Micro-Architectured Materials for Electric Propulsion and Pulsed Power

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Collaborators

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AFOSR Program on Materials and Processes Far From Equilibrium

Presentation Outline

- Objectives and Project Structure.
- Severe, Non-equilibrium Material Environment for Electric Propulsion & Pulsed Power.
- Material Damage & Failure Mechanisms.
- Manufacturing of refractory metal architectures.
- Experimental Testing & Characterization Plan.
- Modeling of Particle-Surface Interaction.
- Surface Instabilities.

Project Objectives

- Enable the development of plasma-resilient, micro-architectured materials for the severe, *far-from-equilibrium* plasma and ion environments in electric propulsion and pulsed power systems.
- Utilize multiscale modeling & experimental verification to understand the mechanisms that limit plasma performance and material lifetime.
- The focus will be on refractory metals in various architectures (e.g. W, Re, Mo) and on candidate fiber reinforced ceramics (e.g. BN).
- The aim is to develop the basic science of materials in the extreme energetic plasma environment, and during electron & ion pulsed power operation.

Approach and Methodology

Approach:

1. Evaluation of surface performance and behavior
   - Measurement of erosion yields (sputtering & exfoliation)
   - Measurements of ion and electron induced secondary electron emission
   - Measurement of performance-limiting surface properties (emissivity, reflectivity, HV standoff, etc.)
3. Evaluation of surface stability and modification in representative environment(s)
   - High sputter-rate plasmas
   - Plasmas with re-deposition
   - High heat flux
   - Other environments (co-deposition, etc.)

Method:

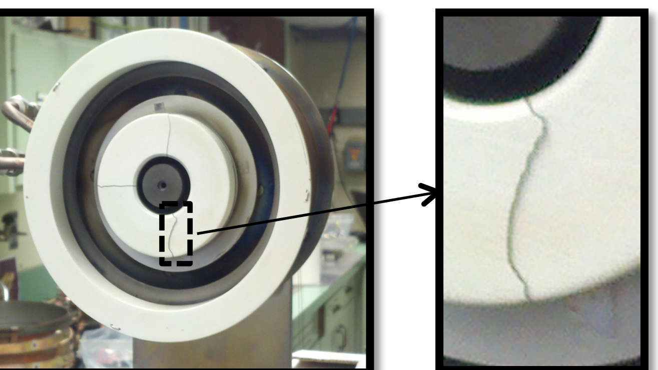
1. Exposure to plasma bombardment from plasma sources
2. Exposure to high heat fluxes from arc-jets & e-guns

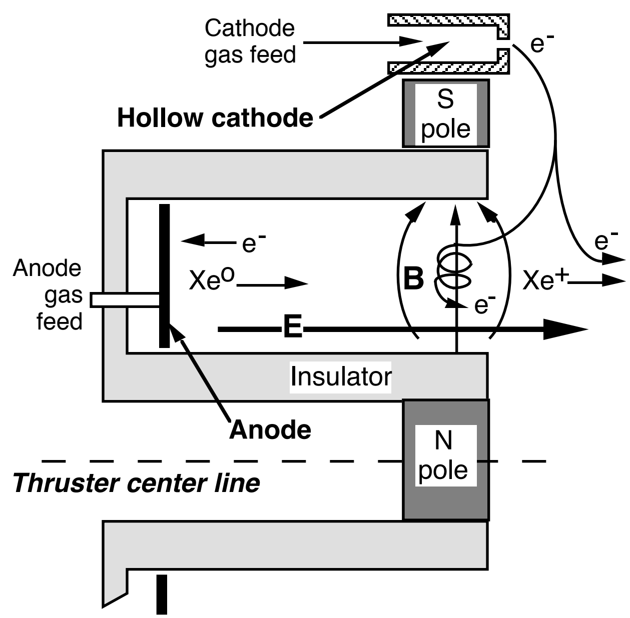
Integrated Plasma Science, Materials, and Manufacturing Team

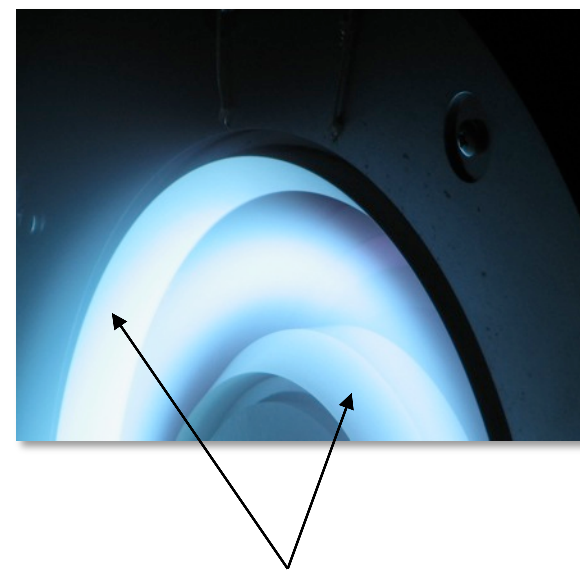
- Propulsion & Aerospace (Wirz - UCLA).
- Plasma science and technology (Goebel – JPL/ UCLA, Raitses, Kaganovich - PPPL).
- Material characterization (Sehirlioglu - CW).
- Materials engineering and high heat flux testing (Sharafat - UCLA).
- Refractory and ceramic material processing and fabrication (Williams - ULTRAMET).
- Multiscale modeling (Ghoniem - UCLA).

Environments for Hall Thrusters

Device	Particle Flux (#/m^2/s)	Particle Energy (eV)	Heat Flux (MW/m^2)	Pulse Duration (s)	Ion/Photon Type	Material	Life Fluence (TJ/m^2)	Lifetime (yrs)
Hall thrusters - ions - electrons	 $1x10^{21}$ $5x10^{22}$	 50 – 300 30 - 100	 0.05 0.8	 CW CW	 xenon electron	Boron nitride	 3 50	1 - 2



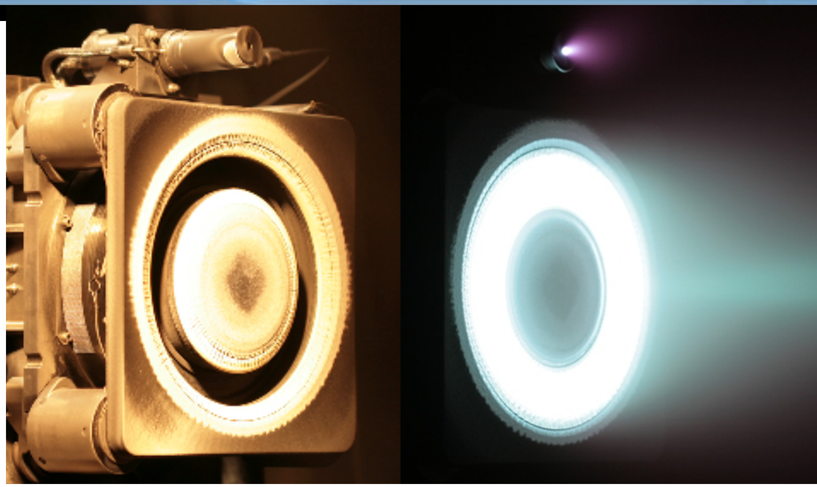




Boron nitride rings erode

Surface Damage of BN/Borosil[1]

U.S. Hall Thruster



BPT-4000, 5,800 hrs

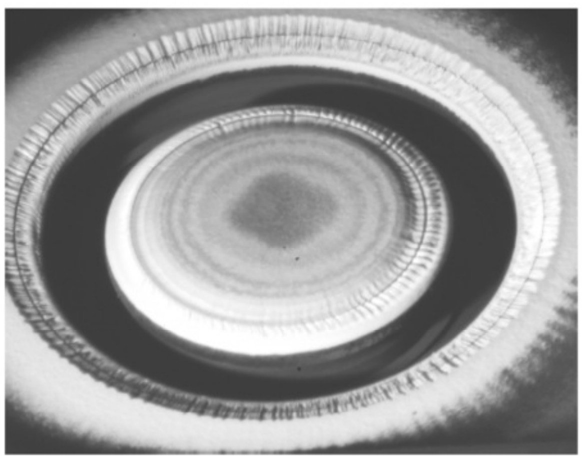


Figure 10 - In-Situ Photograph of Thruster at 10,400 hrs of Operation

BPT-4000, 10,400 hrs

De Grys, K. H., et al., AIAA Paper 2010-6698

Russian Hall Thruster

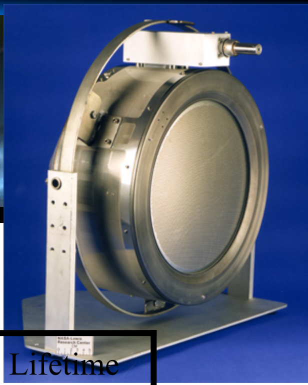
SPT-100, 6,900 hrs

French Hall Thruster

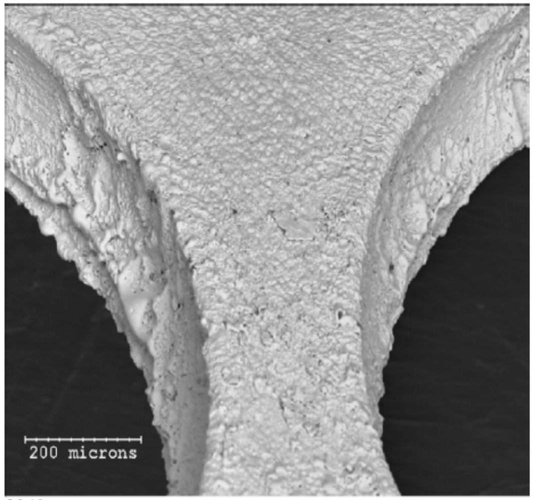
PPS-1350, 10,530 hrs

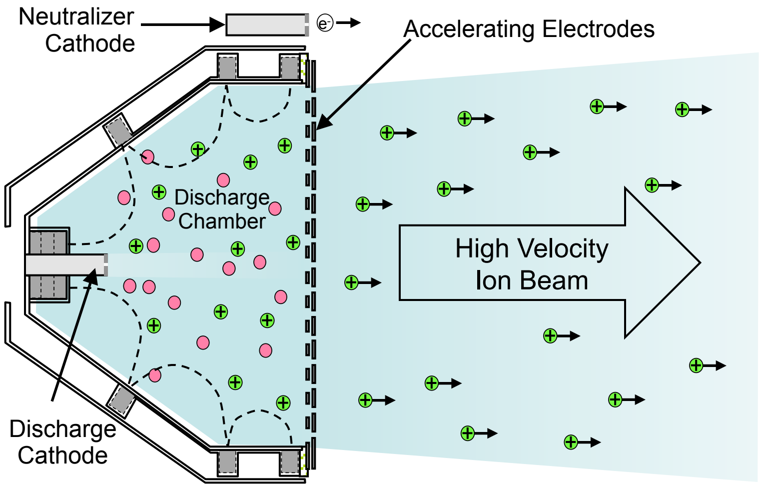
[1]Courtesy *JPL* http://www.jpl.nasa.gov/

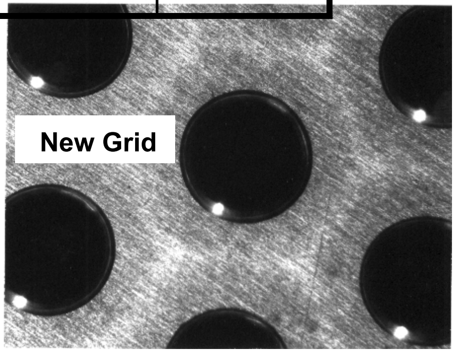
Environments for Ion Thrusters

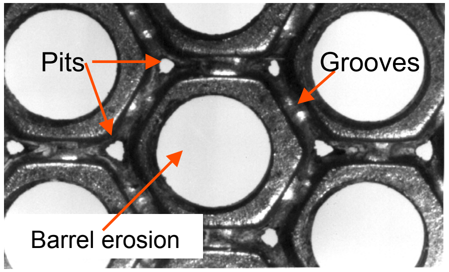


Device	Particle Flux (#/m^2/s)	Particle Energy (eV)	Heat Flux (MW/m^2)	Pulse Duration (s)	Ion/Photon Type	Material	Life Fluence (TJ/m^2)	Lifetime (yrs)
Ion thruster								
- screen grid	3×10^{20}	25- 50	0.0025	CW	Xenon	Moly	0.4	3 - 5
- accel grid	6×10^{18}	250-500	0.0005	CW		Moly	0.08	
- cathode	6×10^{21}	25-50	0.05	CW		Mo/W	7.5	





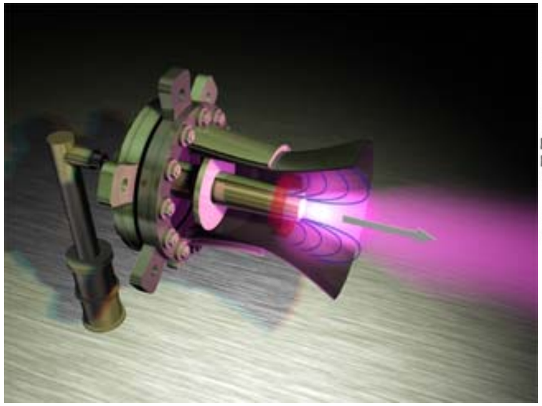


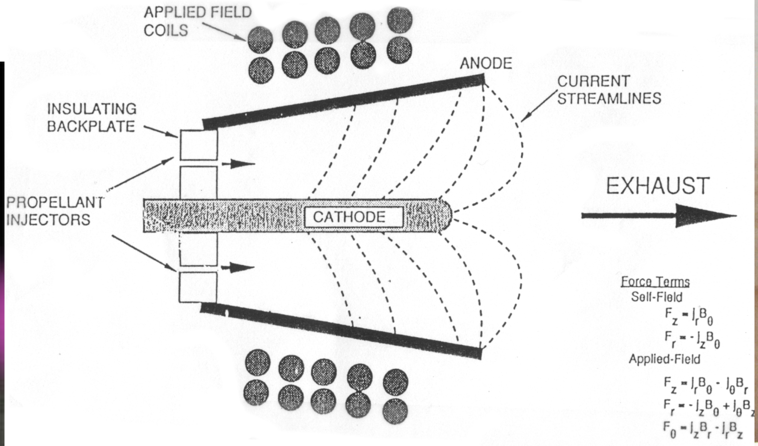


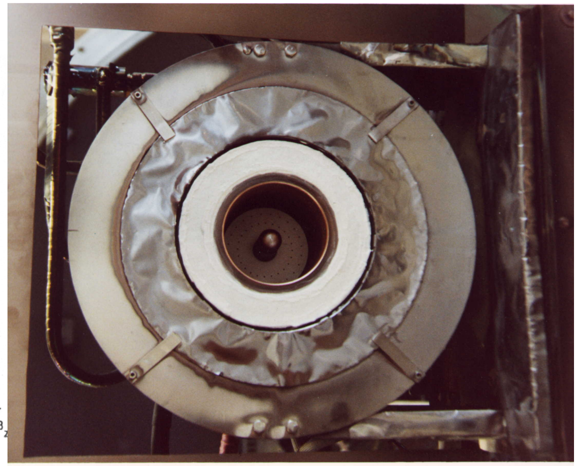
*grid erosion is major issue

Environment for MPD Thrusters

Device	Particle Flux ($\#/m^2/s$)	Particle Energy (eV)	Heat Flux (MW/m^2)	Pulse Duration (s)	Ion/Photon Type	Material	Life Fluence (TJ/m^2)	Lifetime (yrs)
MPD thrusters --Electrons --Li Ions	 10^{24} $2x10^{23}$	50 – 100	8 1.6	10^{-3}- CW	Li, electron	Copper, W	0.5 0.1	0.1 -2

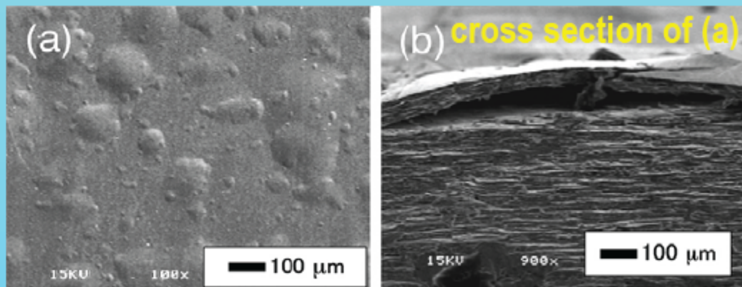




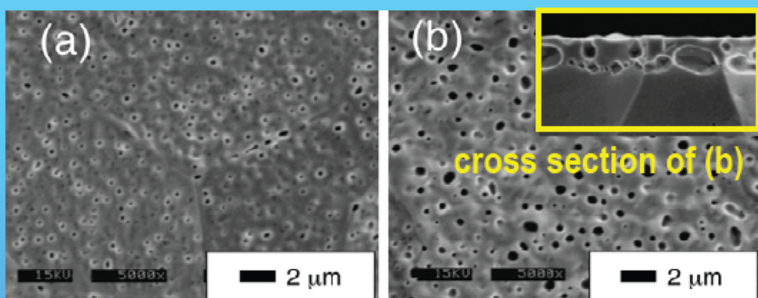


***cathode issues primarily focused on ion erosion and high heat flux**
****anode issues are high heat flux and high energies (causing erosion)**

Blisters and Fuzz @ 50 eV

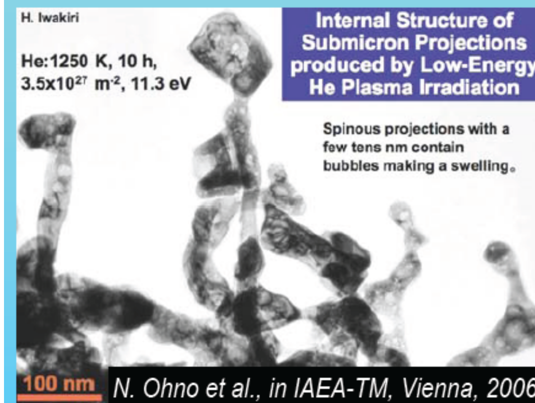


Blisters on a powder met W, 550K, H plasma, 90 eV, fluence 3.4×10^{25} H/m^2



He hole/bubble formation on a powder met W, 2200K, He plasma, 15 eV He, 8.3×10^{22} m^2/s, (a) 1000 s, (b) 10000 s.

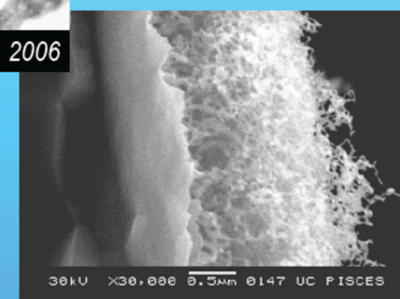
Ohno, Kajita, Nashijima, Takamura, (Nagoya U.)
Surface modification of W and W-coated graphite due to low energy and high fluence plasma and laser pulse irradiation,
J. Nucl. Mat. 363-365 (2007) p1153



NAGDIS-II: pure He plasma
1250 K, 36,000 s,
3.5×10^{27} He$^+$/m^2,
E_i = 11 eV
Ohno et al., Nagoya U.

Transmission electron microscope (TEM) by Kyushu University

PISCES-B: He plasma
1200 K, 4290 s, 2×10^{26} He+/m^2, Ei = 25 eV
Baldwin et. al, Center for Energy Research, UCSD,

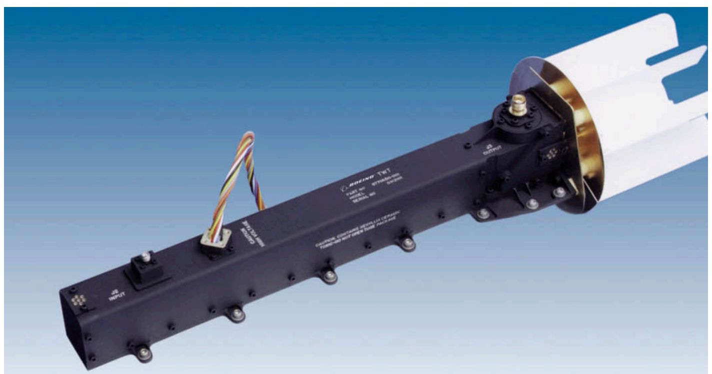


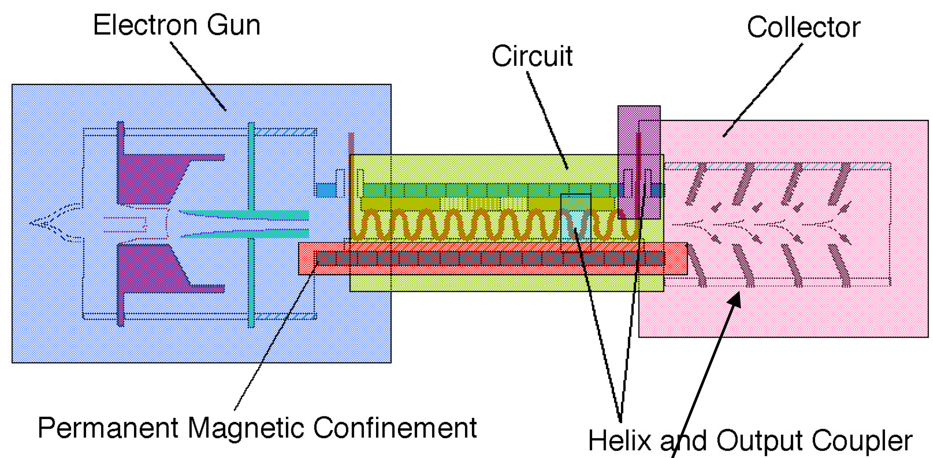
1-6 TJ/m^2 @10-100 eV

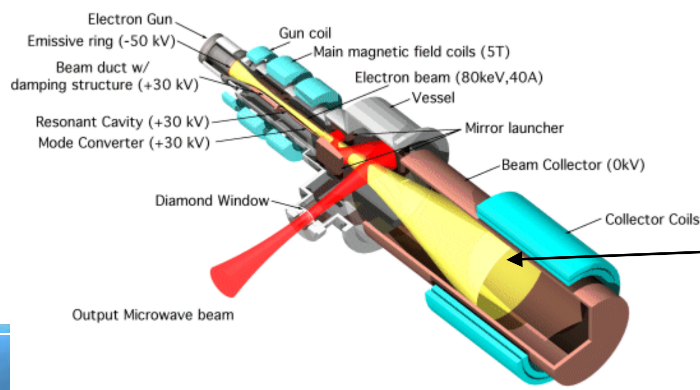
0.1 TJ/m^2 @10-100 eV

Environments for TWTs/Gyrotrons

Device	Particle Flux ($\#/m^2/s$)	Particle Energy (eV)	Heat Flux (MW/m^2)	Pulse Duration (s)	Ion/Photon Type	Material	Life Fluence (TJ/m^2)	Lifetime (yrs)
Gyrotrons (collector)	$2x10^{21}$	≈100kV	16	10^{-3}- CW	Electron	Copper	2.5	1-5
Traveling Wave Tubes (collector)	$1x10^{20}$	1 – 10 kV	0.16	10^{-3}- CW	Electron	Copper, moly, graphite	0.15	25



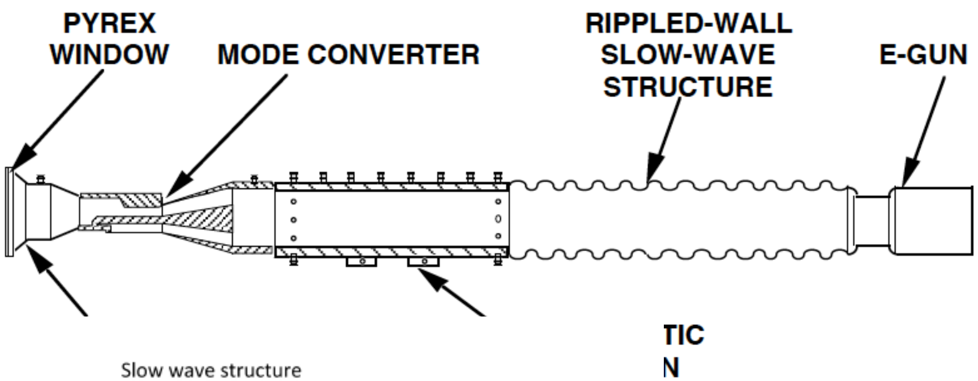


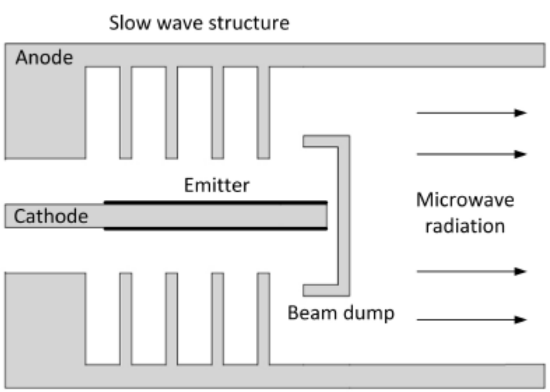


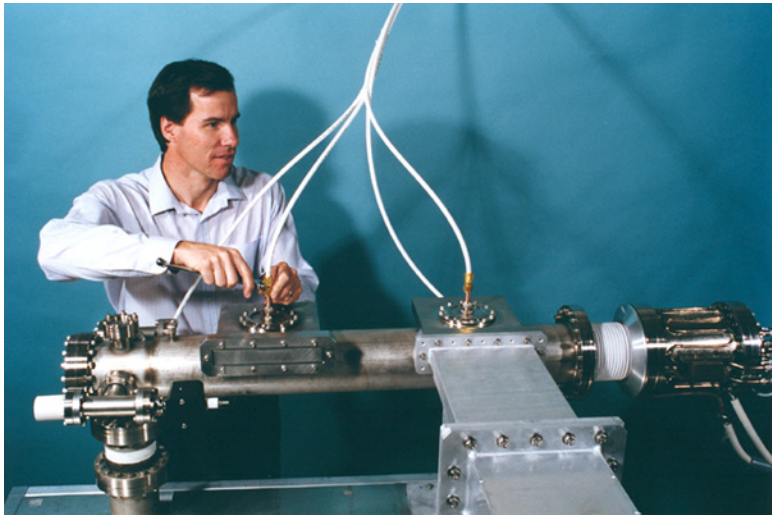
***high electron heat flux in collector**

Environments for HPM Sources

Device	Particle Flux (#/m^2/s)	Particle Energy (eV)	Heat Flux (MJ/m²)	Pulse Duration (s)	Ion/Photon Type	Material	Life Fluence (TJ/m²)	Lifetime (yrs)
HPM sources	1×10^{22}	0.1-1MV	1600	10^{-7}-10^{-5}	Electron	Copper, moly, W	0.05 (1 Hz) 5 (100 Hz)?	1

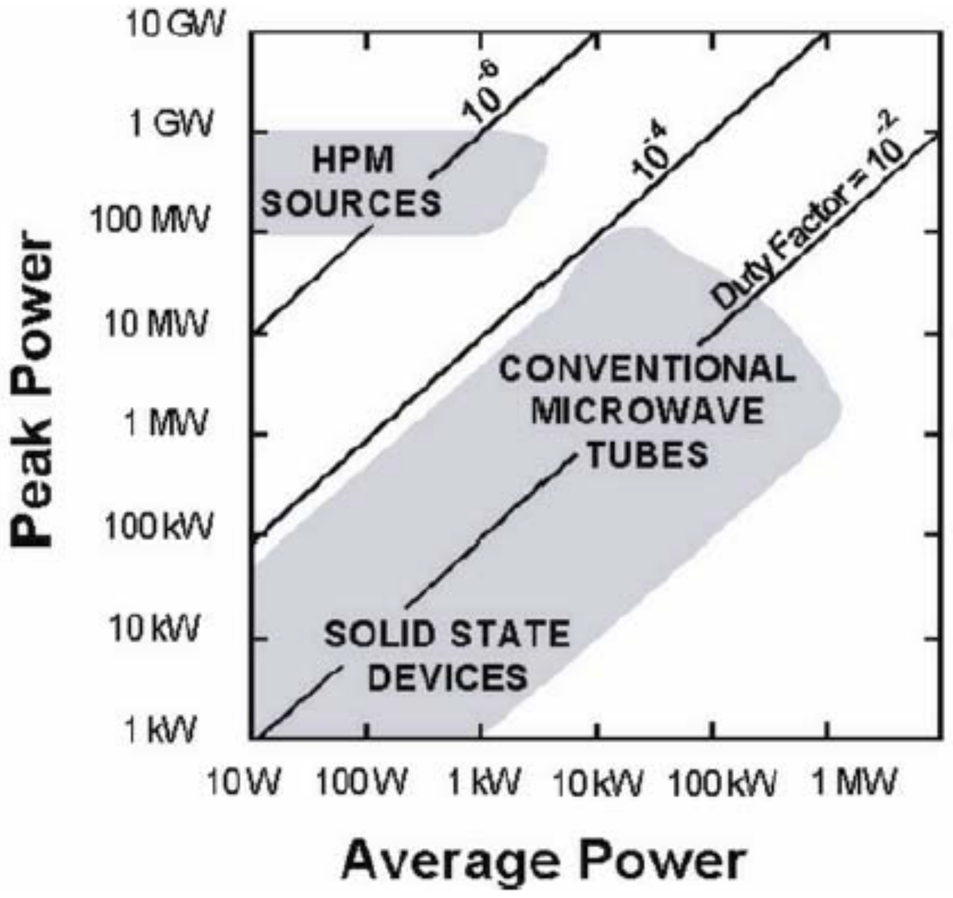


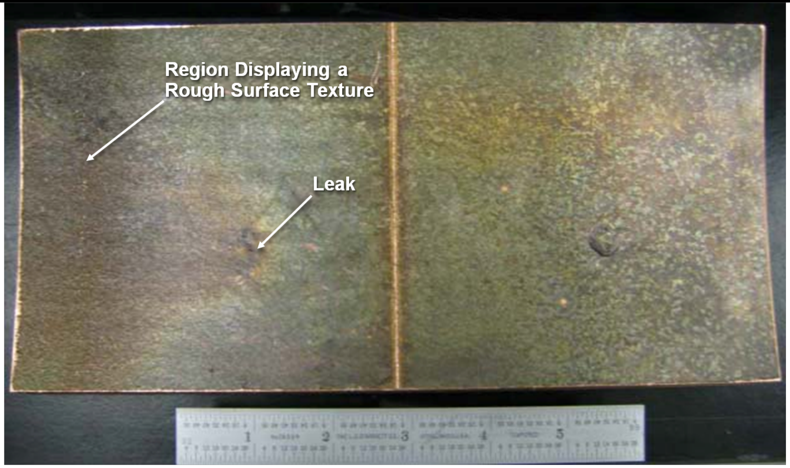


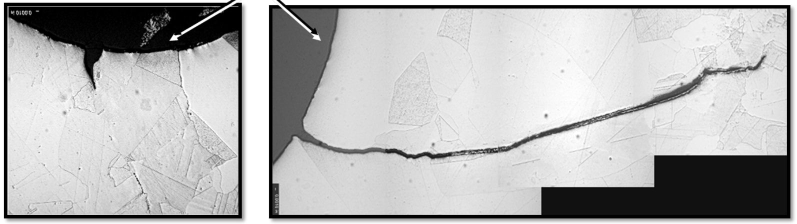


*high electron heat flux in resonant structure and in the e-beam collector

Pulsed Power Material Damage Characteristics







Heat Flux:
~7 MW/m^2

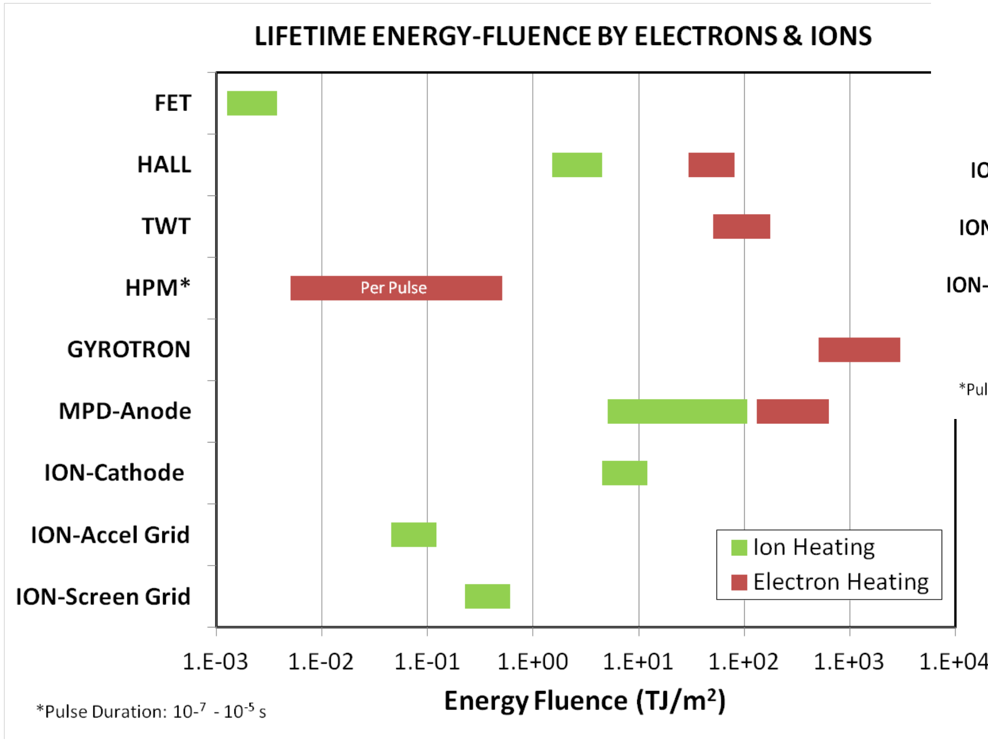
Communications & Power Industries

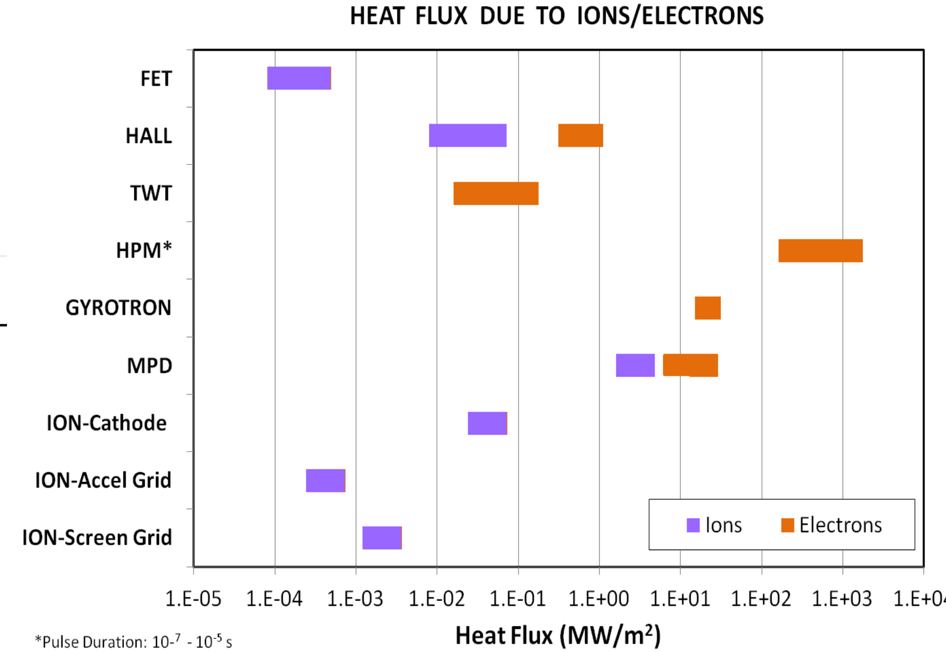
Gyrotron Damage
Coolant Leak Columnar Grain Growth[1]

R.J. Barker and E. Schamiloglu, Eds., *High Power Microwave Sources and Technologies,* New York: IEEE Press/J. Wiley & Sons, 2001.

[1]Courtesy ***Communications & Power Industries*** http://www.cpii.com/

Heat Flux on Materials in EP & PP Applications





[1]SRIM Calculations: http://www.srim.org/SRIM/SRIMLEGL.htm

[2]SESTAR-NIST Calculations: http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html

Research Tasks

>> Task (1): Development of Micro-architectured Materials (refractories and fiber-reinforced composites).

>> Task (2): Multiscale Modeling of Materials (erosive instabilities and thermo-mechanical damage.

>> Task (3): In-situ testing and modeling of plasma-material interactions.

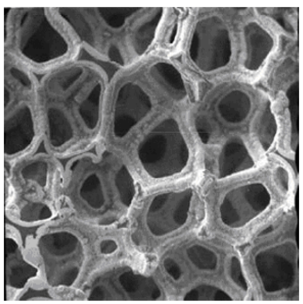
>> Task (4): Measurements and modeling of secondary electron emission in architecture material surfaces.

>> Task (5): Erosion and thermo-mechanical experiments on architecture materials.

>> Task (6): Characterization of materials microstructure and properties.

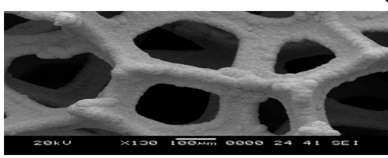
Micro-Architectured Surfaces (Meta-Materials)

Refractory Metal Networks



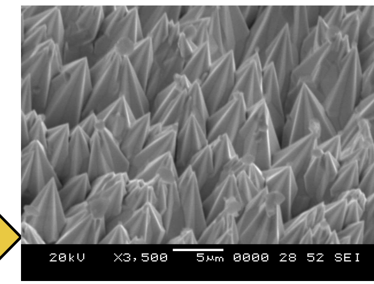
Isotropic

Anisotropic

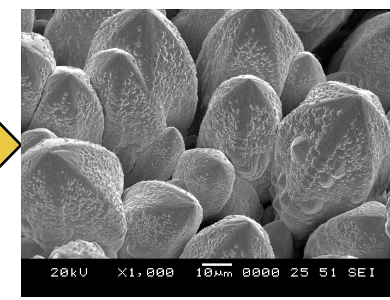


Textured Refractory Surfaces

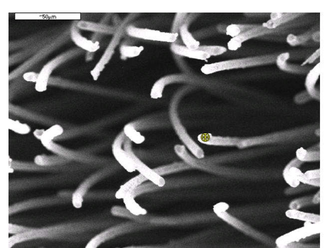
Micro-spears



Micro-Nodules



Micro-Velvets & Micro-brushes

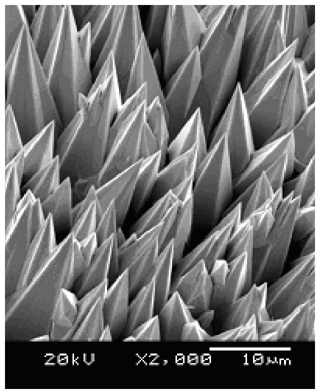


Performance-Enhancement Potential of Micro-Architectured Surfaces

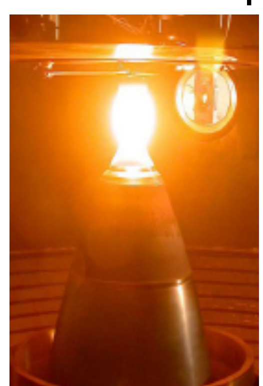
- Electron & ion energies are distributed into 3-D architectured structures of great surface area promoting better heat distribution.
- Net sputtering erosion due is minimized because of geometric trapping of re-deposited atoms.
- Implanted ion residence time in the material is reduced due to fine surface features, thereby facilitating rapid and preventing formation of bubbles and blisters.
- Thermal stress is reduced because fine surface features are capable of a greater level of distortion.
- The high thermal and dimensional stability of CVD refractory armor prevents fragmentation and dust formation.

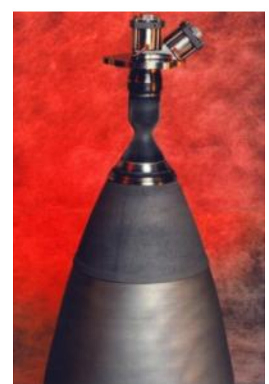
Architectured Materials Processing Plan

Textured Coatings: Ultramet applies high-emittance dendritic rhenium coatings in a production environment to tungsten cathodes used in special-purpose, high-wattage discharge lamps for semiconductor microlithography. These components operate at an impressive 2700°C for 100,000 hours.



Ultramet also applies thin dendritic rhenium coatings to the outer surface of radiation-cooled iridium-lined rhenium combustion chambers used in satellite propulsion systems with over 75 units now in space.





Development of Micro-architectured Materials – Williams@Ultramet

Task 1.1. Development of Textured Micro-engineered Materials

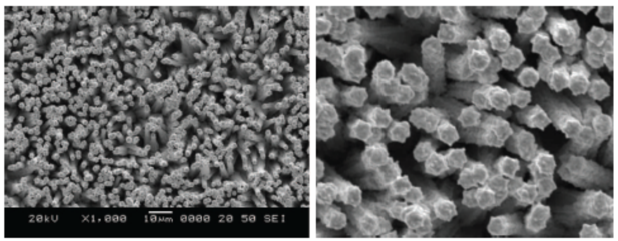


Figure 8: SEM images of CVD tungsten-coated CVD rhenium dendrites

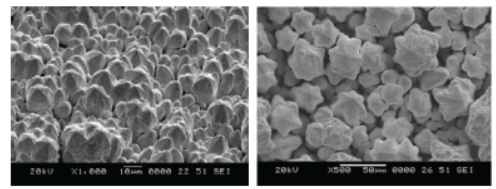


Figure 7: SEM images showing variations in microstructure achieved for CVD nodular tungsten

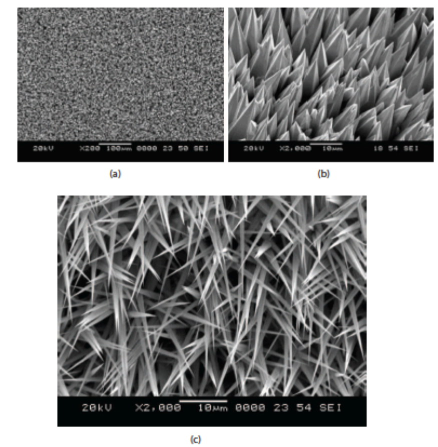


Figure 6: SEM images of dendritic rhenium coating under lower (A) and higher (B) magnifications

Task 1.2. Development of Fiber- Reinforced Ceramic Composites

A minimum of eight material and process variations will be selected from the following potential variables:
(1) Matrix material: BN, Si_3N_4, AlN, TiO_2, Al_2O_3;
(2) Matrix infiltration process: CVI and MI;
(3) Fiber material: alumina, alumina-silica, silicon carbide, carbon;
(4) Surface layer: variable thickness CVD coatings to reduce fiber conductivity contribution.

MATERIALS TESTING PLANS

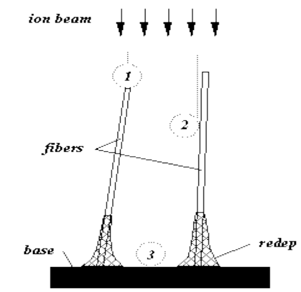
- Materials testing is divided into three categories:
  - High heat flux environments
  - Plasma sputtering environments
  - Low-energy electron bombardment environments (secondary electron yields)

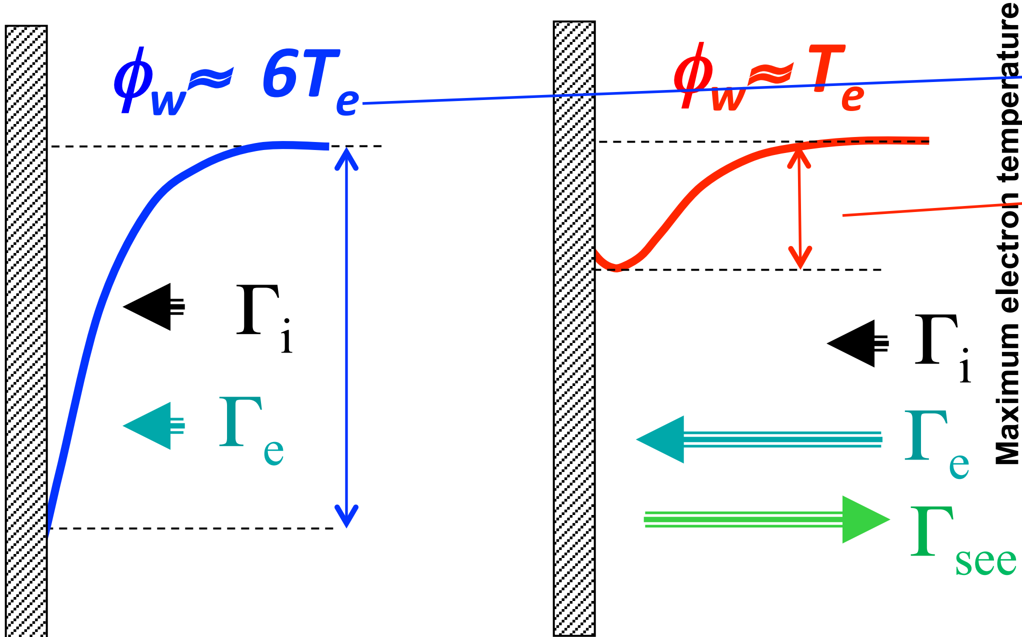
1) **High Heat-flux Testing**
   - Addresses requirements found in vacuum tubes (gyrotrons) & HPM sources
   - Use a modified arc-jet to provide high power, low energy bombardment of material samples at UCLA
   - High power e-beam facilities (at SNLA) will be used later in the program for evaluation of final-engineered materials
2) **Plasma/Sputtering Testing:**
   - Biased samples inserted into the plasma from an rf plasma source at UCLA will be used to measure the sputtering yield of the engineered materials
   - The PISCES Plasma-Surface Interactions facility at UCSD can be used as a backup for sputtering measurements
3) **Secondary Electron Yield Testing:**
   - The facility at PPPL will be used to characterize the secondary electron yield of insulator materials intended for Hall thrusters and other emerging thruster applications

Electron emission from the wall can increase the plasma heat flux to the wall many times

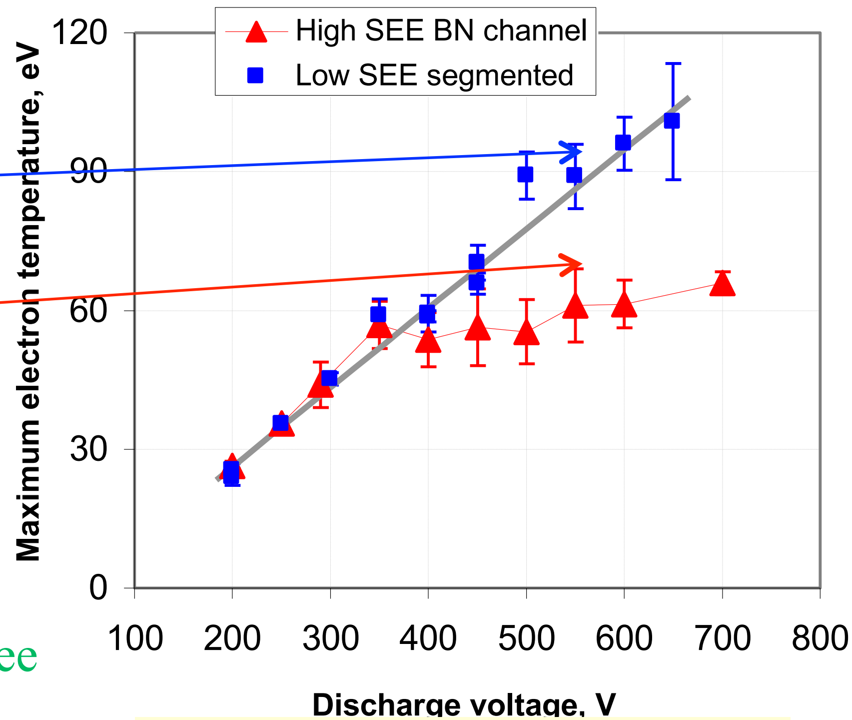
• Without SEE, sheath of space charge near the wall reflects most electrons back to the plasma, thus effectively insulating wall from the plasma (Right Figure)

• SEE reduces the wall potential and allows large electron flux to the wall (Left Figure)





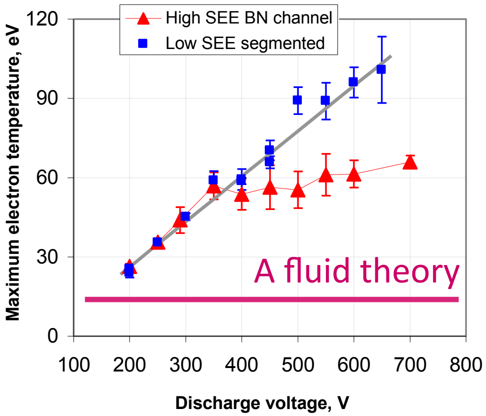
Wall - Sheath - Plasma   Wall – Sheath - Plasma



Y. Raitses et al., Phys. Plasmas 2005

Y. Raitses et al., IEEE TPS 2011

For many plasma applications, electron heat flux to the wall needs to be calculated kinetica



Large quantitative disagreement between experiments and fluid theories for predictions of the electron temperature in Hall thrusters

I. Kaganovich et al., Phys. Plasmas 2007

D. Sydorenko et al., Phys. Rev. Lett. 2009

New non-stationary regimes of plasma-wall interactions are discovered by particle-in-cell simulations

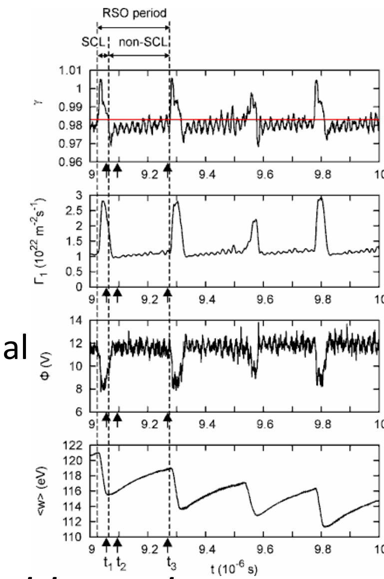
Kinetic simulations predict electron velocity distribution function to be **non-Maxwellian** (anisotropic, depleted, with beams of SEE electrons) leading to a reduced heat flux compared to fluid theory predictions, but enhanced cross-field transport

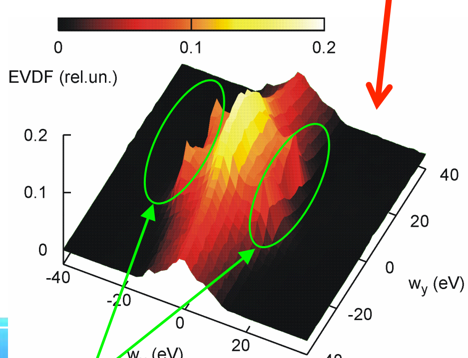
SEE coefficient

Electron wall flux

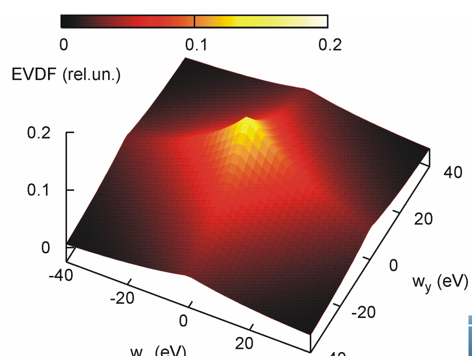
Plasma potential

Mean electron energy





Loss cones and SEE beams



Maxwellian

Classic theory of Hobbs and Wesson cannot be applied to Hall thruster plasma conditions

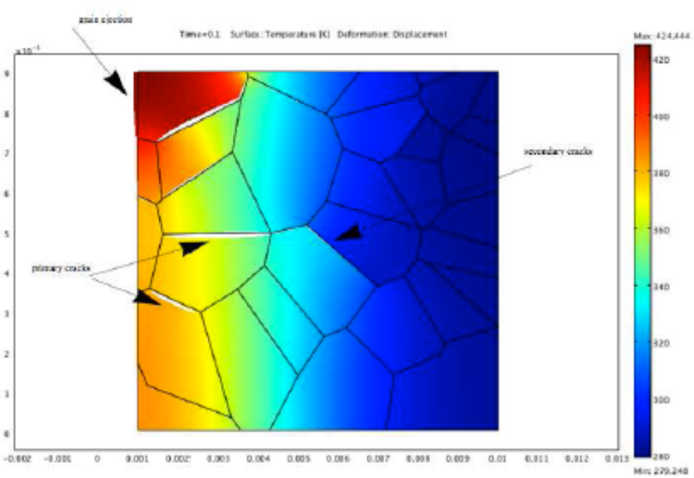
Task 6: Characterization of Materials Microstructure – Sehirlioglu (Funded Separately)

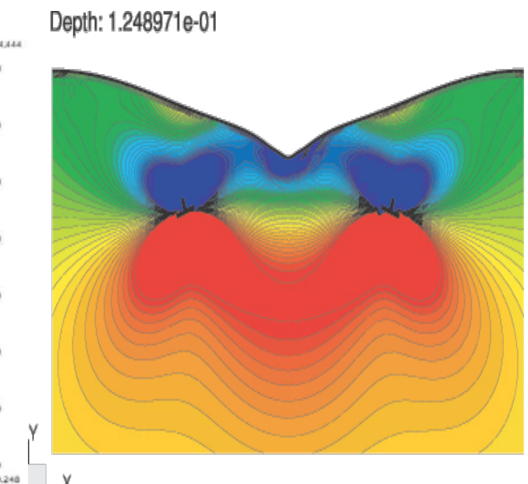
- Temperature dependence of properties.
- Microstructure characterization for: (1) structure-property relationships, (2) preferential erosion sites, (3) erosion rate differences as a function of grain orientation.
- Surface characterization: roughness, chemistry, and ion interaction depth
- Introduction of chemicals as sintering aids to modify the overall chemistry and control several key properties:
  - ✓ 1. Create phonon scattering to decrease thermal conductivity
  - ✓ 2. Increase bonding strength
  - ✓ 3. Modify electrical properties and the band gap structure.

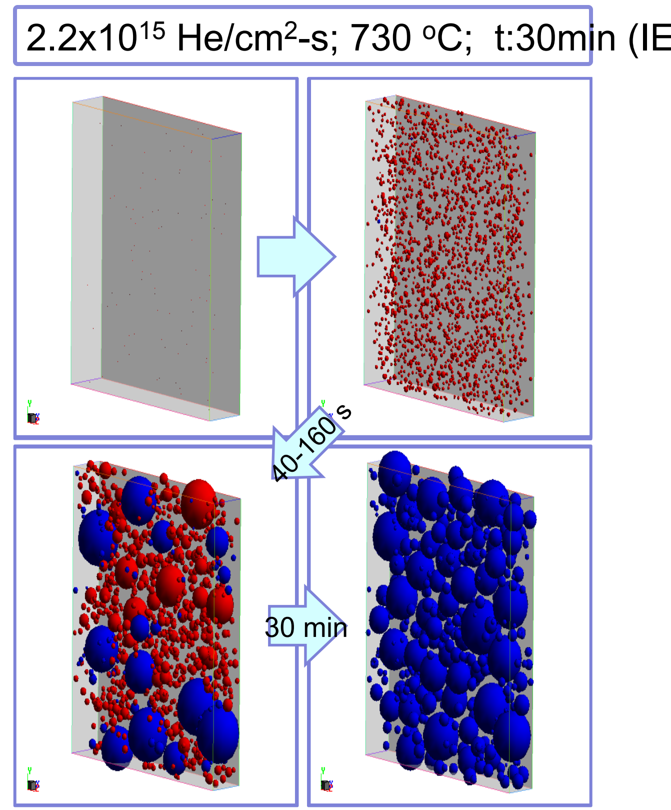
Task 2: Modeling Plasma and Ion Effects on Materials - Ghoniem

Task 2.1: Modeling Thermomechanics of Micro-architectured Surfaces: Multi-physics modeling of energy & particle deposition in CW & pulsed power, FEM modeling of coupled heat conduction, elastoplasticity, and surface fracture.

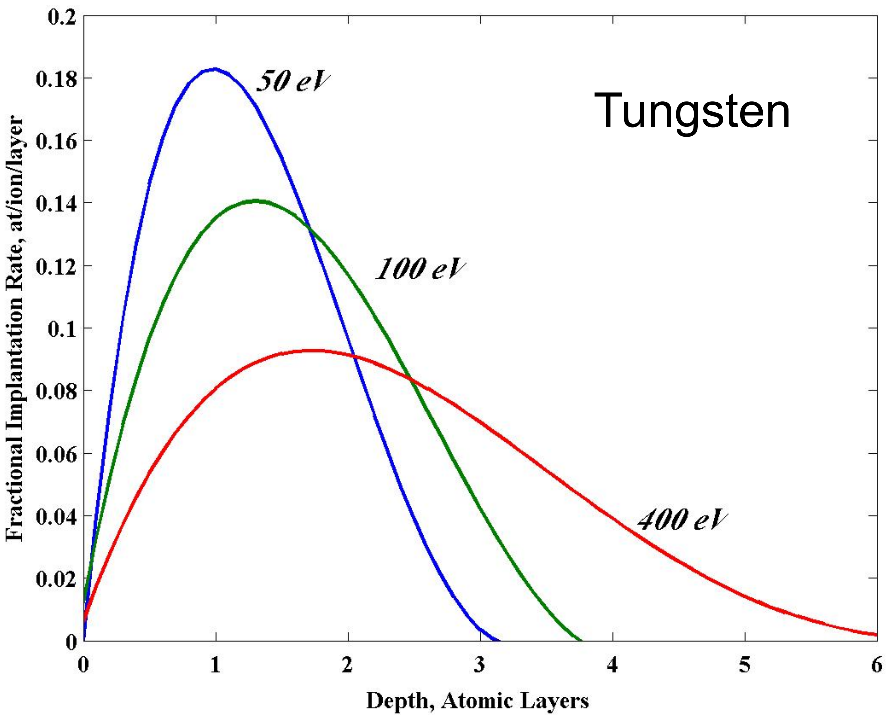
Task 2.2: Erosion/ Redeposition and Surface Evolution Models: Modeling Erosion and Redeposition, Modeling surface stability and roughness:

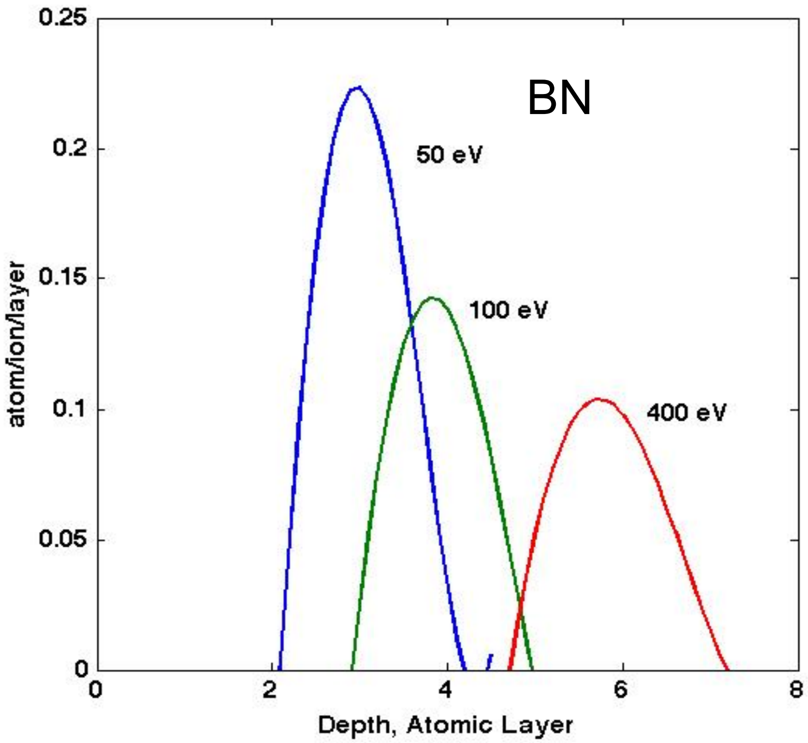


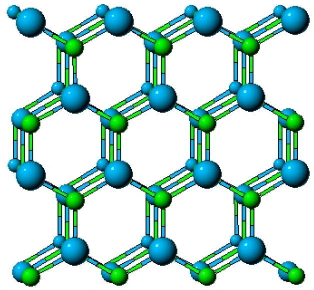




Fractional Implantation Profile of Xenon in Tungsten & BN



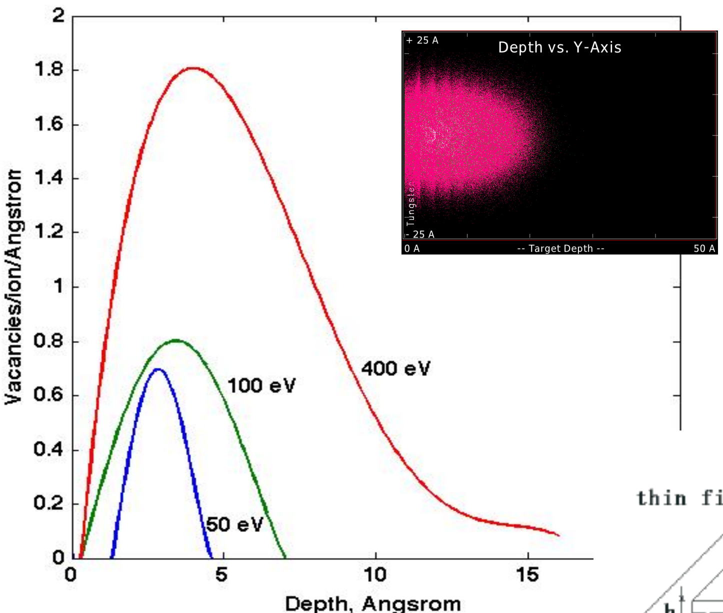




Hall Thruster Flux = 1×10^{17} cm^{-2} s^{-1}

Atoms/cm^2 = 1.6×10^{15}

Vacancy Production in Surface Layers Leads to Surface Instabilities



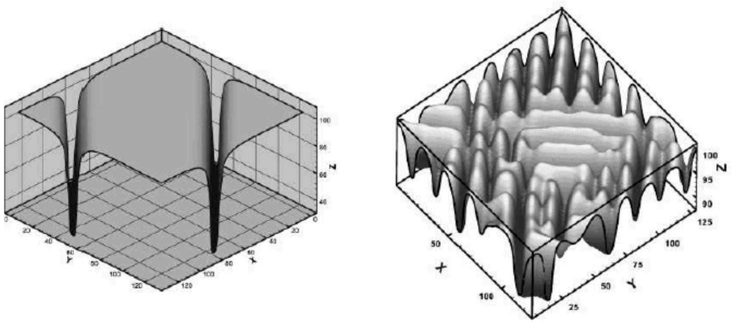
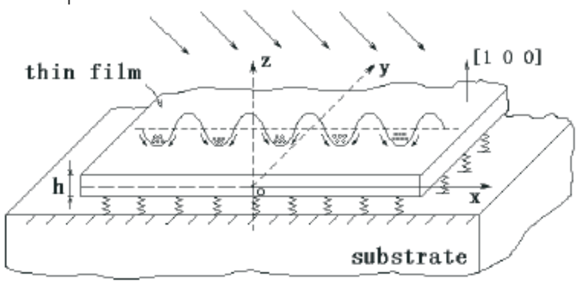


FIG. 14.20. Groove patterns seen under a biaxial stress state in which one side is under tension and the other is under compression [713].



D. Walgraef, N.M. Ghoniem, and J. Lauzeral. Deformation patterns in thin films under uniform laser irradiation. *Phys.Rev.*, B 56:15361–15377, 1997.

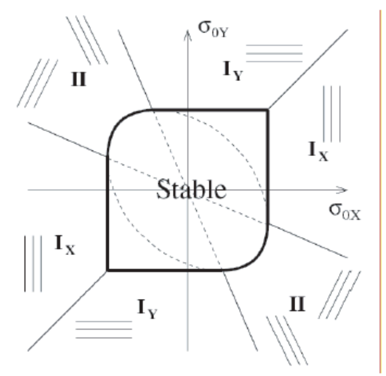


FIG. 14.21. Phase diagram for roughening (crack) pattern selection in biaxially

$$\nabla.\mathrm{U} = -zm\Delta\xi\,,$$

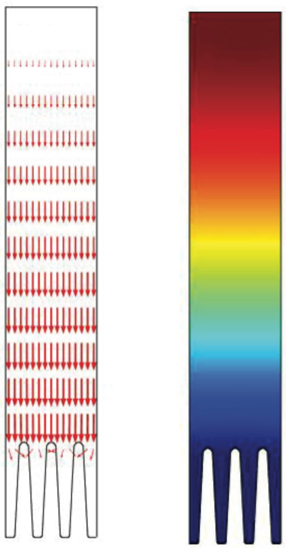
$$\partial_t^2\xi + \frac{c^2h^2}{12}\Delta^2\xi - \frac{c^2}{2}\sigma_{ij}\partial_{ij}^2\xi + \frac{\theta_v}{\rho h}(C_+ - C_-) = 0\,,$$

$$\partial_t C = D_\perp \partial_{zz}^2 C + D_\parallel \Delta C - \frac{C}{\tau} + \boldsymbol{\nabla}\frac{\theta_v D_\parallel C}{kT}\boldsymbol{\nabla}(\boldsymbol{\nabla}\cdot\mathbf{U}) + \nabla_z\frac{\theta_v D_\perp C}{kT}\nabla_z(\boldsymbol{\nabla}\cdot\mathbf{U}) + g\exp[-\frac{E_f}{kT}](1+\theta_v\boldsymbol{\nabla}\cdot\mathbf{U})$$

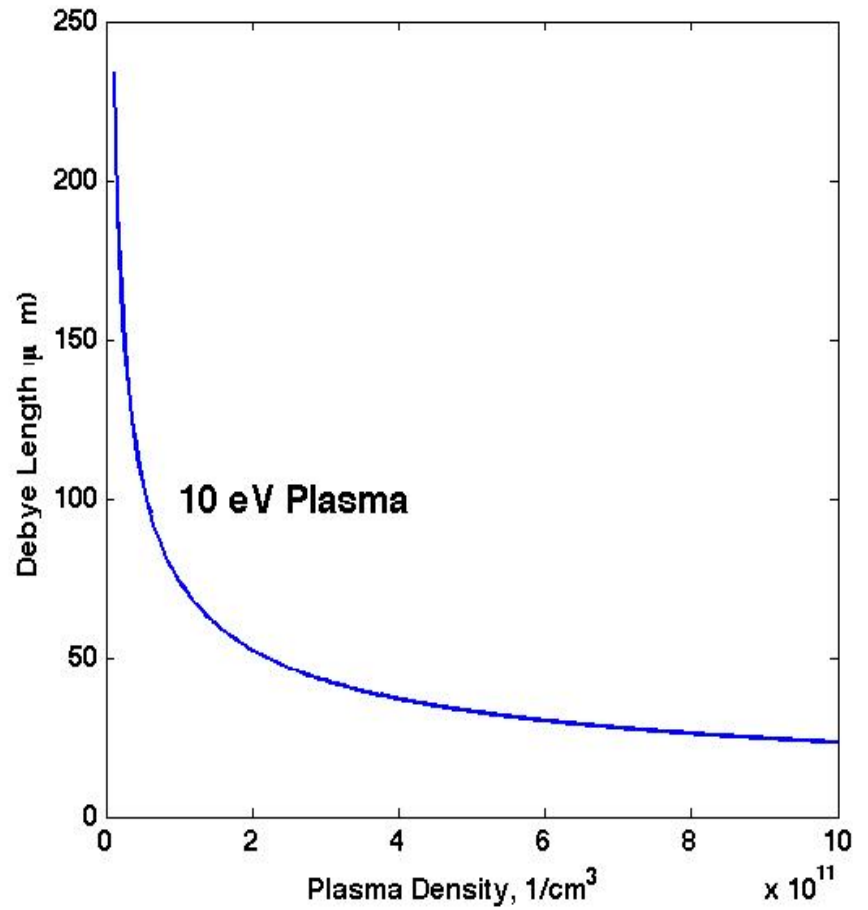
Jerome Paret. Long-time dynamics of the three-dimensional biaxial grinfeld instability. *Physical Review E*, 72:01105–1–5, 2005.

Plasma Sheath Modeling

Deep Sheath



$$\lambda_d = \sqrt{\frac{\varepsilon_0 k T_e}{n_0 e^2}} \approx 740\sqrt{T_{ev}/n_0}$$



Shallow Sheath