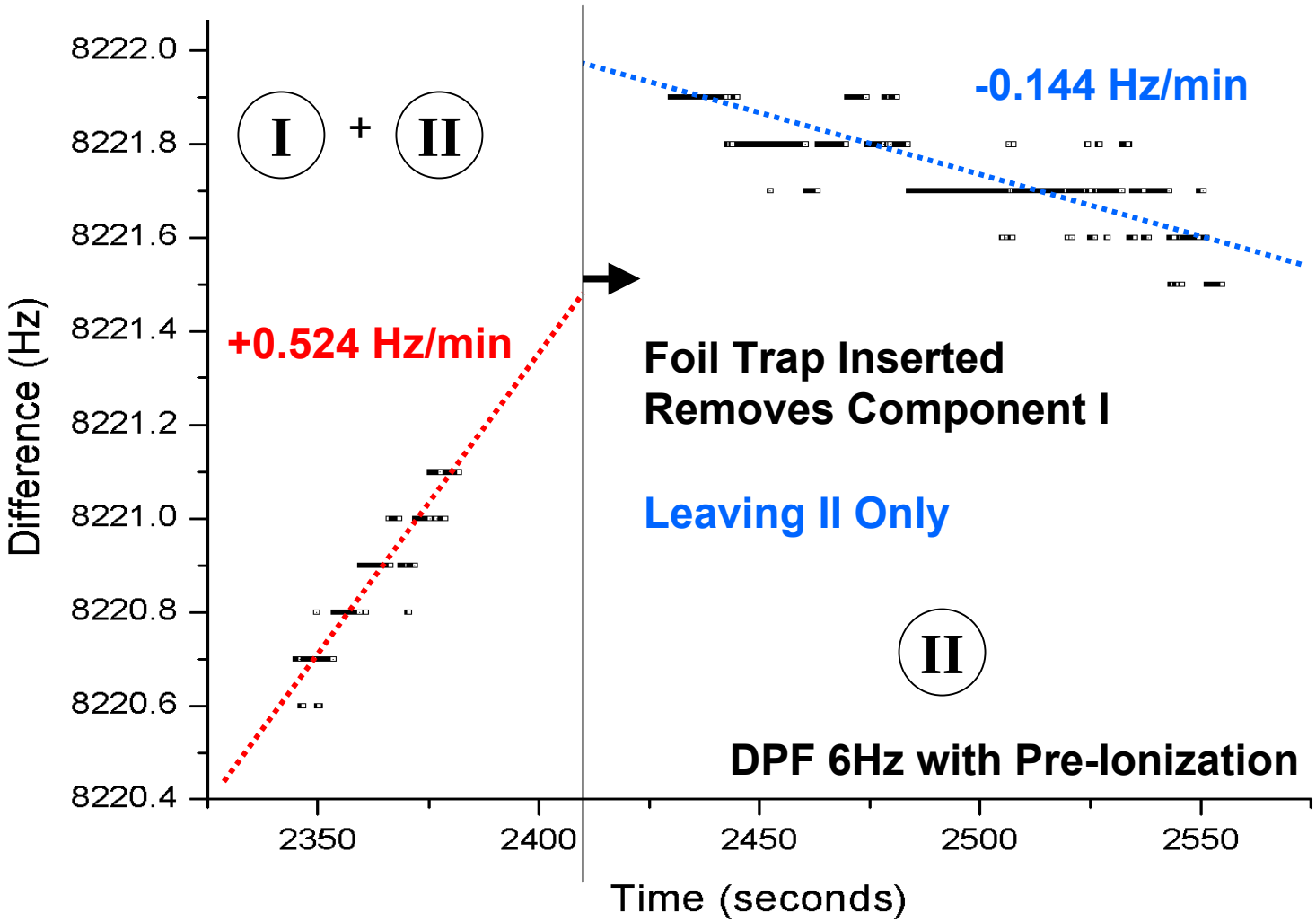
Foil Trap Off-Axis Sees Mostly Components I and II



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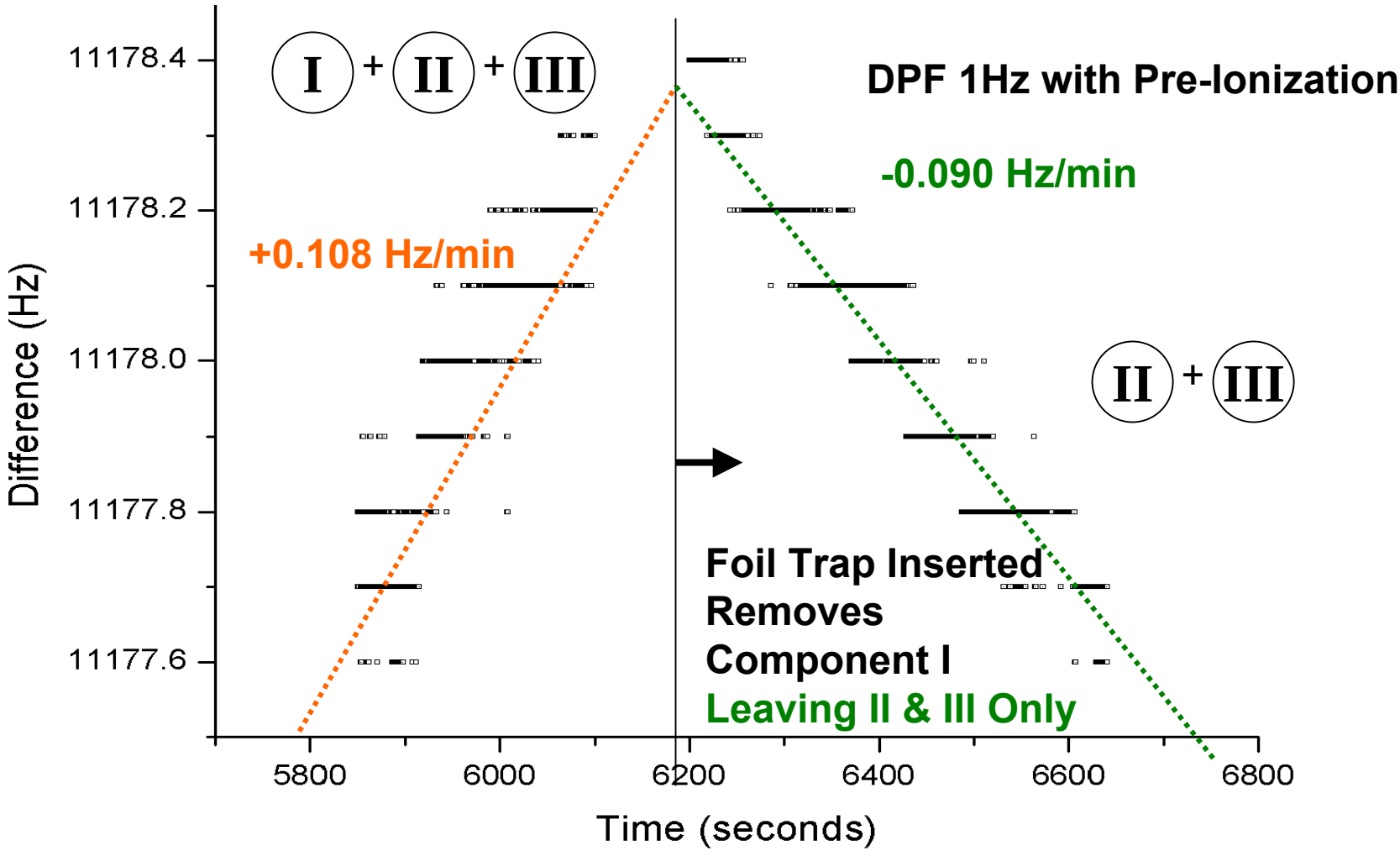
Foil Trap On-Axis Sees Components I, II & III



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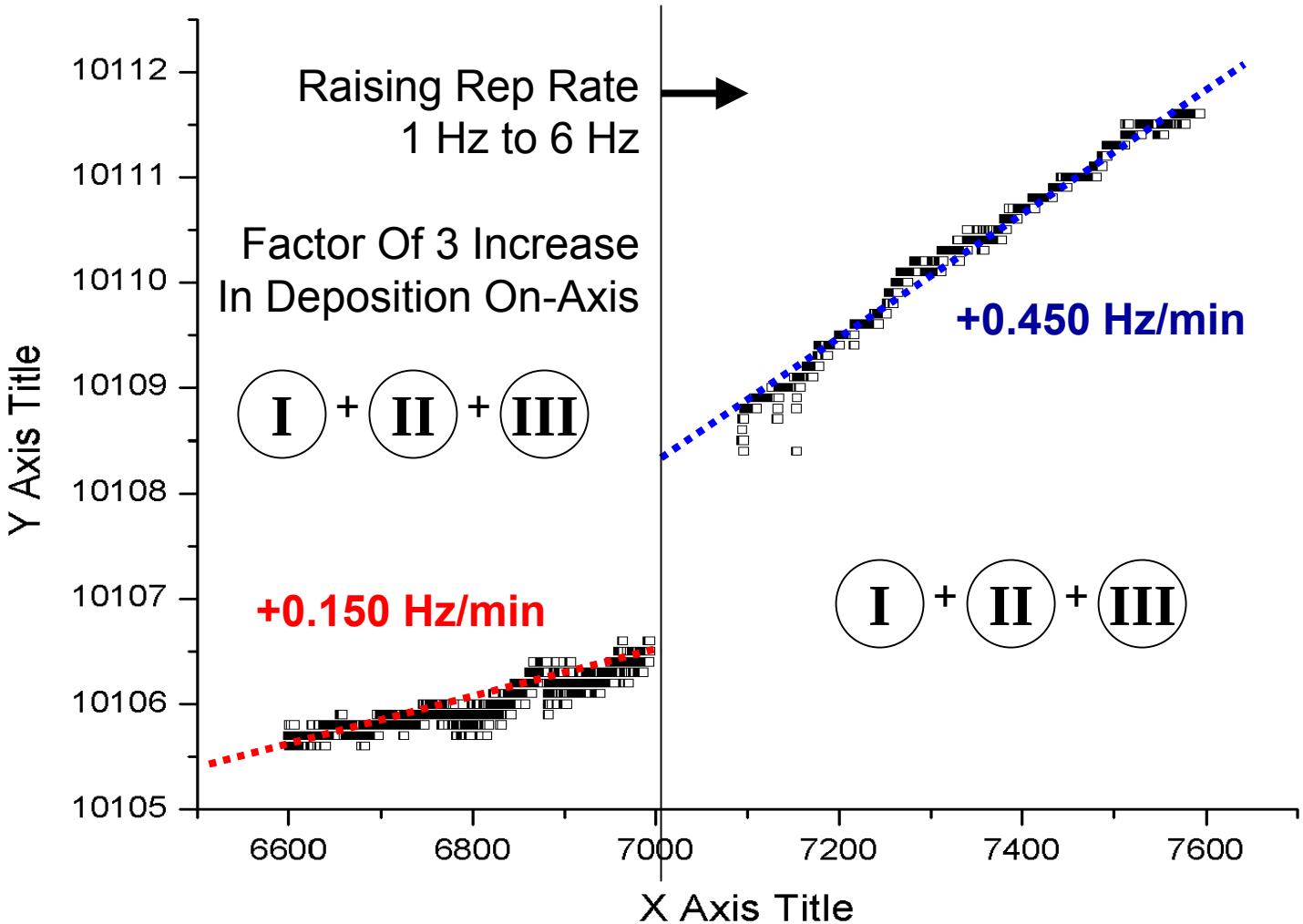
Rep Rate Comparison



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Numeric Analysis

- **QCM slopes can give magnitude of components**
- **Off axis: I + II =.524 [Hz/min]**

  II = -.144 [Hz/min]
- **On axis: I + II + III = (.450/.150) x.108 [Hz/min]**

  II + III = (.450/.150) x -.090 [Hz/min]
- **4 equations; 3 unknowns → over-constrained !**
- **Solve for I and III using last three equations:**

  I → +.594 II → -.144 III → -.126
- **Plugging into the first equation:**

  I → +.506 II → -.144 III → -.126

I is within 15% - model works!

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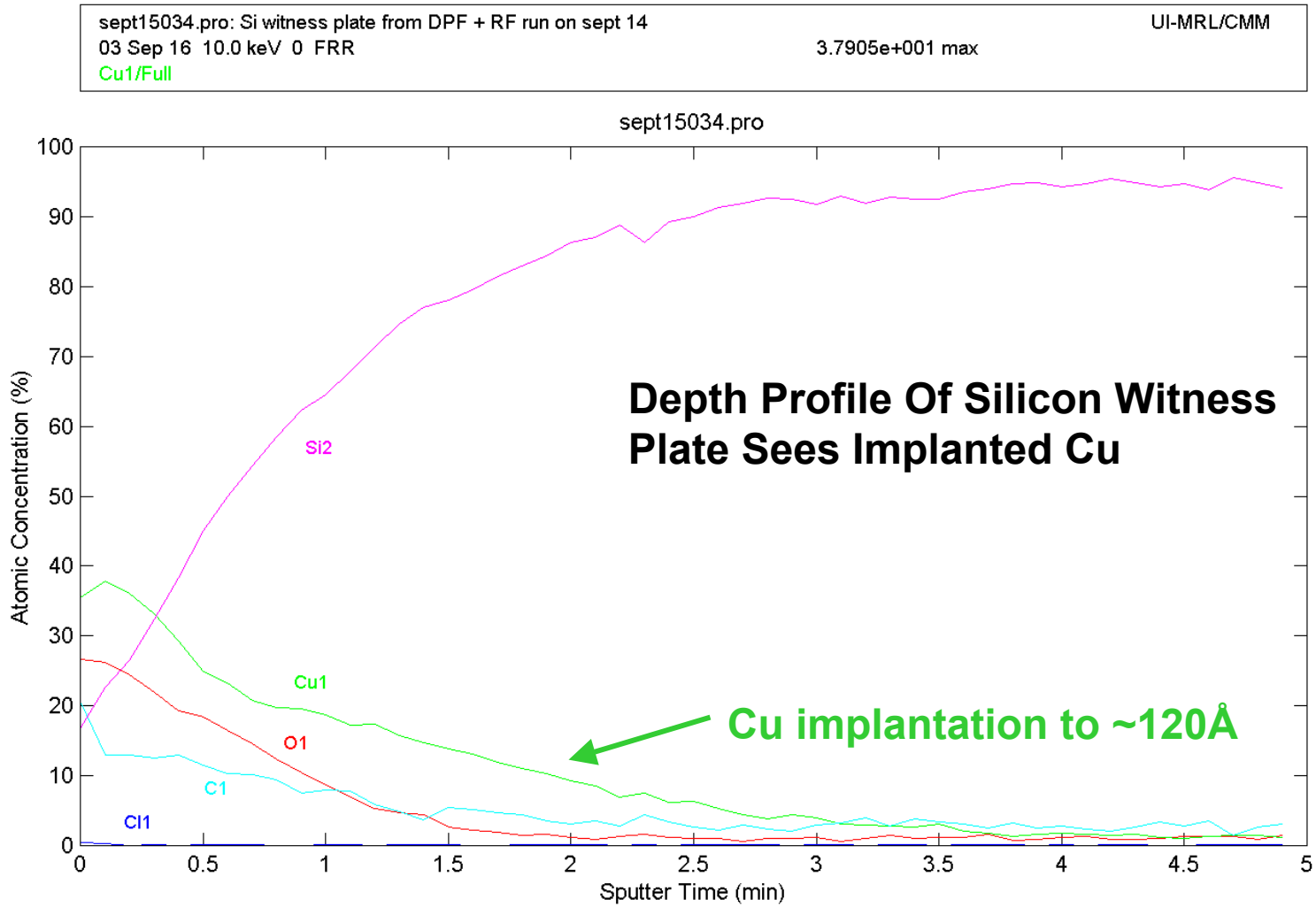
Auger Debris Characterization



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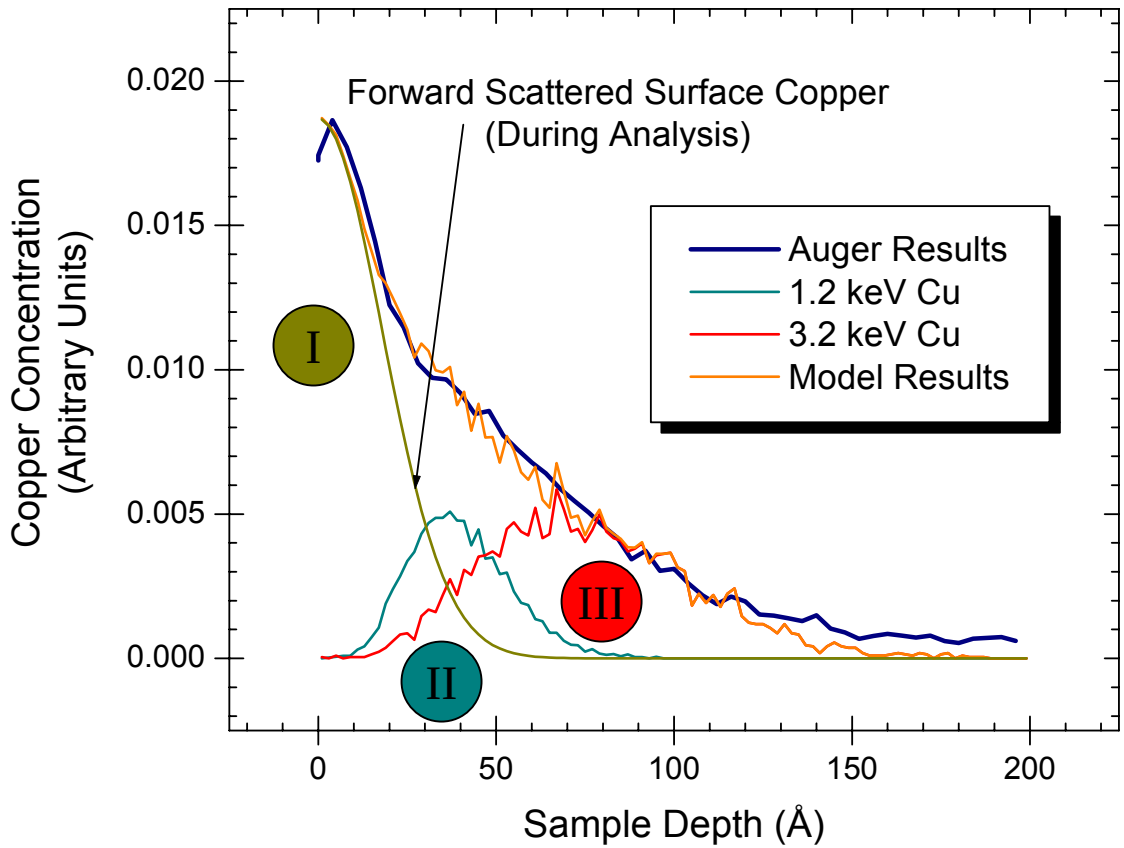
Copper Deposition Profile For DPF With Pre-Ionization

- **Auger spectroscopy showed copper driven in as deep as 160 Å into the Si witness plate**
- **SRIM modeling verifies TOF current measurements: namely two dominant ion energies at 1.2 keV (breakdown ions) and 3.2 keV (pinch ions) plus surface Cu driven in during analysis**
- **Note: Component II (breakdown ions) is smaller than Component III (pinch ions) when Pre-Ionization is ON.**



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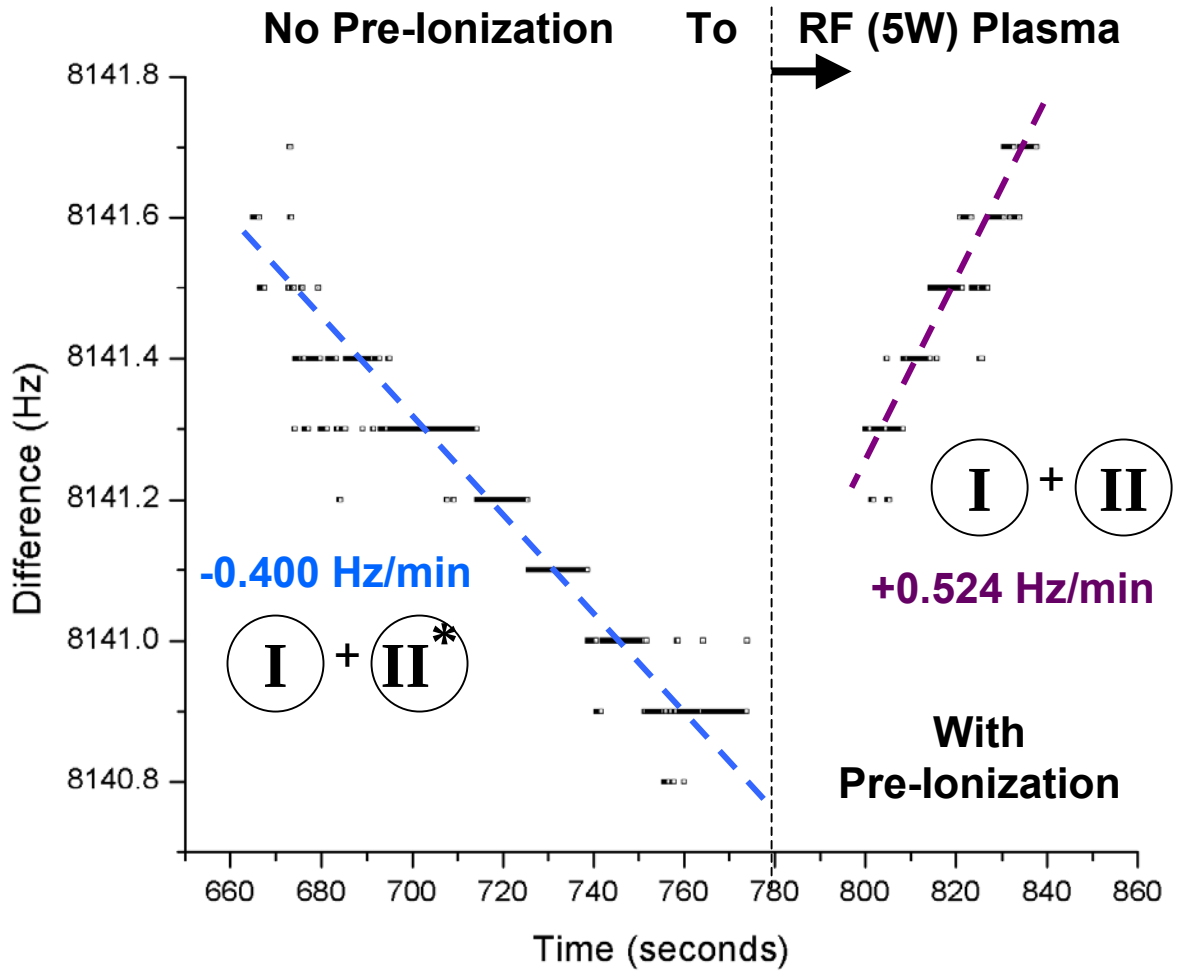
Importance Of Pre-Ionization

- Operating the DPF without pre-ionization leads to violent discharge formation and many more breakdown ions (Component II*).
- The secondary RF plasma acts as a pre-ionization source for improved uniformity, thereby decreasing breakdown ion flux.
- Component II* is huge compared to II.



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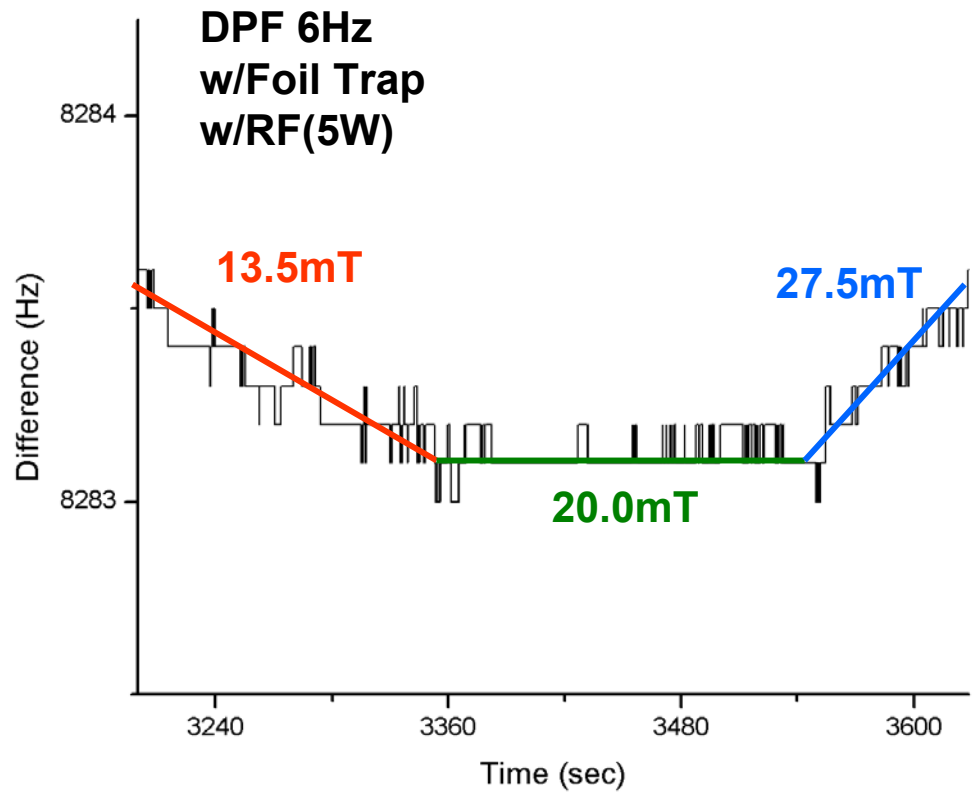
Components II & III Affected By Pressure

- **Fast-ion-induced erosion is dependent on gas pressure**
- **Increase of pressure leads to shorter MFP (<10cm) for keV Ar^+ in Ar gas**
  - Scattering causes Ar^+ to scatter into foil trap before hitting QCM
- **Ar^+ scattering leads to less erosion on QCM**
  - Result is net increase in mass at QCM



Pressure (mT Ar)	13.5	20.0	27.5
Slope (Hz/min)	-0.144	0.0	+0.226

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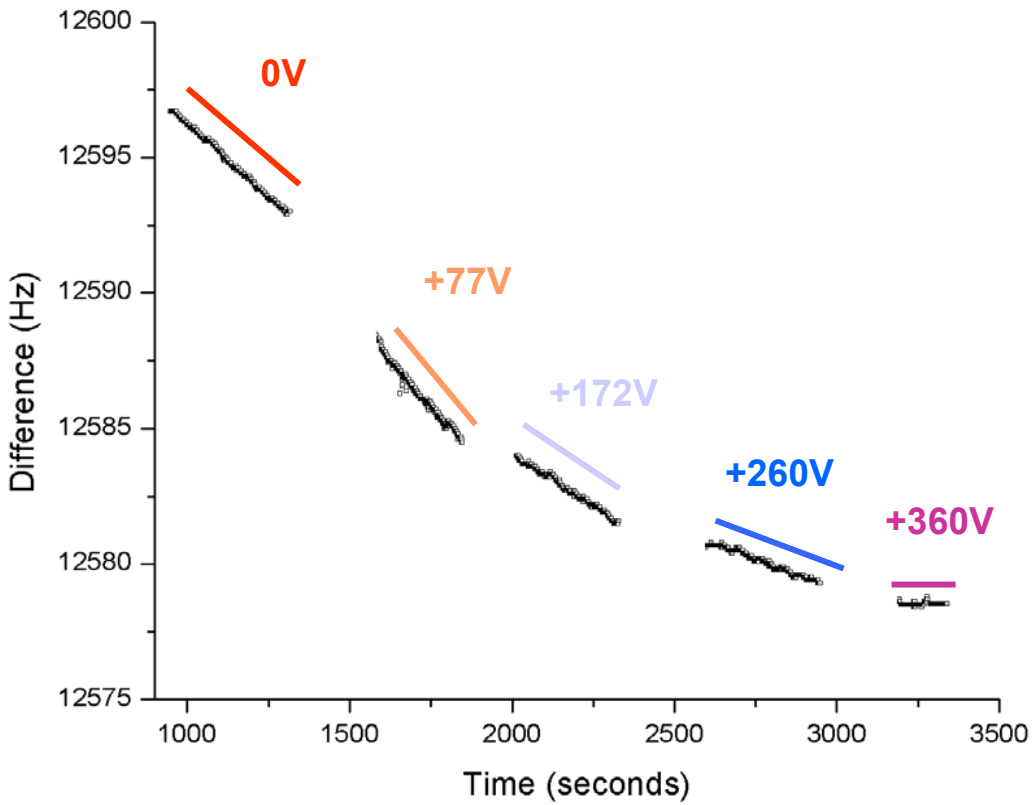
Bias Grid to Repel Erosive Ions (II & III)

Transition to Deposition (with Caveats)

- Applying a bias to the lower GEA screen repels some incoming ion flux.
- Raising bias from 0V to +360V, reduces the incoming ion steam, balancing fast ion erosion (Components II & III) with sputter deposition (Component I).
- Caveat: Fast ions from the pulse produce secondary electrons and a weak plasma beneath the grids, leading to some additional ion formation and erosion. This may explain increase of erosion going from 0 to 77V.



Repeller Voltage (V)	0	77	172	260	360
Slope (Hz/min)	-0.065	-0.097	-0.044	-0.027	~0

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Estimated Protection Factors

Type of Debris	Foil Trap Alone	Foil Trap with RF Plasma
Sputtered Electrode Material	Real Big Number	Real Big Number x 10 *(90+% Ionization)*
Fast Ions	1	Big Number *(electrostatic shielding)*
Fast Neutrals	1	Big Number x10 *(e-shielding + ionization)*
Sn Vapor	Real Big Number (which might not be enough)	Real Big Number x 10 (which may be enough) *(90+% Ionization)*

Next Steps

- **Improved Pinch Conditions**
  - Higher Rep Rate
  - Shorter Pulse Width
  - Other Gas Mixtures (He, Xe, etc.)
- **Optimize RF Efficiency For Best Mitigation**
  - Frequency (w/geometry)
  - Coil Parameters (Helical Resonator)
  - Pressure
  - Magnetic Shielding, Faraday Shielding And Bias Voltages
- **Work W/ Source Suppliers To:**
  - ***Shrink Size (<4") Anticipated***
  - Integrate w/ EUV Sources
  - Lower Cost Of Ownership
  - Have plasma mitigator also serve as the preionizer Stage
- **Improved Diagnostics**
  - Directional Gridded Energy Analyzer
  - Angularly resolved debris measurements
  - Extensive Spectroscopy
- **Continue To Build Understanding Of Debris Generation Mechanisms And Mitigation Schemes**
  - Verify debris component model
  - Assess Debris Mitigation Affect On EUVL Output
- **Estimate Lifetime Effects**
  - Optimization Of Debris Mitigation and Protection Factors For Ionic Species

Summary

Illinois Debris-mitigation EUV Application Laboratory Results-to-Date

- **Functional IDEAL experiment less than one year old**
- **Demonstrated plasma-based debris mitigation concept**
- **Improved RF source with workable RF plasma shielding**
- **Created unique diagnostic capabilities**
- **Identified debris components**
- **Available for industrial collaborations**

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- **International Sematech**
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