Plasma Interactions with Materials and Metamaterials

Prof. Richard Wirz

University of California, Los Angeles
Dept. of Mechanical & Aerospace Engineering
Director, Plasma & Space Propulsion Lab
Director, Energy Innovation Lab

MIPSE Seminar
October 10, 2017

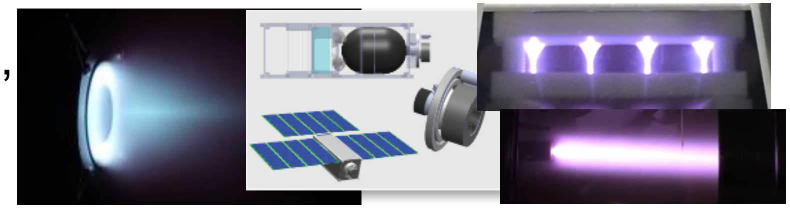
UCLA

PLASMA & SPACE PROPULSION LABORATORY

UCLA Plasma & Space Propulsion

Plasma Technology

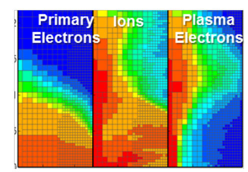
Electric Propulsion,
Plasma Devices,
Cathodes

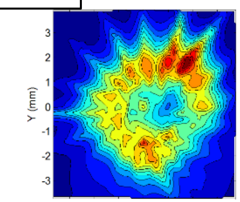


Plasma-Material
Interactions

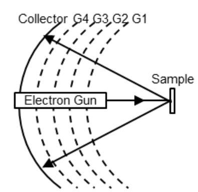
Applied Plasma Science

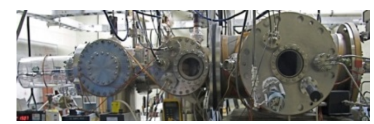
Plasma
Confinement





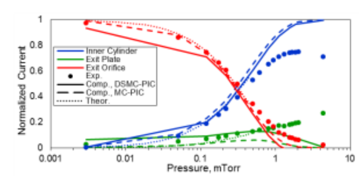
i-SEE
e-SEE
i-n





Plasma Physics

Canonical Experiments for
Plasma Model Validation



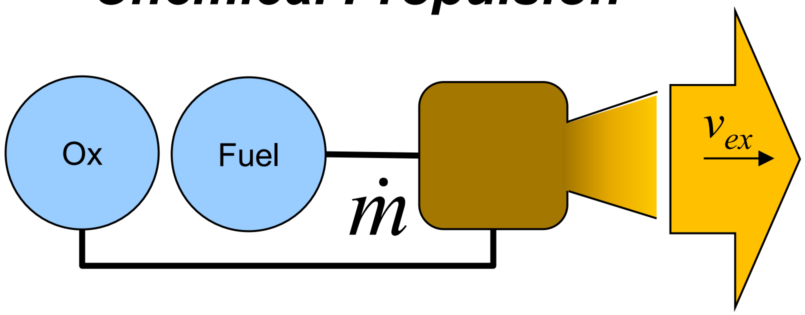
“Plasma Propulsion”

a.k.a. Electric Propulsion (EP)

Chemical & Electric Propulsion

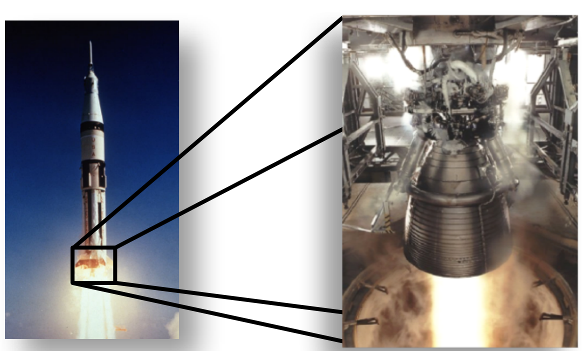
$$Thrust = \dot{m}\overline{v}_{ex}$$

Chemical Propulsion

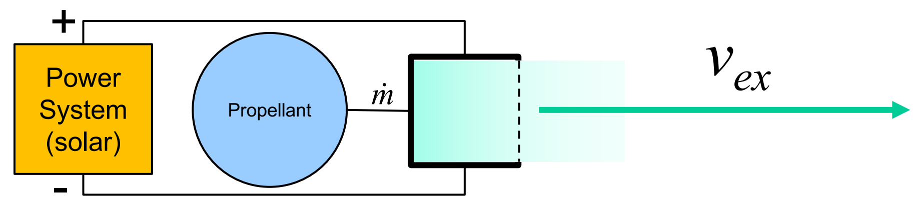


- Propulsion energy in Fuel/Ox chemical energy
- v_{ex}-limited by the propellant's *energy density*

$v_{ex} \cong 3 - 4$ km/s
$T \cong 1$ N – MN+

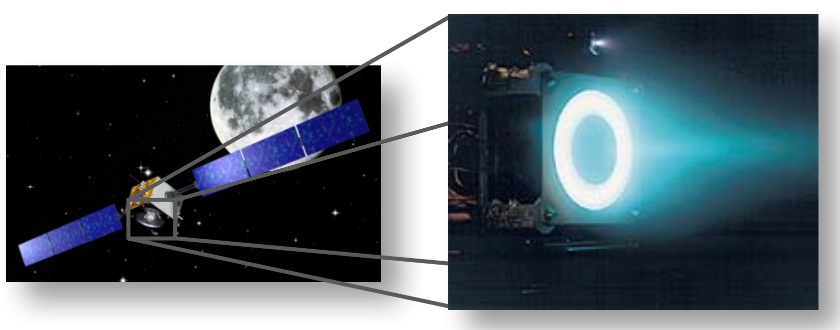


Electric Propulsion



- Propulsion energy from "Power System" (unlimited)
- Thrust-limited by the available *electric power*

$v_{ex} \cong 5 - 100+$ km/s
$T \cong 0.1 - 100$'s mN

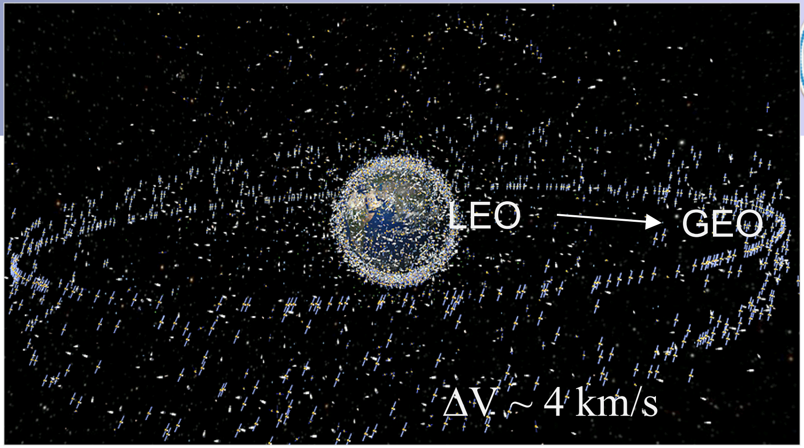


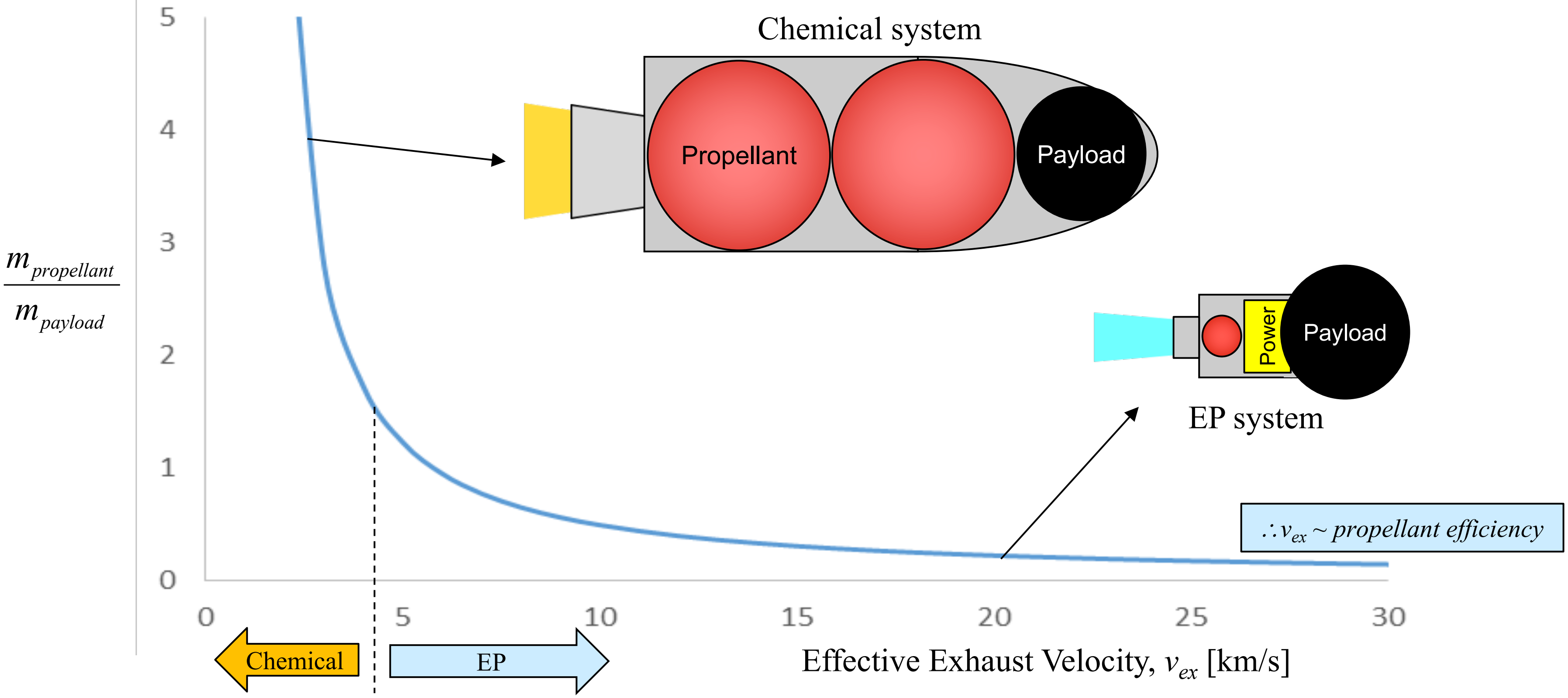
Images: NASA, ESA

Propellant Mass Req't

Rocket Equation

$$\frac{m_{propellant}}{m_{payload}} \approx \left(\exp\left(\frac{\Delta V}{v_{ex}} \right) - 1 \right)$$

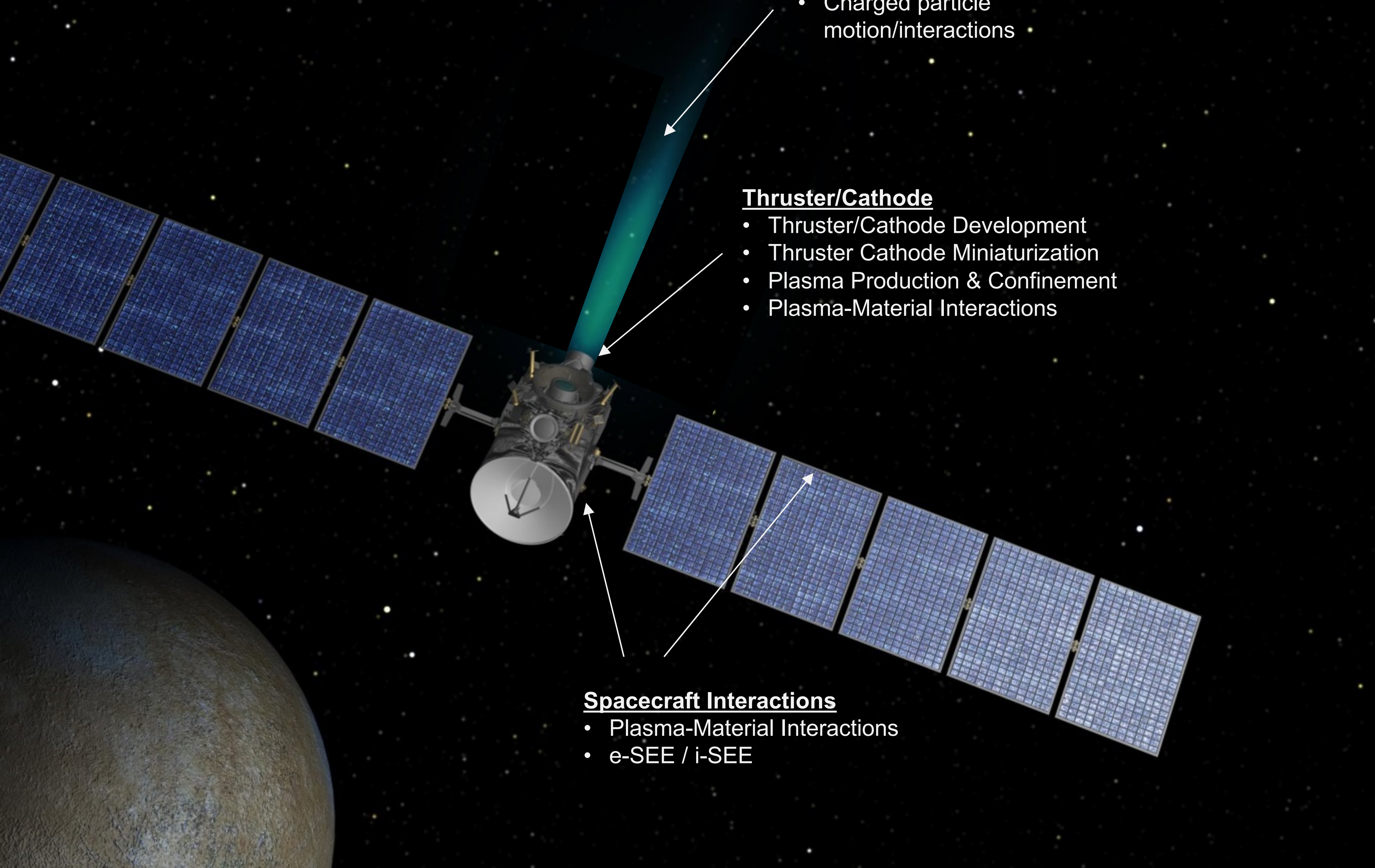




EP Challenge

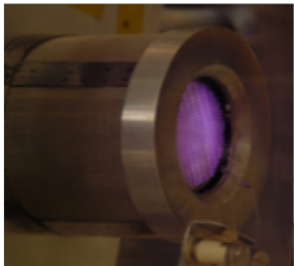
$$\text{Mission Impulse} = \int Thrust * dt$$

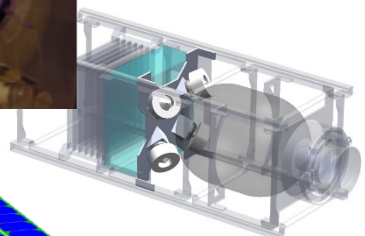
Electric Propulsion Research Areas

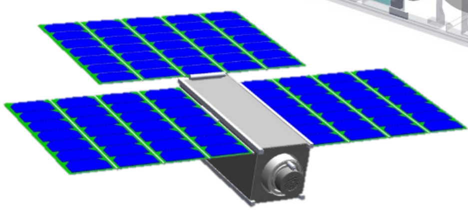


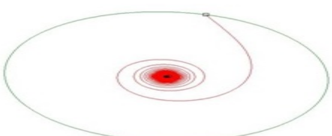
Electric Propulsion Technologies

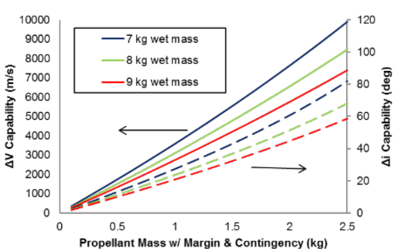
Ion Thrusters



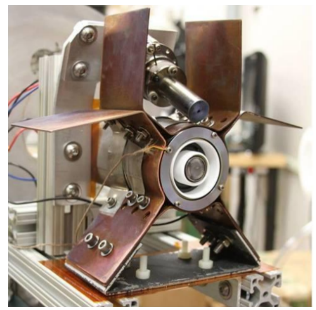


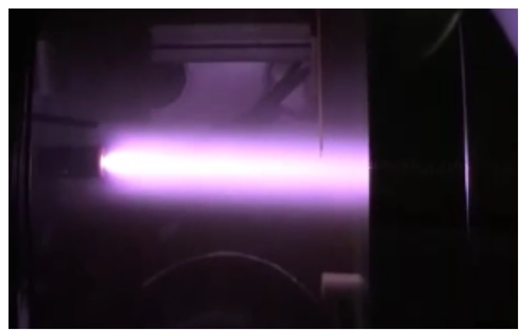




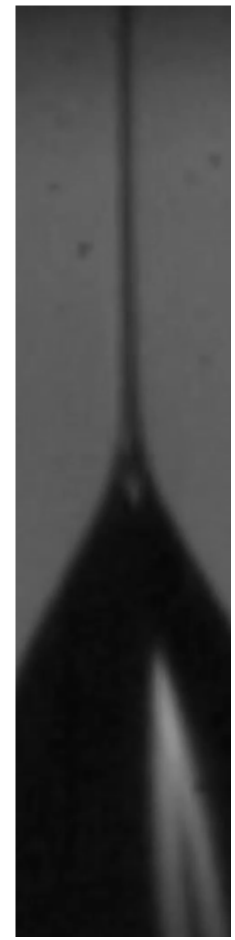


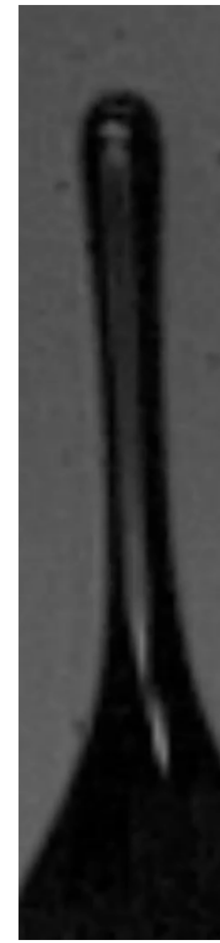
Plasma Thrusters & Cathodes





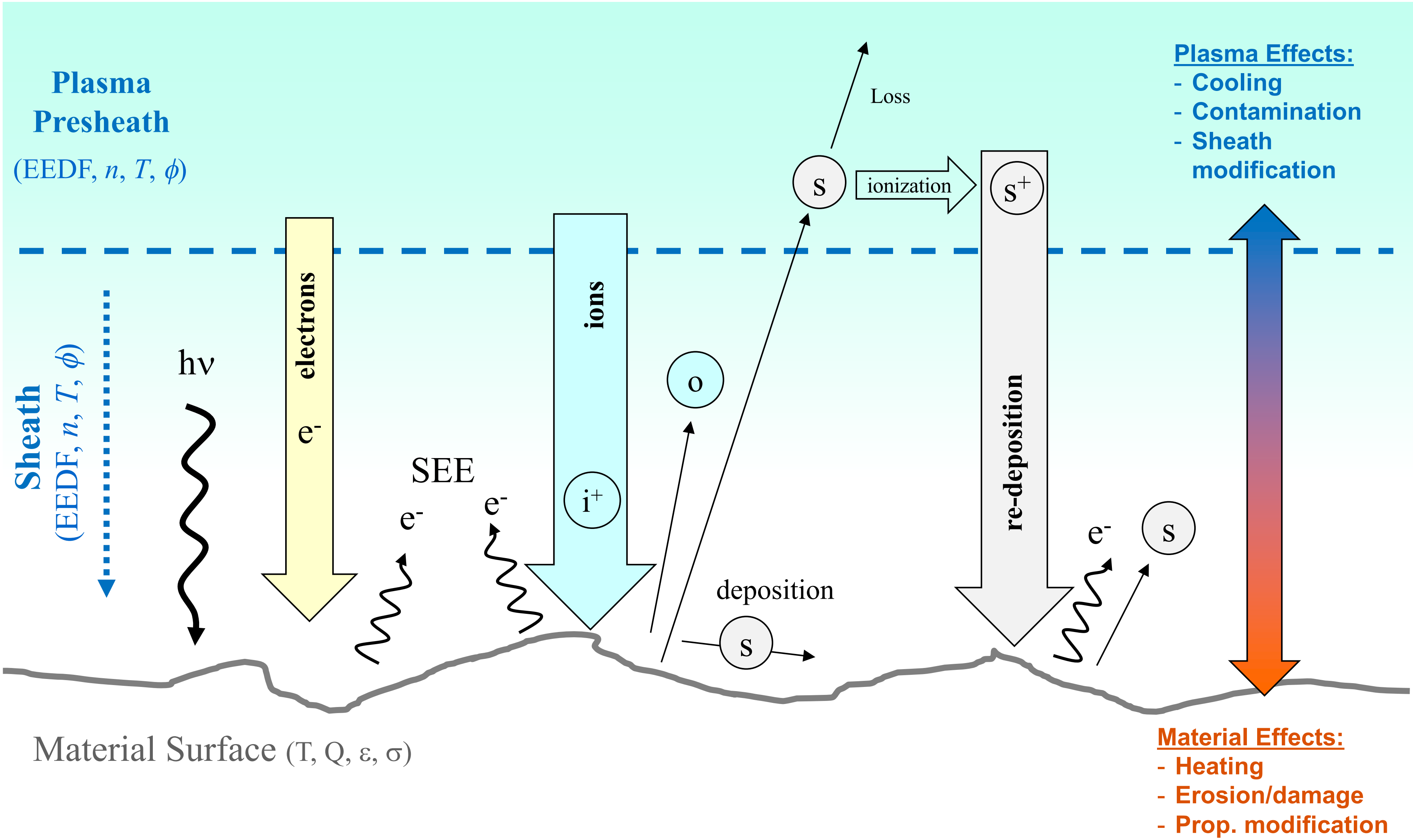
Electrospray Thrusters



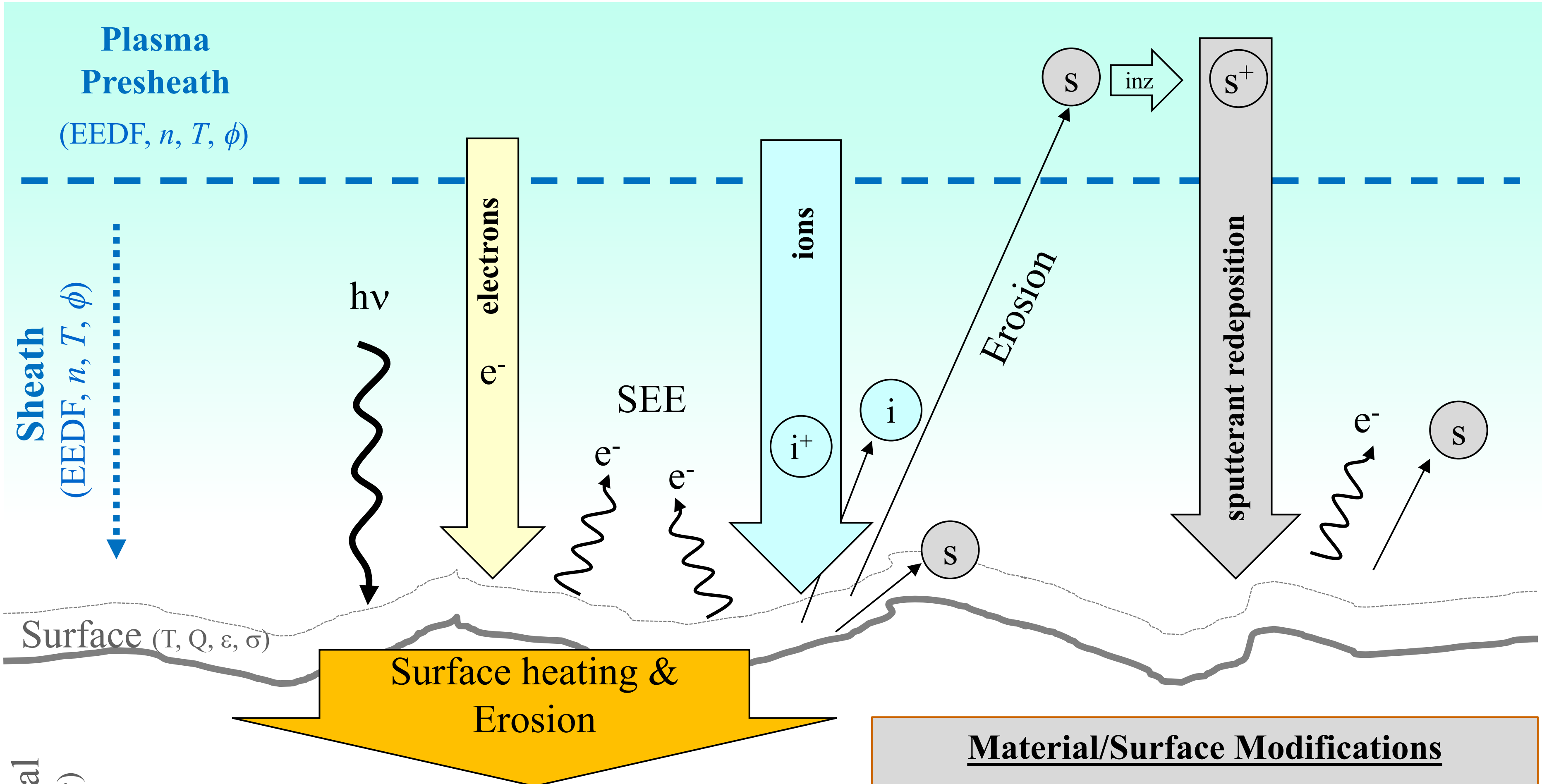


PLASMA-MATERIAL INTERACTION (PMI)

Plasma-Material Interaction (PMI)



Plasma-Material Interaction (PMI)



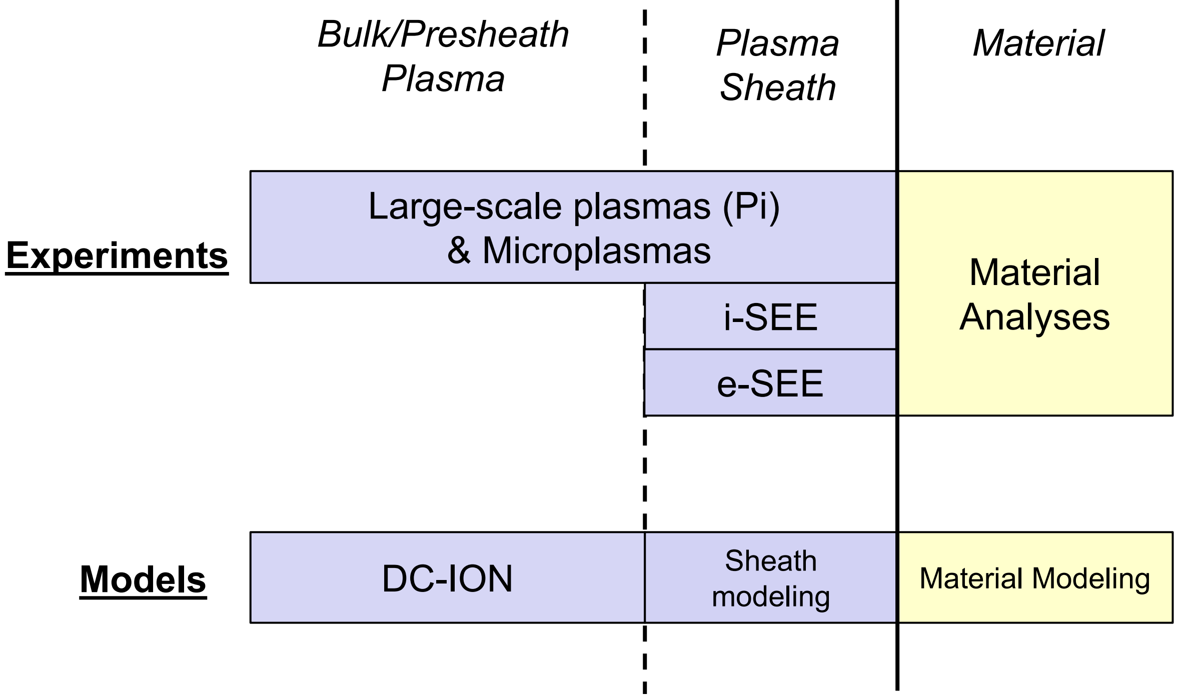
Species	~Power (W/cm²)
i^+ (~2-50 eV)	**0.3**
e^- (~2-10 eV)	**0.5**
hν (~12 eV, AR-VUV)	**0.3**

Material/Surface Modifications

Material Properties: Quality factor (Q), permittivity (ε), conductivity (σ)

Kinetic Mechanisms: Sputter, deposition/redeposition, deformation, fracture, flaking, evaporation, etc.

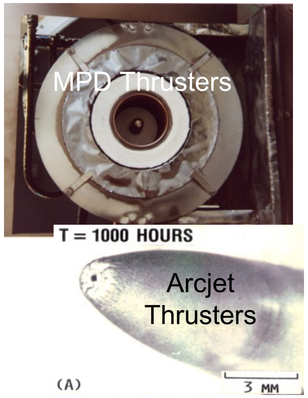
PMI Experimental and Modeling Efforts

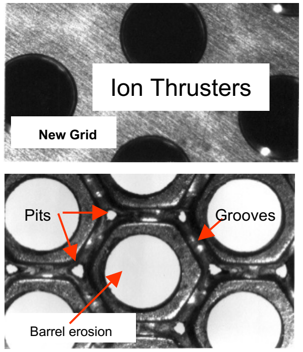


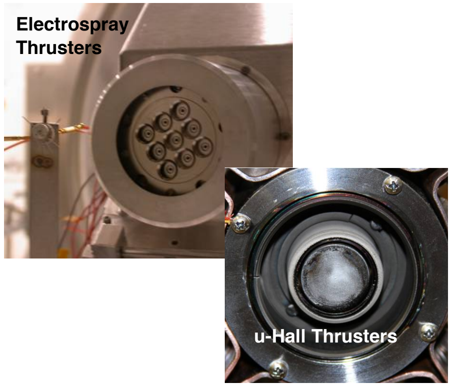
Pi = UCLA Plasma-Interactions Facility
PMI = Plasma Material Interactions

PMI Applications

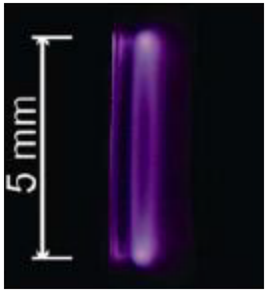
- **Electric Propulsion**

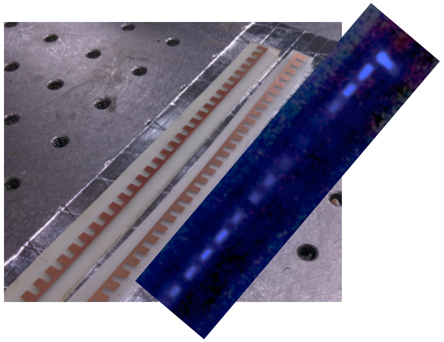


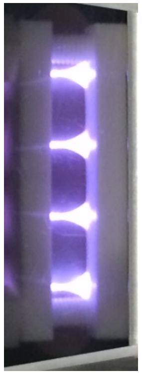




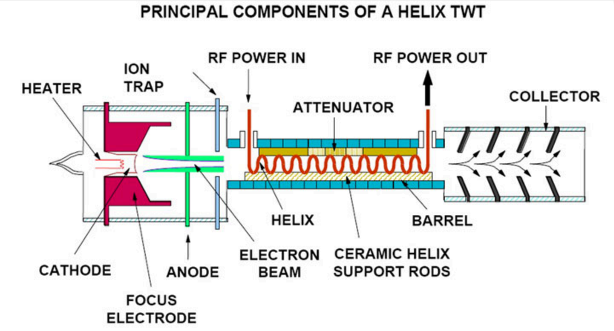
- **Microplasmas**
  - **AFOSR MURI: "Plasma-Based Reconfigurable Photonic Crystals and Metamaterials"**
    - **Stanford, Penn State, Texas, Tufts, UCLA, UW**







- **Other**
  - **TWTs, Gyrotrons, High Power Microwave (HPM)**
  - **Fusion devices**



PMI Diagnositcs & Modeling

- Diagnostics

	Diagnostic	Measurement
intrusive	Langmuir probes	n_e, T_e
	Faraday probe	1-D ion energy/flux
	Emissive probes	plasma ϕ
	$E\times B$ probe	species mix
	Retarding Potential Analyzer (RPA)	ion energies
non-intrusive	Quartz Crystal Microbalance (QCM)	differential/angular sputter
	Emission Spectroscopy (OES)	relative species properties
	Laser Ti:Sapphire (+ doubler)	species properties/motion
	Micro-ion gauges	neutral density
	Residual Gas Analyzer (RGA)	partial gas densities
	Long Distance Microscopy (LDM)	surface morphology/imaging
	High Speed Videography	Imaging, visual analysis
	Ex-situ: SEM, EDS, XRD, profilometry, precision scale	surface imaging, composition, mass loss

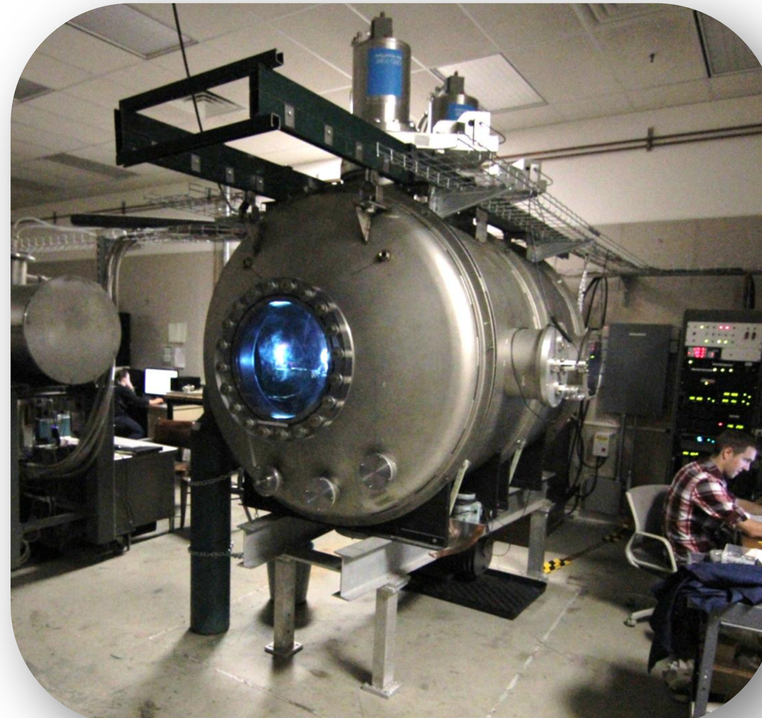
- Modeling
  - Plasma Confinement
    - Multi-species
    - Multi-physics
    - 2D/3D
  - Ion Extraction and species interactions
    - i-n
    - MEX
    - CEX
  - Plasma-Material Interactions
    - e-SEE, i-SEE, i-n
    - Sputtering
  - Device Performance and Lifetime

UCLA: Plasma-interactions (Pi) Facility

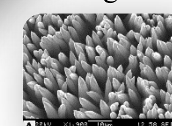
UCLA-Pi Facility: Examine the behavior of materials for a wide range of plasma conditions

Parameter	Range
Plasma density	~10^{15} to10^{18} m^{-3}
Electron temperature	1 to 10 eV
Ion energy	10 to 400 eV
Ion flux to target*	10^{21} to 10^{23} m^{-2}s^{-1}
Target area	≈5 cm^2

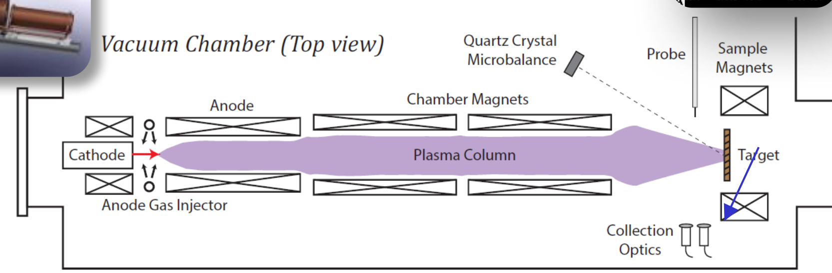
	Diagnostic	Measurement
intrusive	Langmuir probes	n_e, T_e
intrusive	Faraday probe	1-D ion energy/flux
intrusive	Emissive probes	plasma ϕ
intrusive	$E \times B$ probe	species mix
intrusive	Retarding Potential Analyzer (RPA)	ion energies
non-intrusive	Quartz Crystal Microbalance (QCM)	differential/angular sputter
non-intrusive	Emission Spectroscopy (OES)	relative species properties
non-intrusive	Laser Ti:Sapphire (+ doubler)	species properties/motion
non-intrusive	Micro-ion gauges	neutral density
non-intrusive	Residual Gas Analyzer (RGA)	partial gas densities
non-intrusive	Long Distance Microscopy (LDM)	surface morphology/imaging
	Ex-situ: SEM, EDS, XRD, profilometry, precision scale	surface imaging, composition, mass loss



Target



Plasma Source

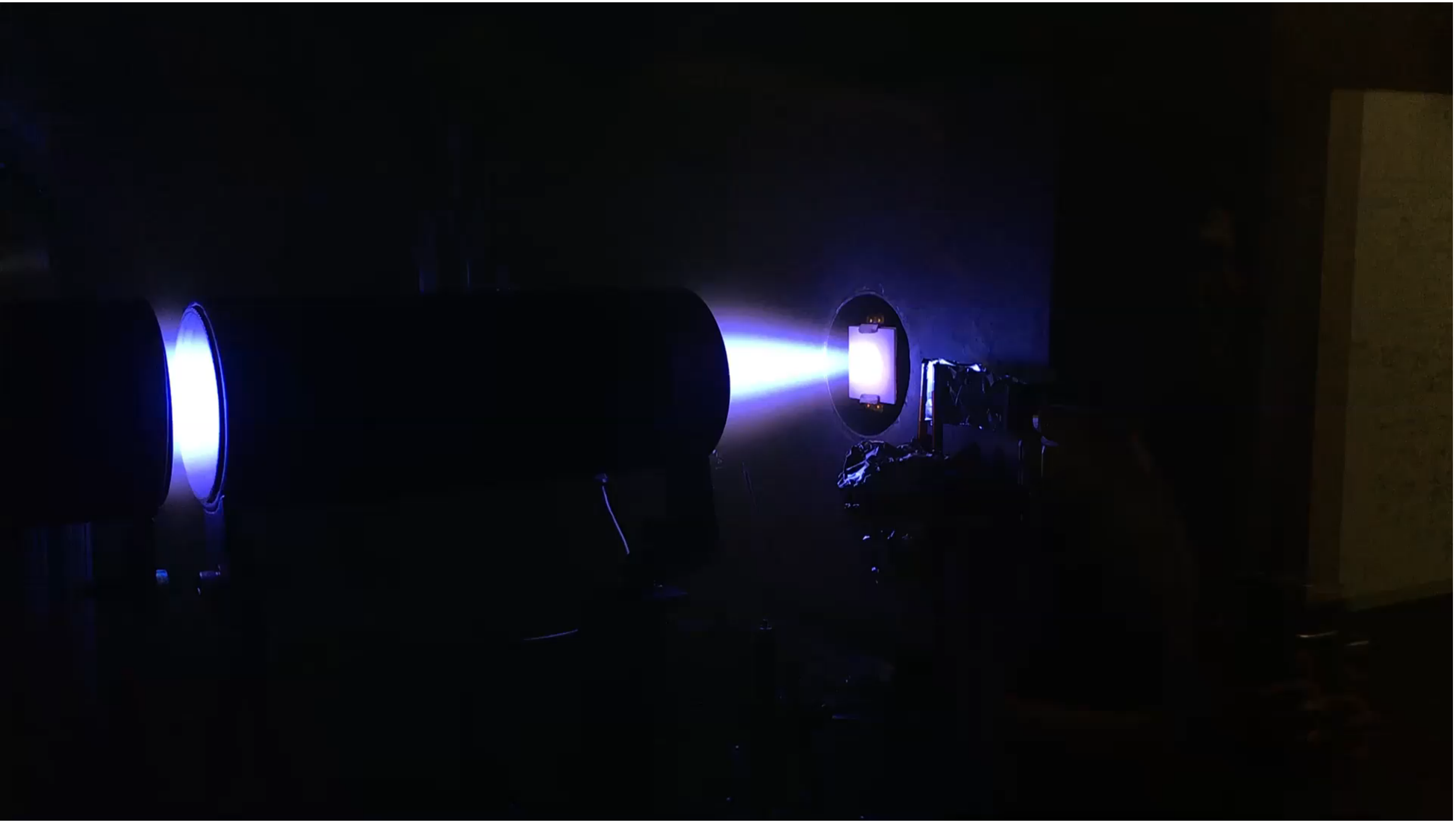


AFOSR DURIP, FA2386-13-1-3018

Matlock, Goebel, Conversano, Wirz, *PSST* (2014)

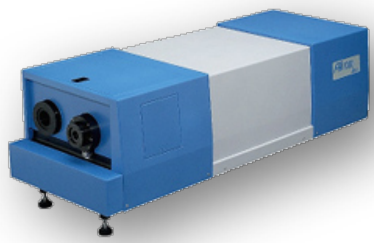
Pi Facility Operation

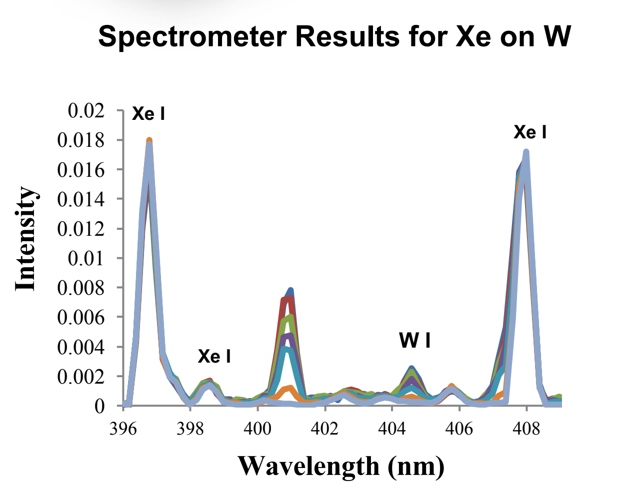
<u>Movie:</u> Pi Facility in operation. Target at far right, source at far left.



Many Eyes…

Long focal length spectrometer w/ CCD and PMT detection (Horiba FHR1000)

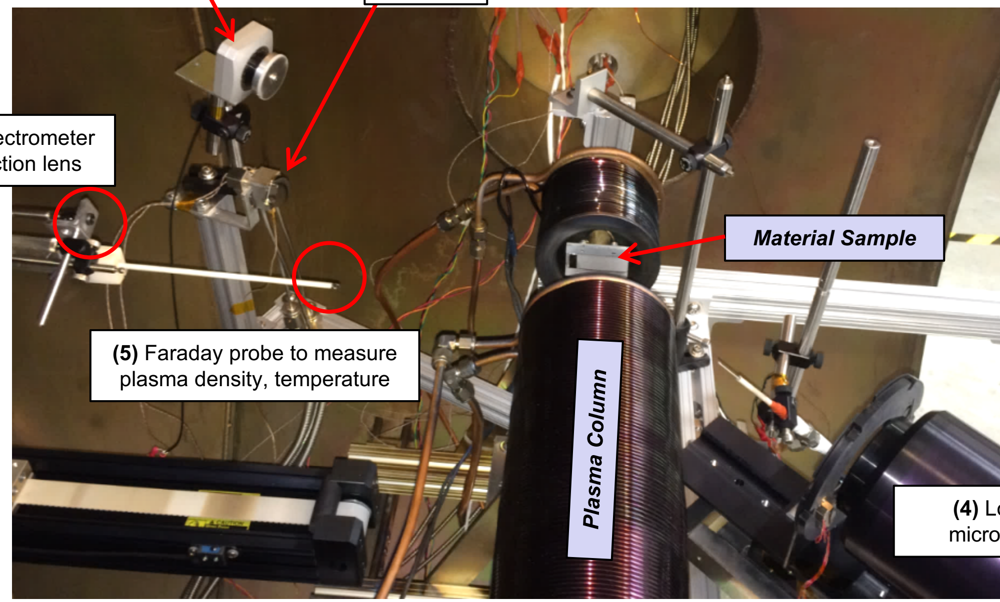




(2) Witness plate on rotary stage for time-resolved composition measurements

(3) QCM

(1) Spectrometer collection lens

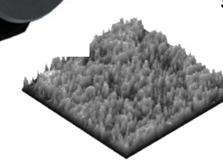


(5) Faraday probe to measure plasma density, temperature

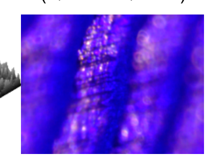
(4) Long distance microscope (LDM)

(6) Ti: Sapphire Laser System

Monitors material topology *in-situ* (Questar QM100)



3D profilometry



In-situ image

Matlock T.S., Goebel D.M., Conversano R., Wirz R.E., "A dc plasma source for plasma–material interaction experiments," *Plasma Sources Sci. Technol.* 23 (2014) 025014 (11pp)

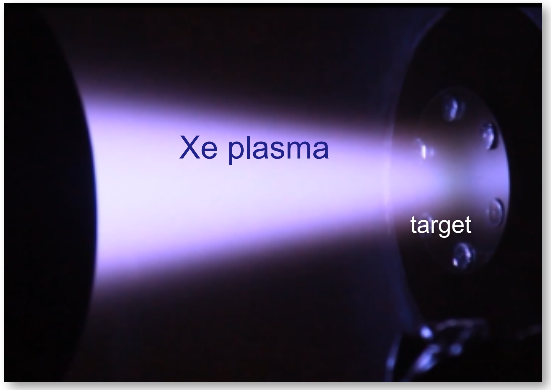
The need for non-intrusive diagnostics

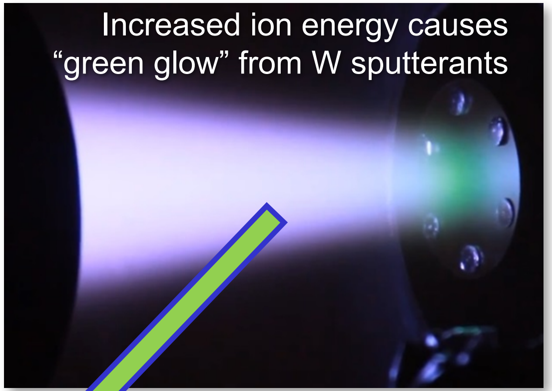
YouTube Link: https://www.youtube.com/watch?v=RxRyxiMQt5M

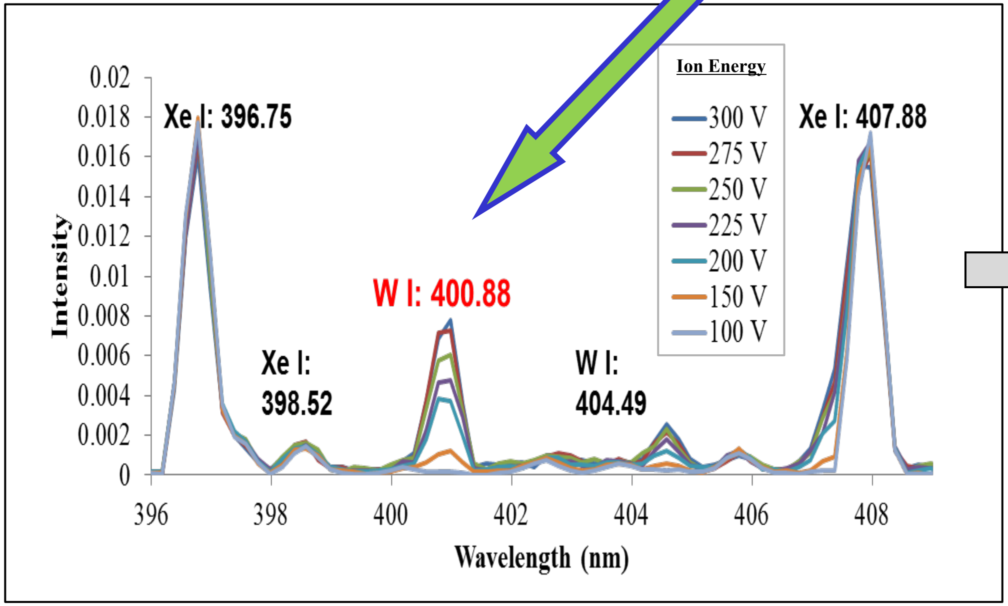
<u>Movie 1:</u> shows electrostatic probe disturbing the plasma in the Pi Facility very near the target surface

YouTube Link: https://www.youtube.com/watch?v=6k_X5q5IUWQ

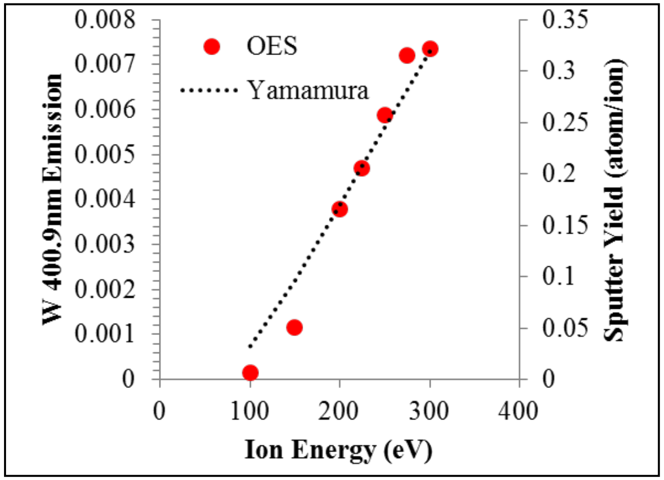
<u>Movie 2:</u> shows "green glow" of sputtered atoms excited near the target surface



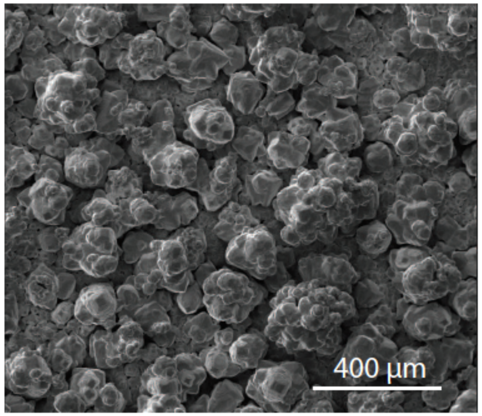




Li G., Wirz R., *Physics of Plasmas,* in prep (2016)



Y. Yamamura & H. Tawara, *Atomic Data & Nucl. DataTables*, **62**, 149-253 (1996)



PMI
FOR
MICRO-ARCHITECTURED SURFACES

Dr. Chris Dodson

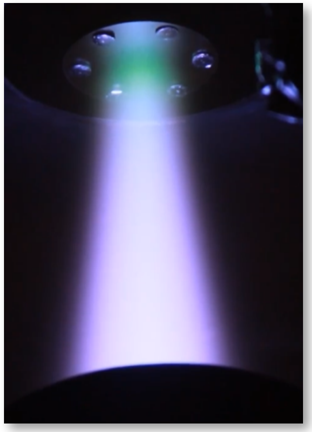
Cesar Huerta

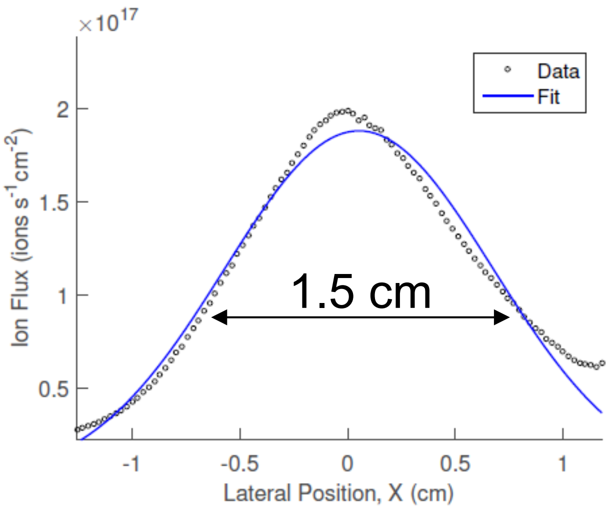
Gary Li

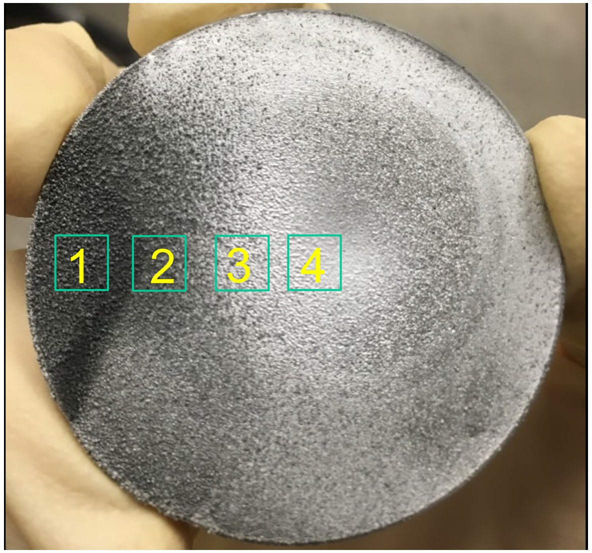
Ani Thuppul

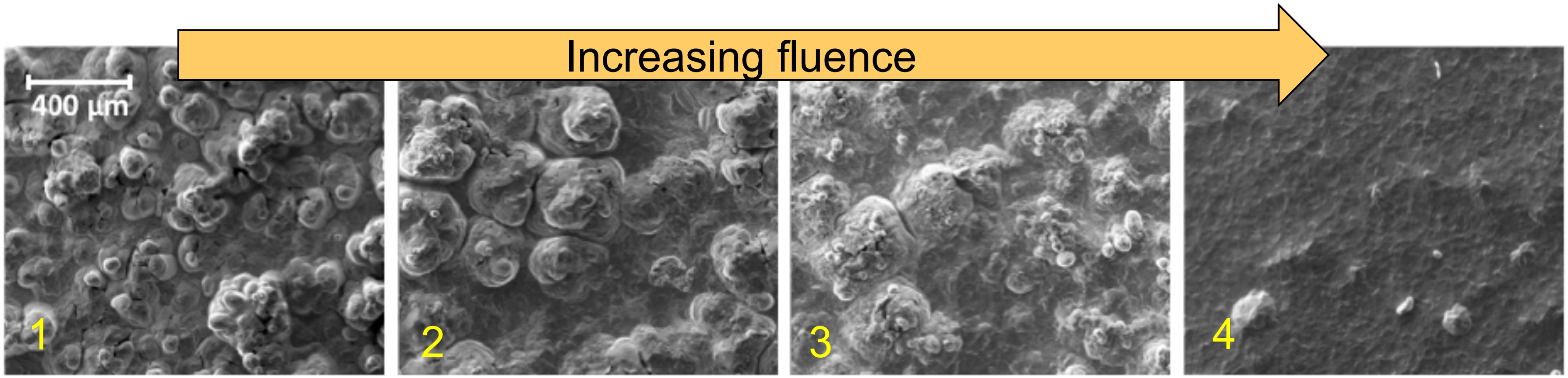
Angelica Ottaviano

Radial fluence variation







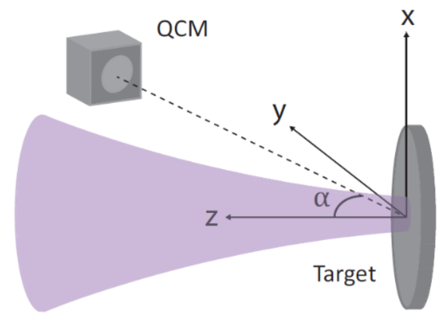


Note: Radial flux gradient enables analysis of multiple sites across the surface that experience different levels of fluence over during plasma exposure. Thus providing greater insight into material lifetime and erosion mechanisms.

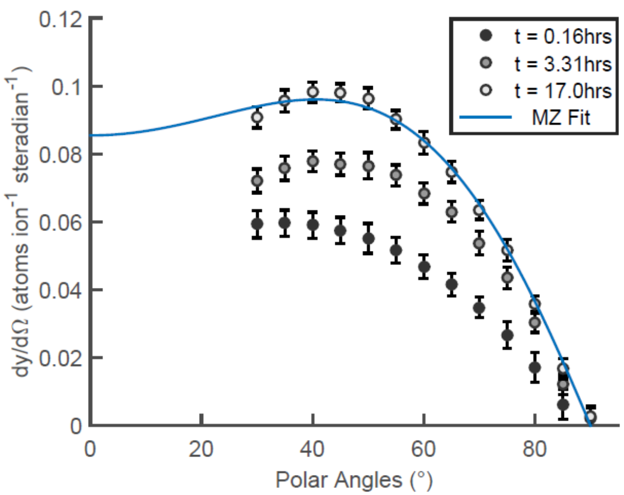
Matthes, C., Ghoniem, N., Li, G., Matlock, T., Goebel, D., Wirz, R. Fluence-dependent sputtering yield of micro-architectured materials, *(Appl. Surf. Sci.) 2017*

Sputtering Yield Analysis: QCM

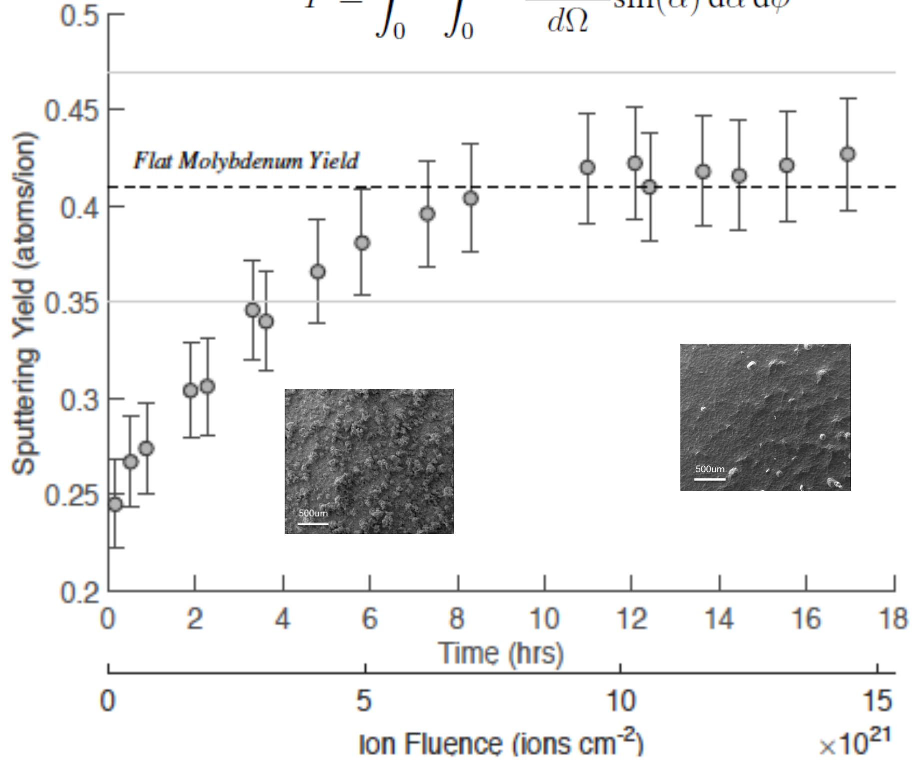
- **QCM diagnostic provides the <u>first-ever</u> in-situ measurements of sputtering yield for a microarchitectured surface**
- **Shows reduction in sputtering yield for more highly featured surfaces**



$$\frac{dy(\alpha)}{d\Omega} = \underbrace{\left(R(\alpha)A_s\frac{N_A}{m}\right)}_{\text{sputtered atoms incident on QCM}} \Big/ \underbrace{\left(\frac{J_t}{e}\right)}_{\text{ions incident on target}} \Big/ \underbrace{\left(\frac{A_s}{r_{qcm}^2}\right)}_{\text{solid angle subtended by QCM}}$$



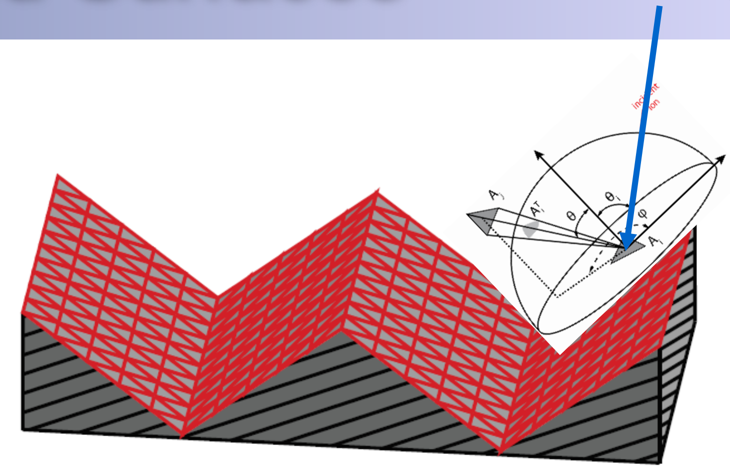
$$Y = \int_0^{2\pi}\int_0^{\pi/2}\frac{dy(\alpha)}{d\Omega}\sin(\alpha)\,d\alpha\,d\phi$$

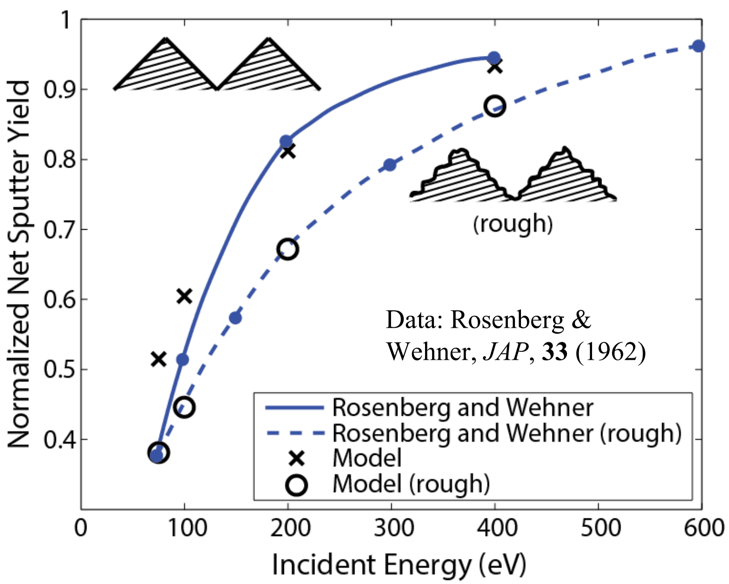


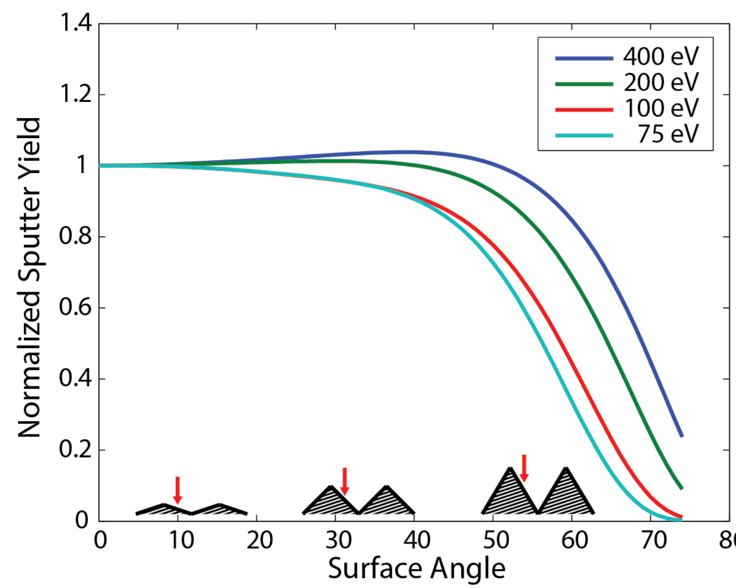
Li, G., Matlock, T., Goebel, D., Matthes, C., Ghoniem, N. , Wirz, R., *Plasma Sources Science Tech* (2017)

Modeling PMI for Featured Surfaces

- Technique
  - Monte Carlo VF sputtering erosion model
- Results
  - Reduction in net erosion with featured surfaces due to <u>sputter-deposition</u>
  - Increased erosion with surface pitch

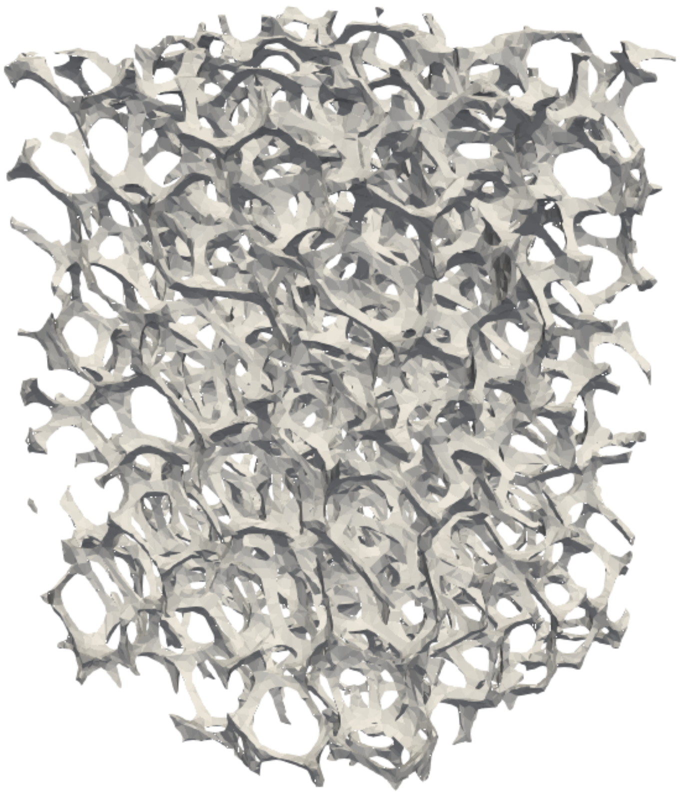


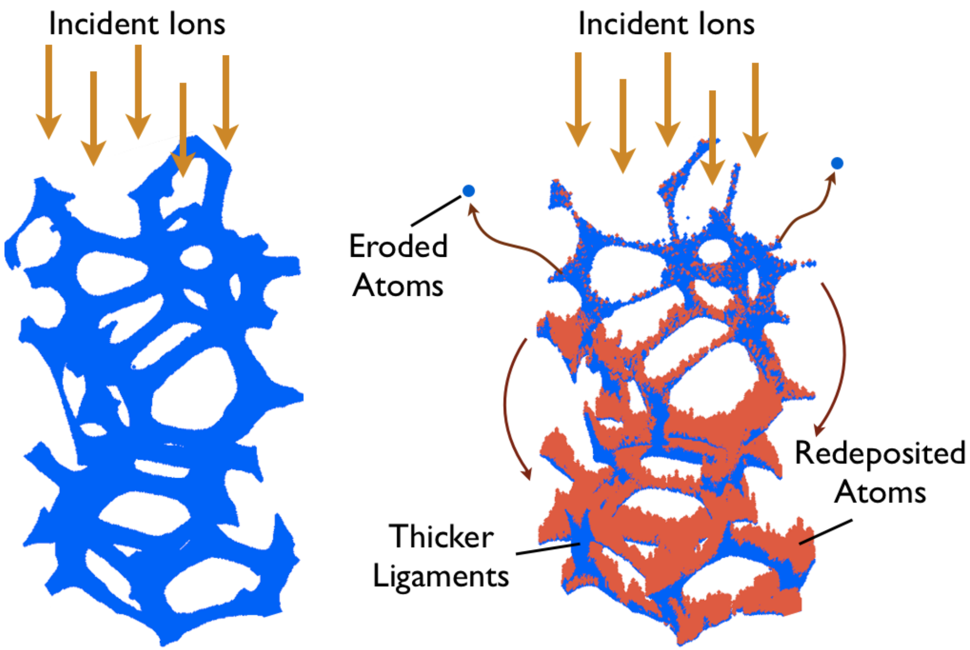




Huerta C.E., Matlock T.S., Wirz R.E., *J. Appl. Phys.* 119, 113303 (2016)

Plasma-Resilient Foams?



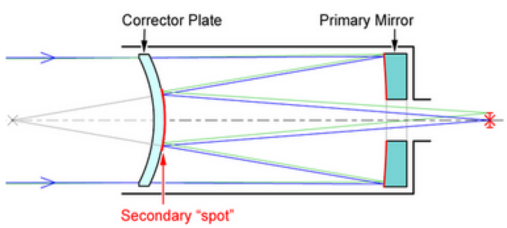


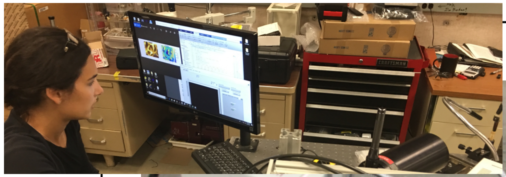
Ghoniem, Marian, Po, Wirz,
"Resilient Self-Healing Materials for the Extreme Environment of Space Electric Propulsion & Power," AFOSR Aug 2018

Long-Distance Microscopy (LDM)

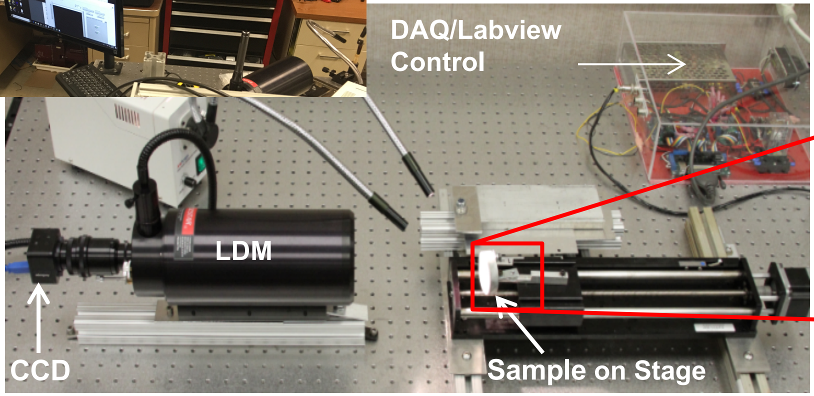
- Objective: In-situ observation of material response to plasma
- Capabilities:
  - Enables in-situ high-resolution imaging of surface structures
  - Focus variation profilometry (FVP) enables height maps and image reconstruction (see next slide). Used to track surface morphology changes in-situ
  - 2.8 µm lateral resolution, 33 µm depth of field @ 650 nm
  - < 2.8 µm height resolution

Maksutov-Cassegrain Design



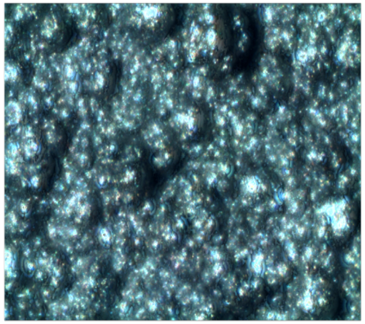


Benchtop Development

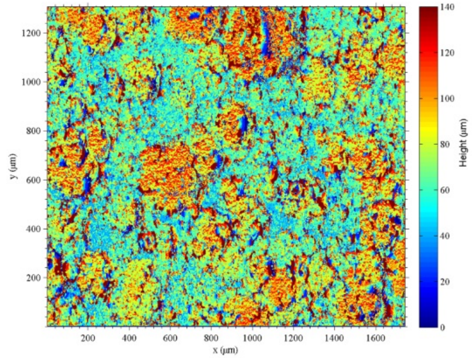


Microarchitectured Sample

Reconstructed Image

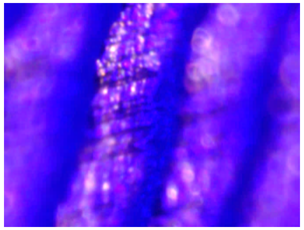


Surface Height Map



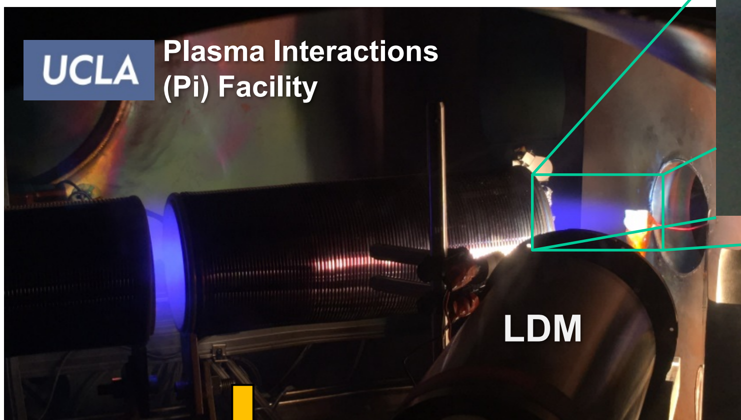
- Challenges to Long-Distance Microscopy
  - Stabilization: vibrations, thermal drifts
  - Lighting
  - Image processing difficult for highly-structured surfaces

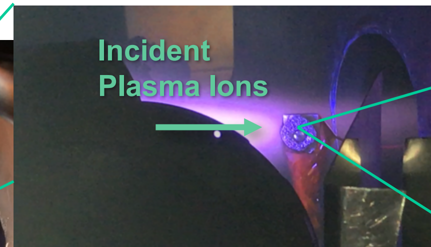
Plasma In-situ imaging

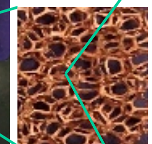


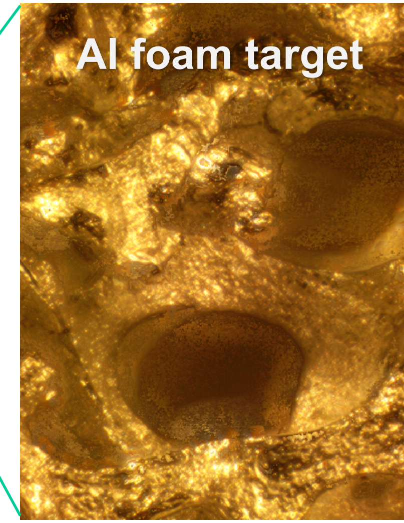
In-Situ Observation of Plasma-Foam Interaction

- **First-ever *in-situ* observation of plasma interaction with a textured surface**
- 17-hour plasma exposure (300 V ions)



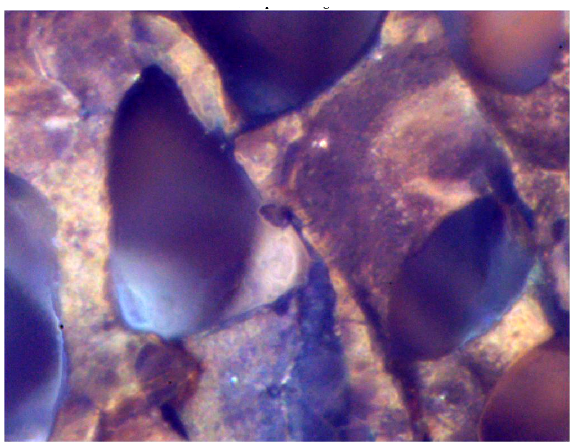




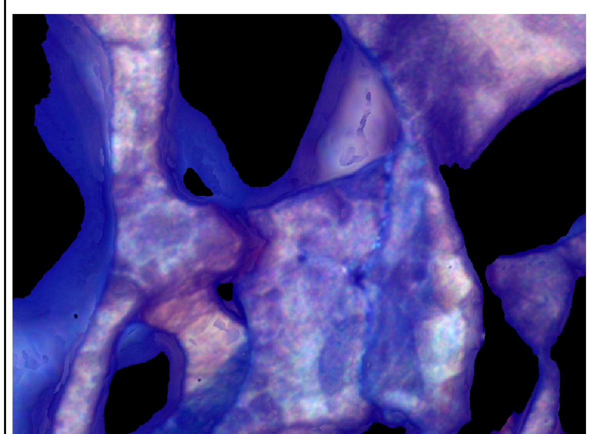


Wirz R.E., et al., "Long Distance Microscopy of Plasma Facing Surfaces," Under preparation for *JVST* (2018)

Composite 3D video of images from LDM Focus Variation Profilometry

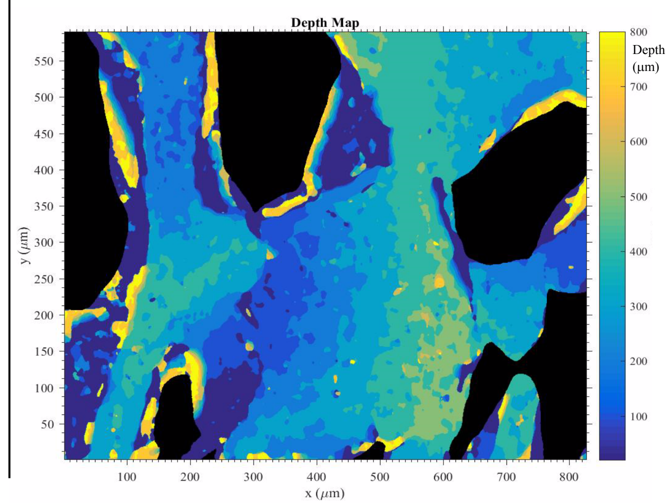


3D Video after stabilization, normalization, and filtering



Depth Map 3D Video

100 microns



Plasma-Material Interactions…

Dr. Marlene Patino

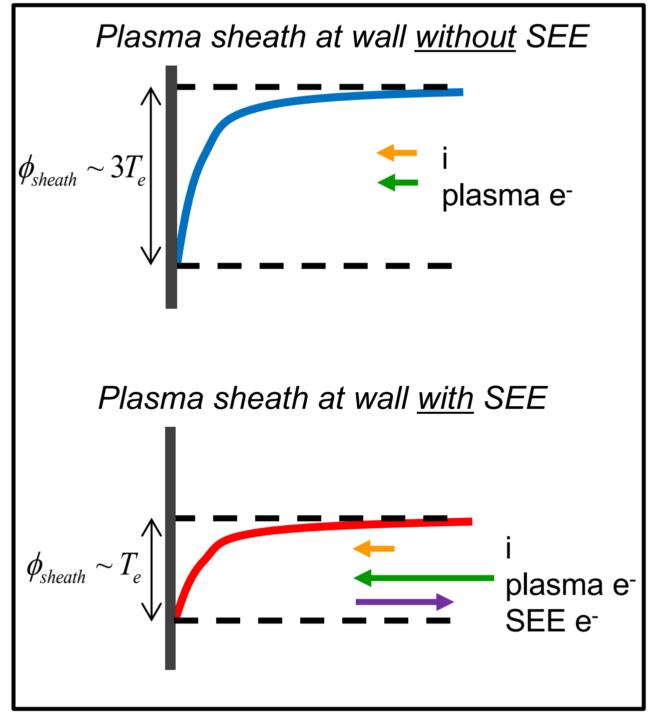
Secondary Electron Emission (SEE)

Cesar Huerta

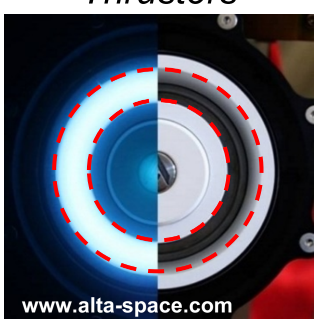
- **Reduced sheath potential in plasma devices**[1] (plasma thrusters,[2-4] plasma processing,[5-6] fusion[7-10])
  - →Increased plasma heat flux to the wall
  - →Increased power losses

$$\phi_{sheath} = T_e \ln\left[\frac{1-\delta}{\sqrt{2\pi m_e/m_i}}\right]$$

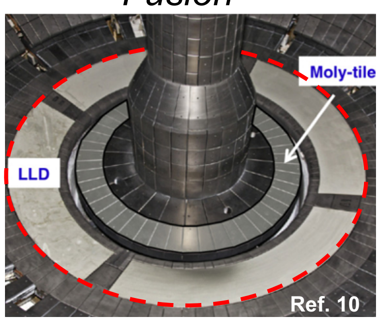
- **e^- multipacting & cloud formation in accelerators**[11-12]
  - → beam instabilities & overheating



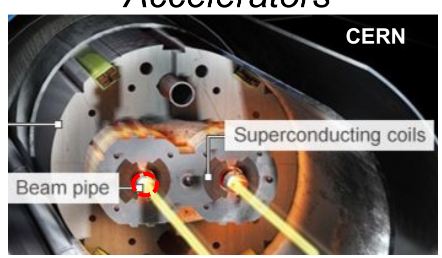
Thrusters



Fusion

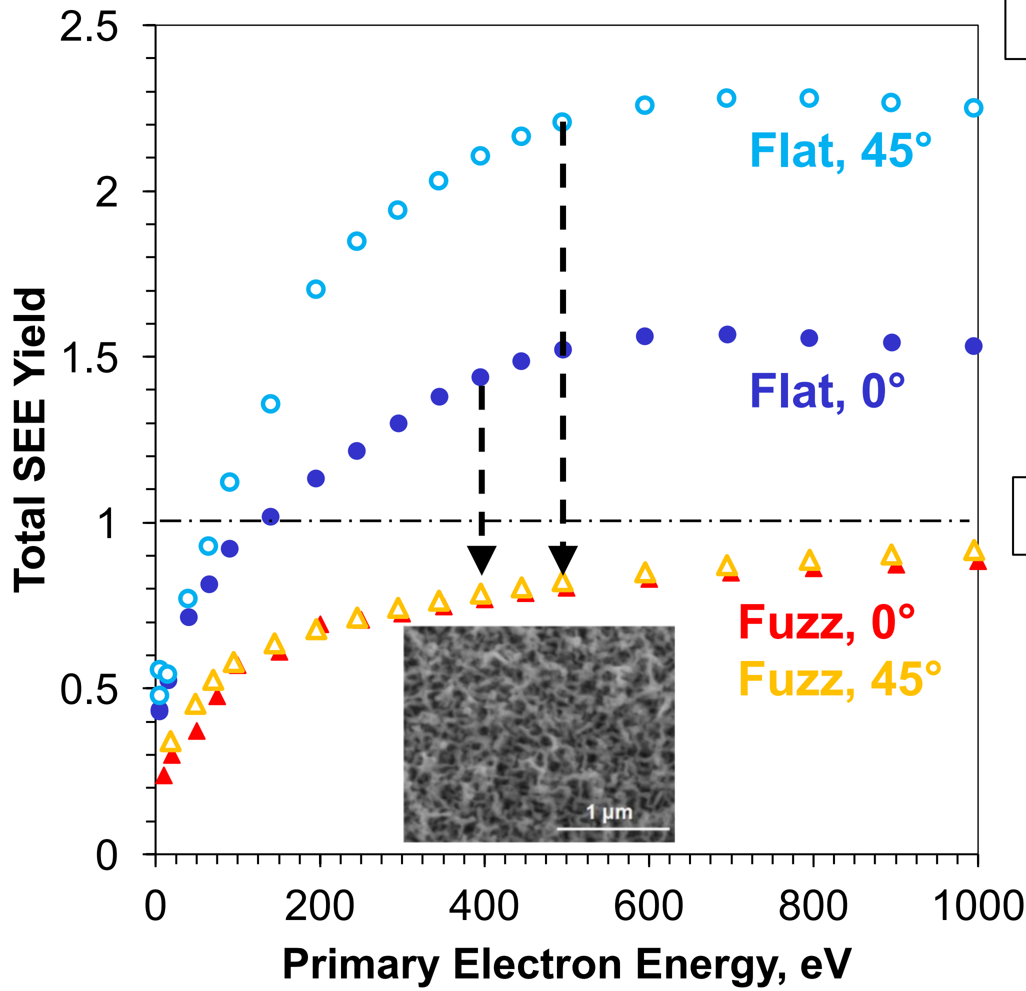


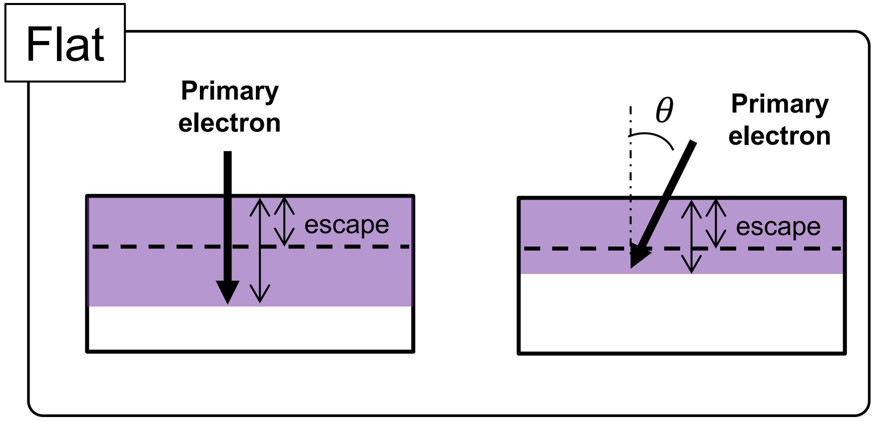
Accelerators

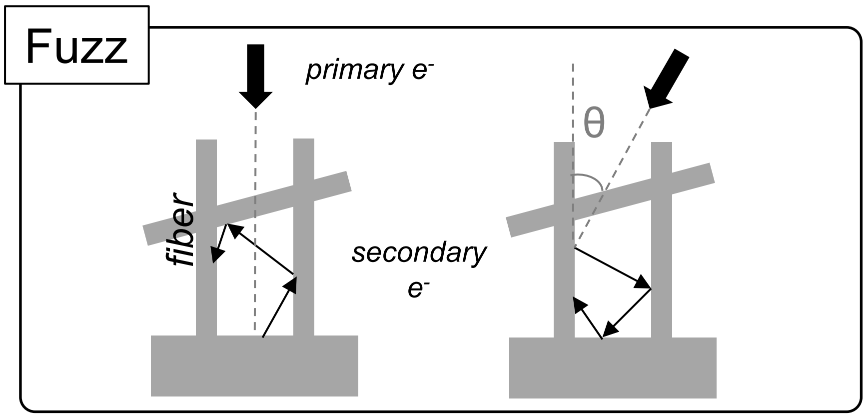


[1] Hobbs G D, Wesson J A, *Plasma Phys.***9** (1967)
[2] Raitses Y, et al., *Phys. Plasmas* **13** (2006)
[3] Raitses Y, et al., *IEEE Trans. Plasma Sci.***39** (2011)
[4] Sydorenko D, et al., *Phys. Plasmas* **15** (2008)
[5] Perry A J, et al., *J. Vac. Sci. Technol. B* **9** (1991)
[6] Goree J, *Plasma Sources Sci. Technol.* **3** (1994)
[7] Farhang H, et al., *J. Phys. D: Appl. Phys.* **26** (1993)
[8] Gunn J P, *Plasma Phys. Control. Fusion* **54** (2012)
[9] Lee W, Krasheninnikov S I, *Phys. Plasmas* **20** (2013)
[10] Ono M, et al., *Fusion Eng. Des.* **87** 1770 (2012)
[11] Cimino R, et al., *Phys. Rev. Lett.*, **93** 014801 (2004)
[12] Cimino R and Demma T, *Int. J. Mod. Phys. A*, **29** 17 (2014)

e-SEE, for tungsten "fuzz"





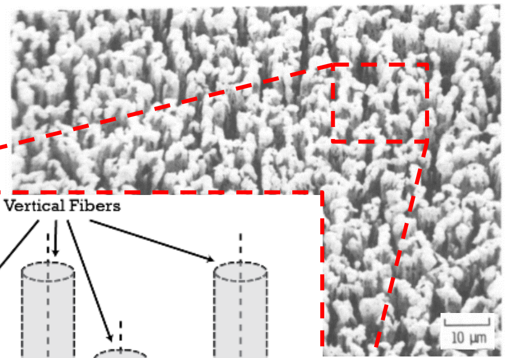


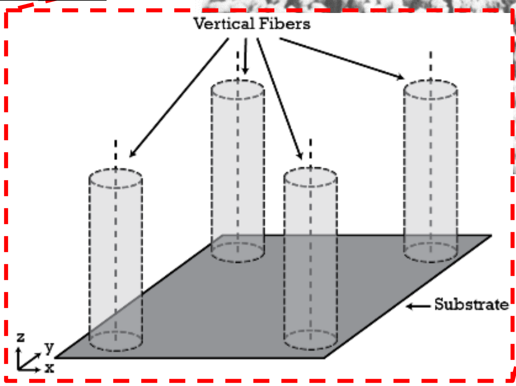
Patino M.I., Raitses Y., Wirz R.E., "Secondary Electron Emission from Nanostructured Tungsten Fuzz Formed on Smooth Tungsten," *Applied Physics Letters*, Nov 2016

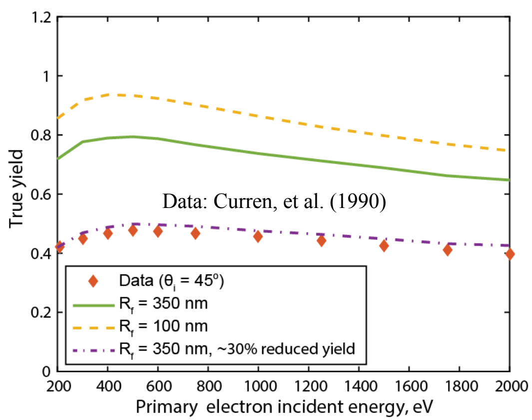
PMI: e-SEE modeling (results)

Multi-dimensional Monte Carlo model developed to predict e-SEE for featured surface geometries

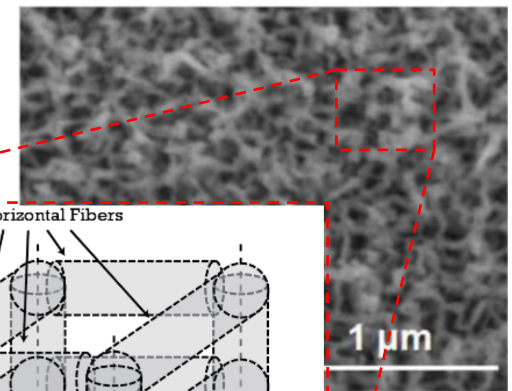
Copper carpet

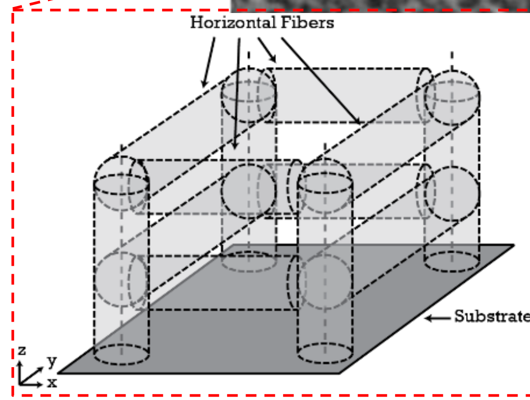


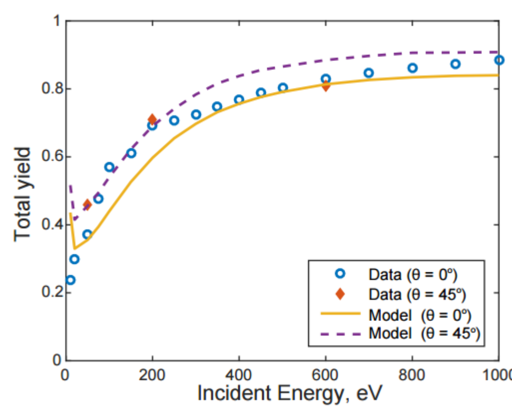


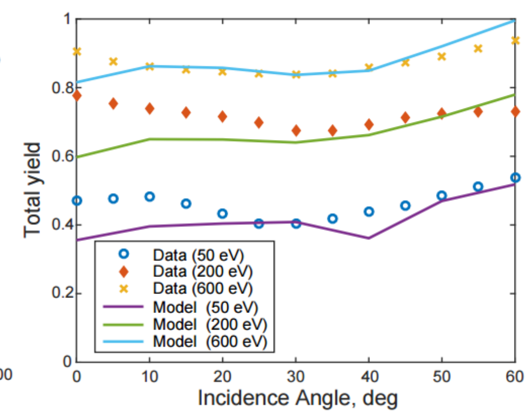


Tungsten fuzz







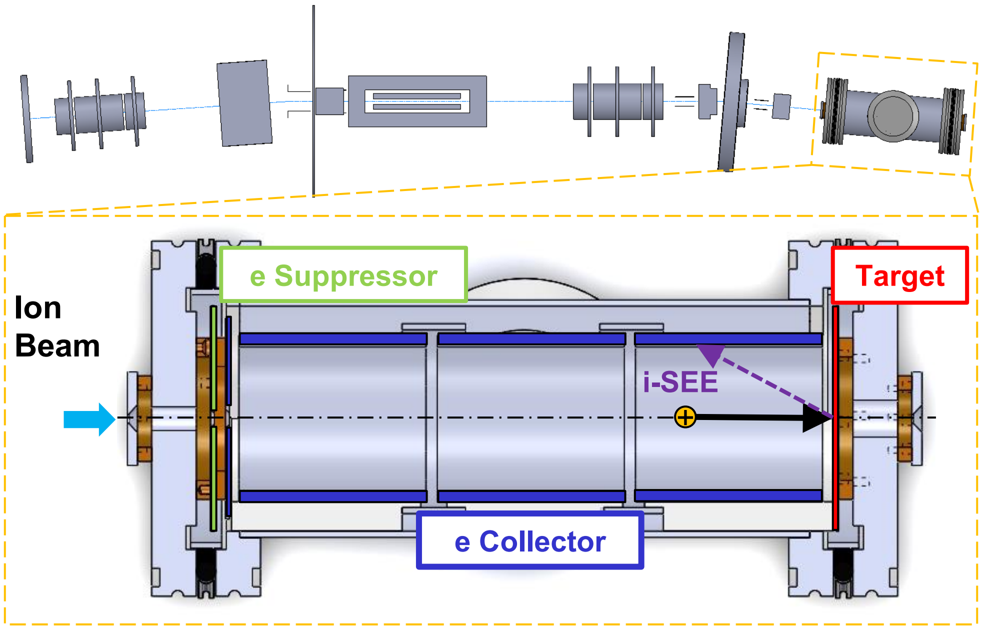


Huerta C.E., Wirz R.E., AIAA-2016-4840 (2016)
Huerta C.E., Patino M., Wirz R.E., *J. Phys. D: Appl. Phys.* , 2017

i-SEE Experiment

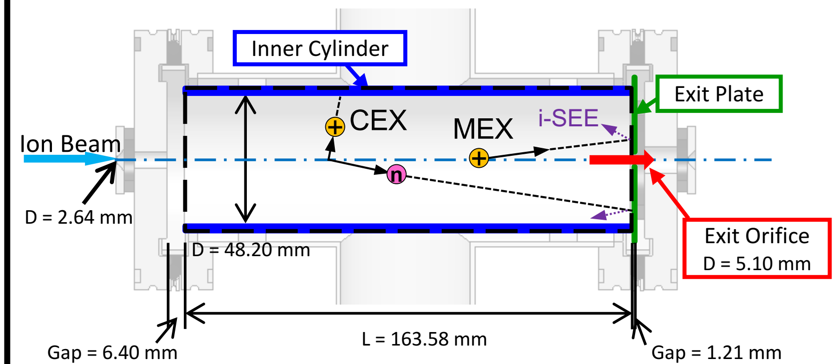
Objective: Characterize ion-induced SEE (i-SEE) for relevant plasma environments.

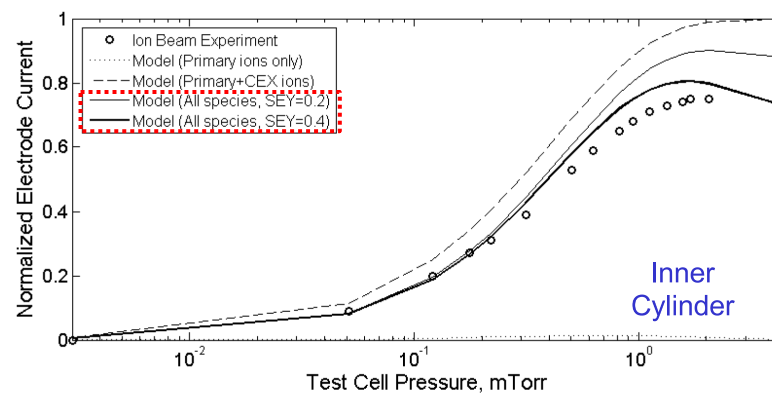
Approach: Use canonical "test-cell" experiment to assess i-SEE in controlled environment



- HV (10^{-8}Torr) facility with mass analyzed ion beam (0.5-2keV)
- Materials under investigation
  - Graphite (calibration)
  - C velvet
  - SS-316
- Preliminary results, $\gamma_{1.5\text{keV Xe+ on SS-316}} \approx 0.3$
- Collaboration with Dr. Lee Johnson, JPL

Previous/related efforts: *Characterized ion-atom collision for validation of plasma models[1-5]*





Related output:

[1] Wirz et al. (2011) IEPC-2011-122

[2] Araki and Wirz (2011) AIAA-2011-3740

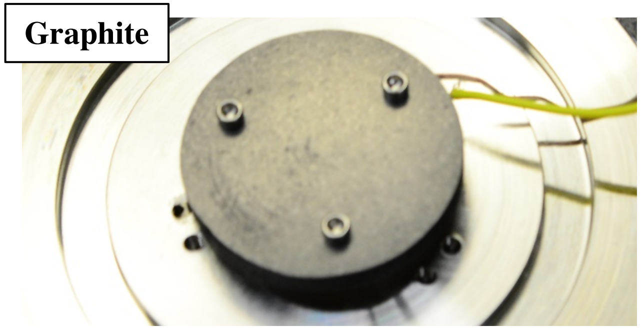
[3] Araki and Wirz (2013) *IEEE Trans. Plasma Sci.*, **41**, 3

[4] Giuliano and Boyd, (2013) *Phys. Plasmas,* **20**

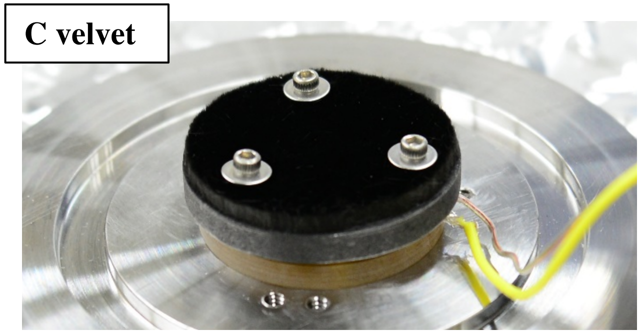
[5] Giuliano and Boyd, (2013) *J. Appl. Phys.*, **113**, 11

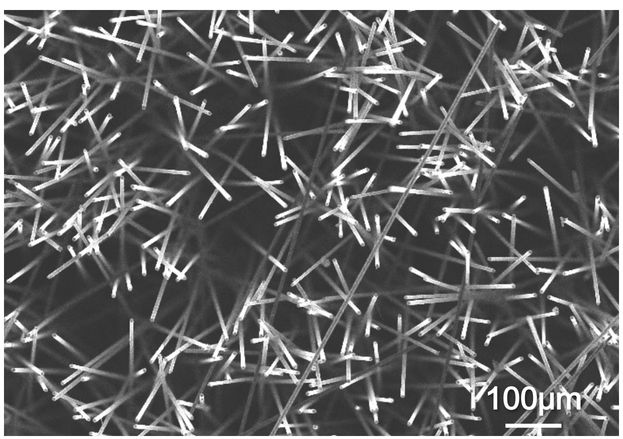
i-SEE, for carbon “velvet”

Graphite

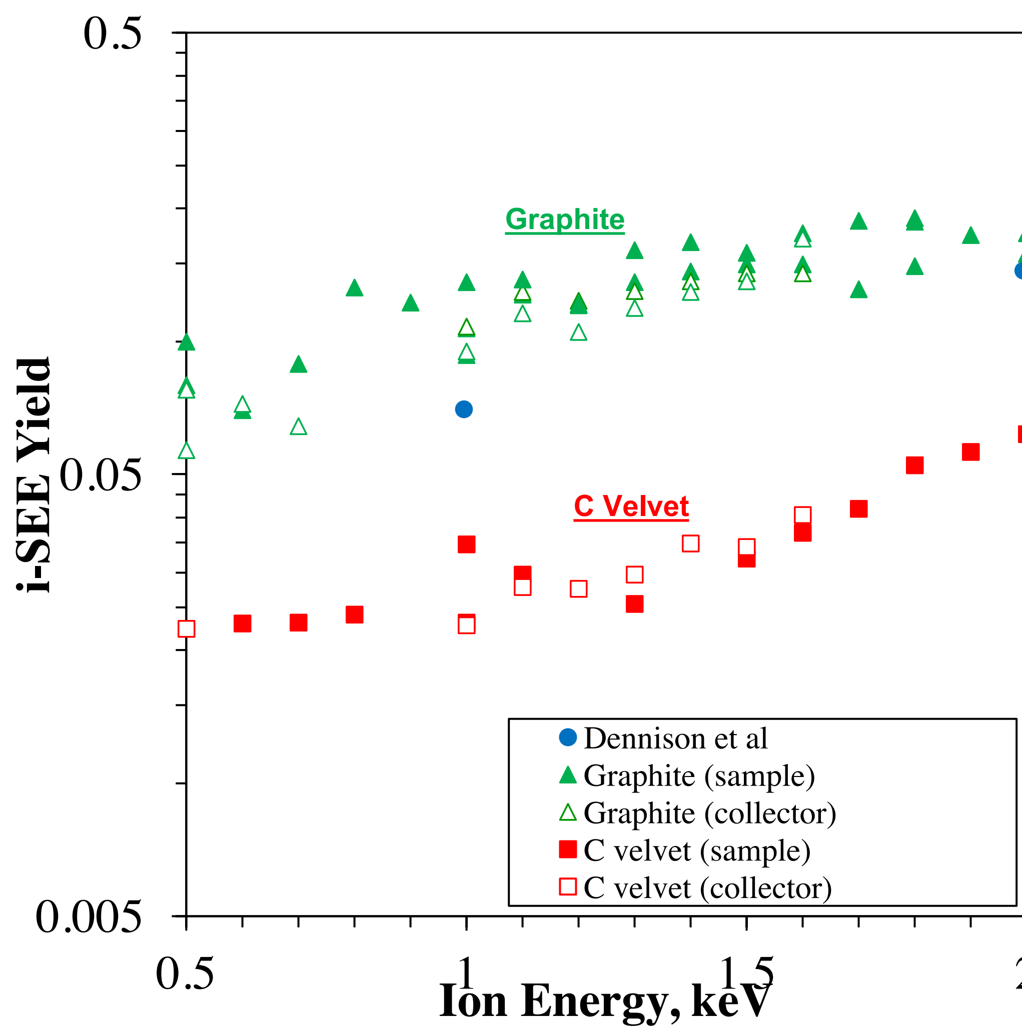


C velvet





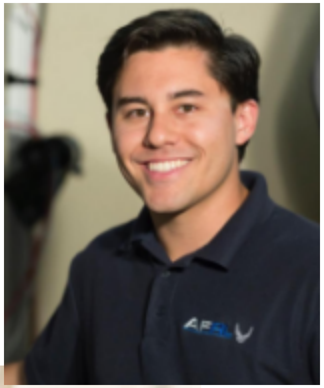
$L_{fiber} = 2.6mm$, $D_{fiber} = 6.8\mu m$



Dennison et al. (2003) *8th Spacecraft Charging Technology Conference*
Patino, Wirz, *Phys. Rev. Ltrs.*, (2018)

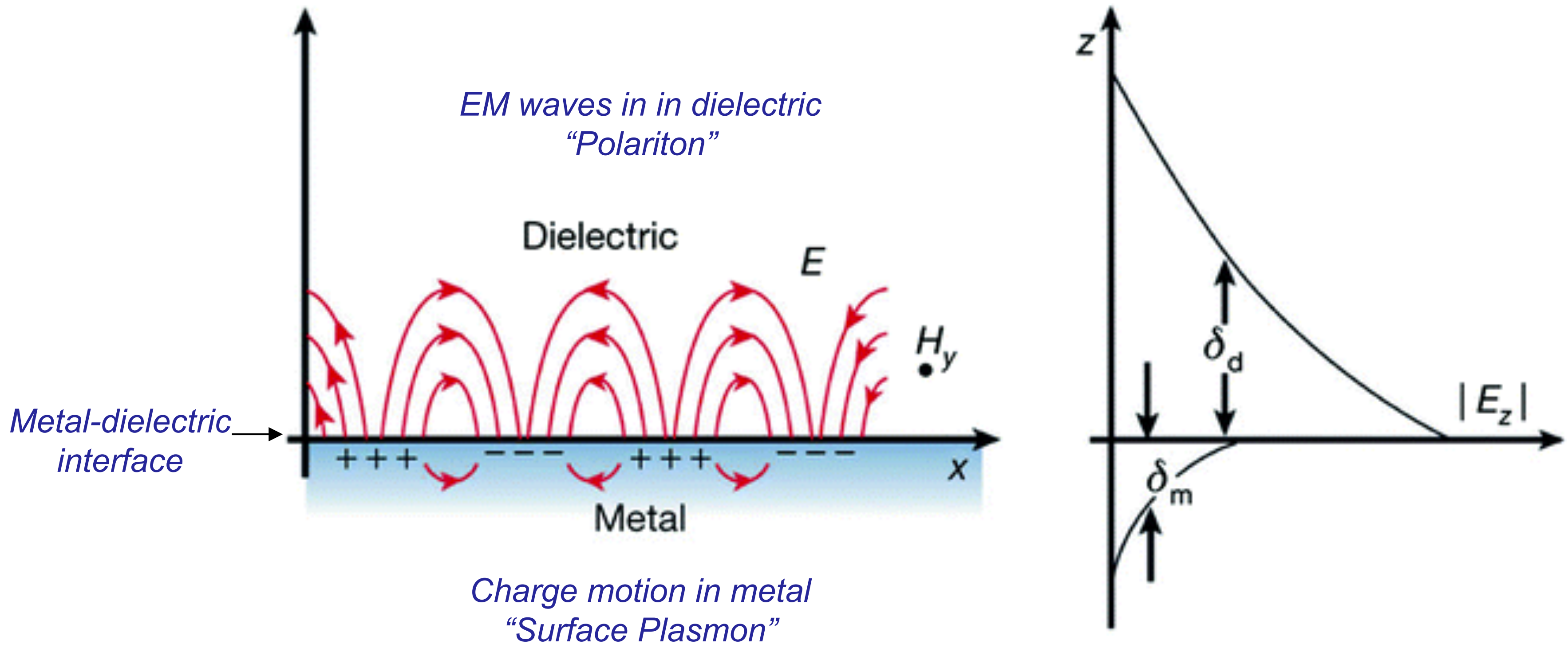
PLASMA METAMATERIAL INTERACTIONS

Nolan Uchizono



Stephen Samples

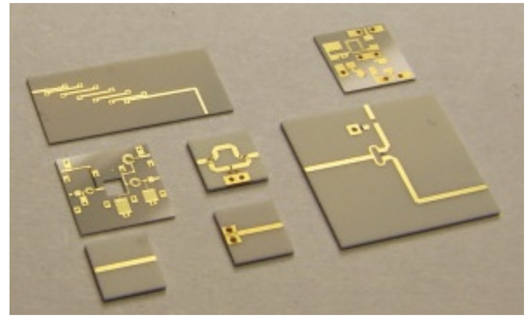
Surface Plasmon Polaritons (SPPs)

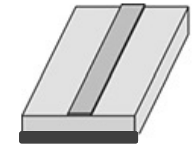


"Plasma-based reconfigurable photonic crystals and metamaterials" AFOSR MURI 2015
Stanford, UCLA, U. Texas, Tufts, Penn State, U. Washington

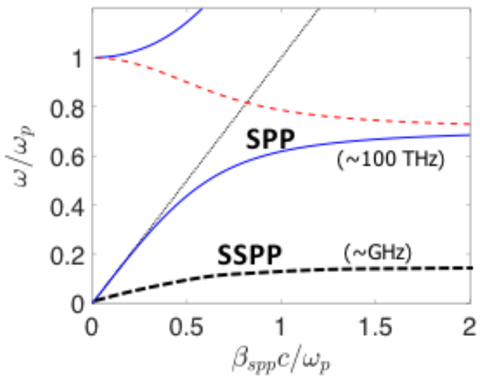
Plasma-Functionalized Metamaterials

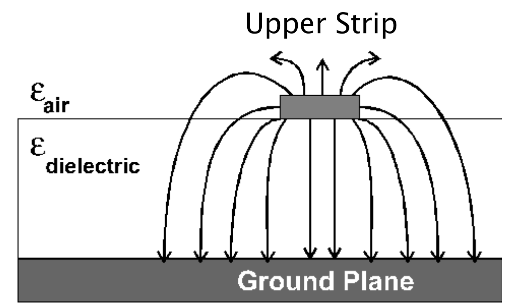
- Objective: Plasma-functionalization of metamaterial microwave circuit transmission lines
- Microstrip Waveguides: used commonly by microwave electronics for EM wave transmission[1]
- Plasma-Functionalization: Plasmas can be used to modify the strong field region between the upper strip and ground plane
- Approach: Use slow-wave metamaterial microstrips where signal is carried by "spoof" surface plasmon polaritons above the surface.

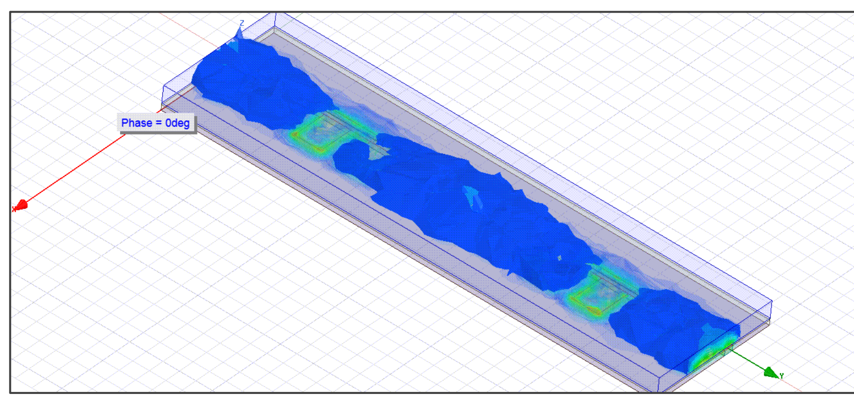




microstrip waveguide transmission lines



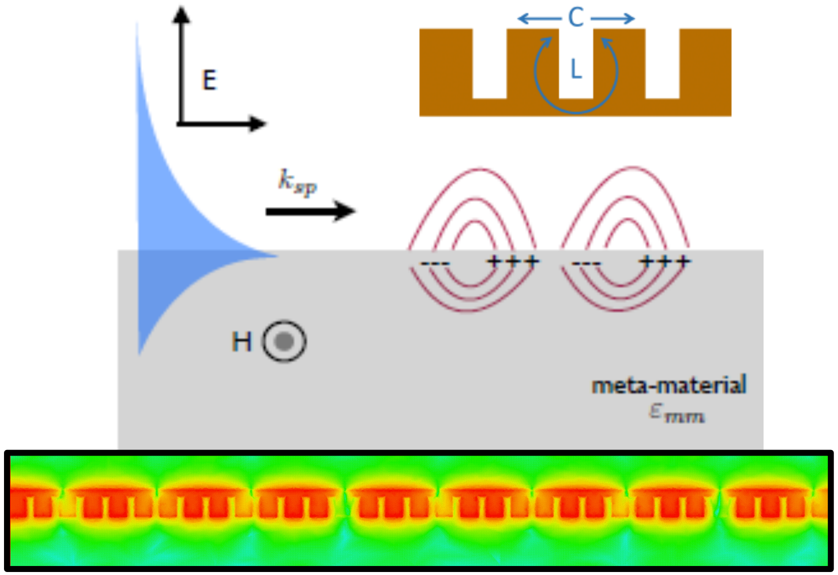


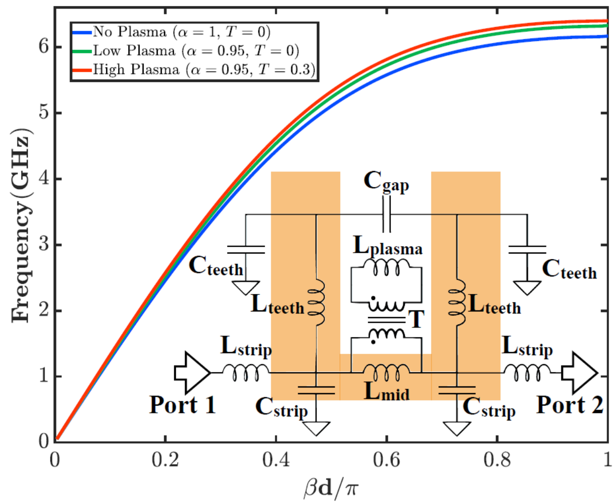


[1] "Microwave Engineering", D. M. Pozar, 2004

Spoof surface plasmon polaritons (SSPPs)

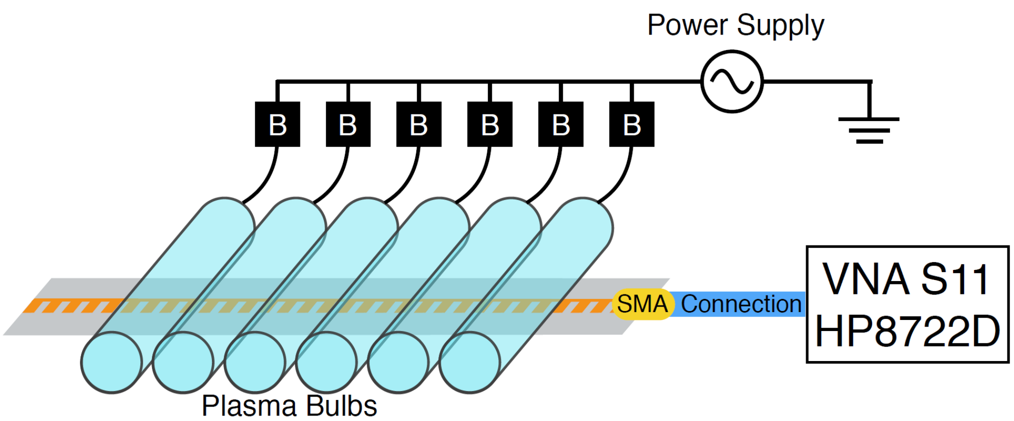
- Corrugated structures support "spoof" surface plasmon (SP) EM waves propagating at dielectric–metamaterial interfaces
- Equivalent circuit element representation
  - Models the unit cell with lumped parameters
- Plasma-functionalization: plasma at the interface expected to alter the dispersion
  - Lumped parameters can approximate plasma effects

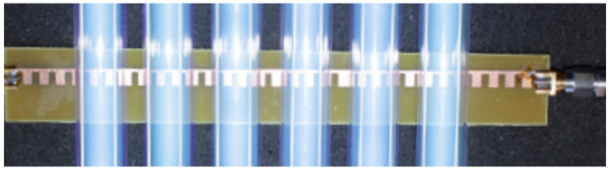




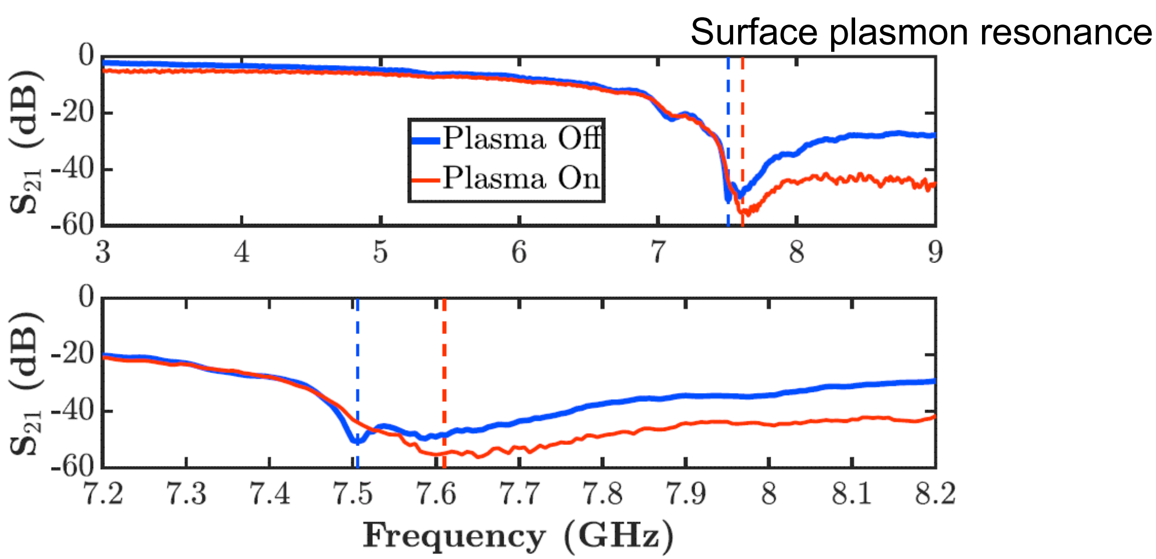
F. J. Garcia-Vidal, L. Martın-Moreno, and J. B. Pendry, J. Opt. A: Pure Appl. Opt. 7, S97 (2005)
Lee, R., Wang, B. and Cappelli, M.A., 2017. Applied Physics Letters, 111(26), p.261105.

Plasma Modification of Spoof Plasmons



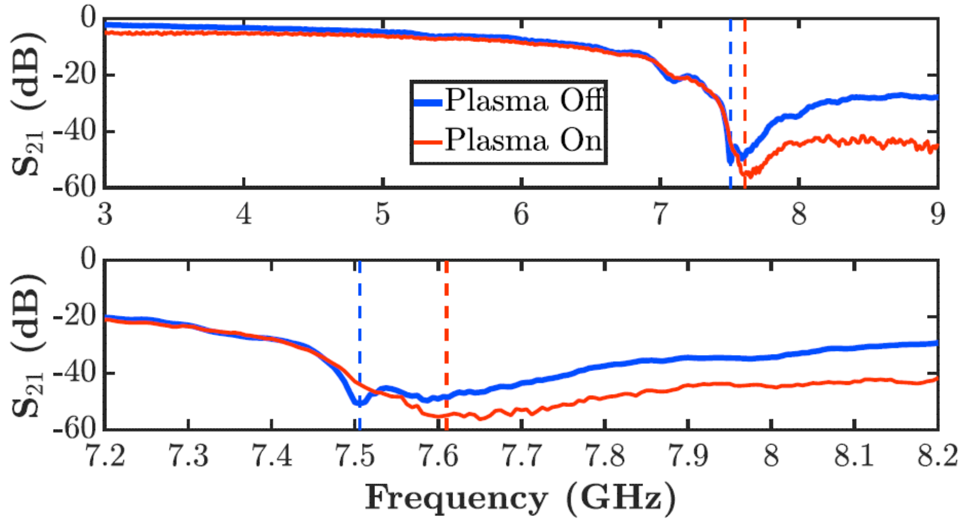


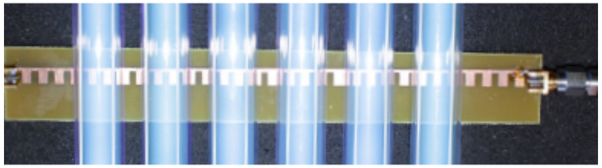
Transmission Gain (S_{21})



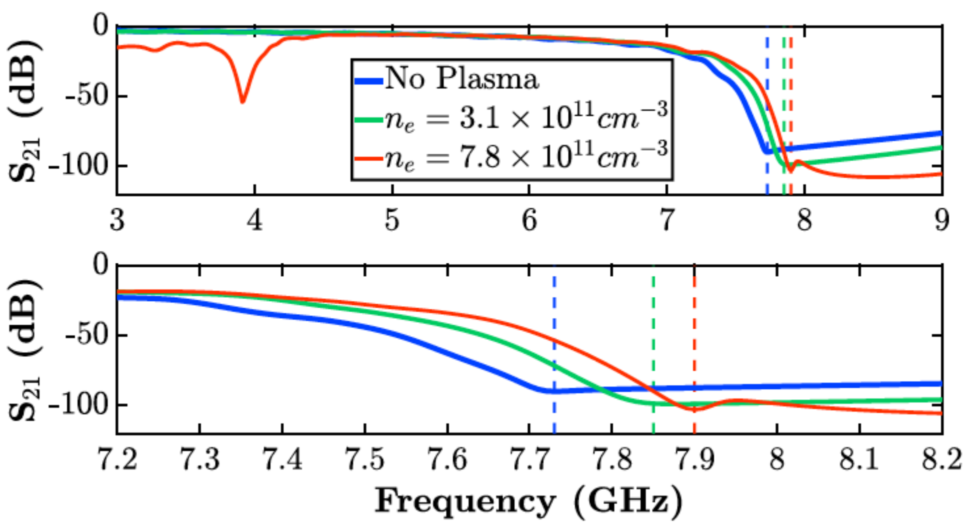
"Plasma modification of spoof plasmon propagation along metamaterial-air interfaces", Lee, R., Wang, B. and Cappelli, M.A., 2017. Applied Physics Letters, 111(26), p.261105.

Plasma Modification of Spoof Plasmons



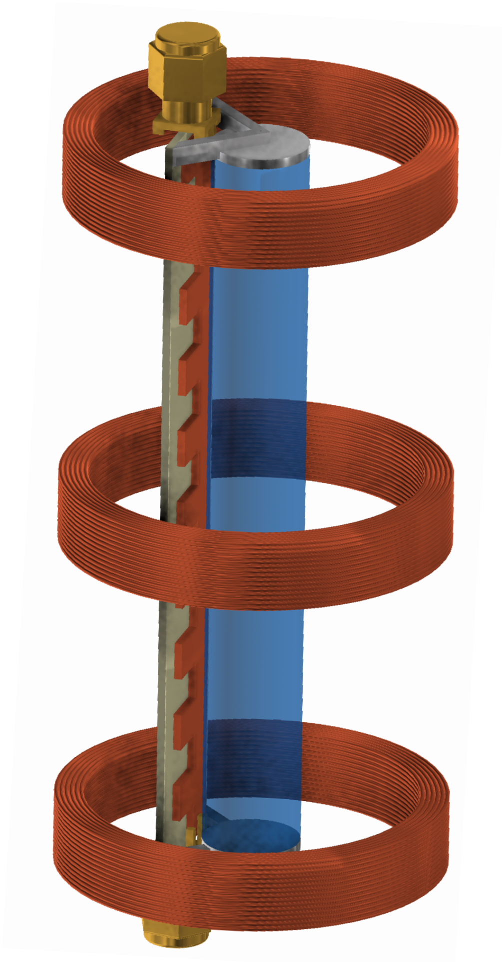


Experiment

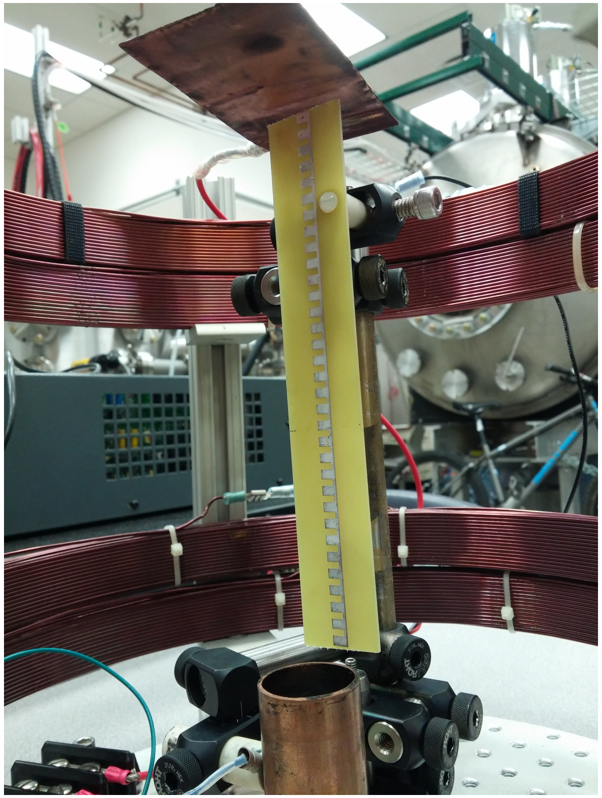


Model (HFSS)

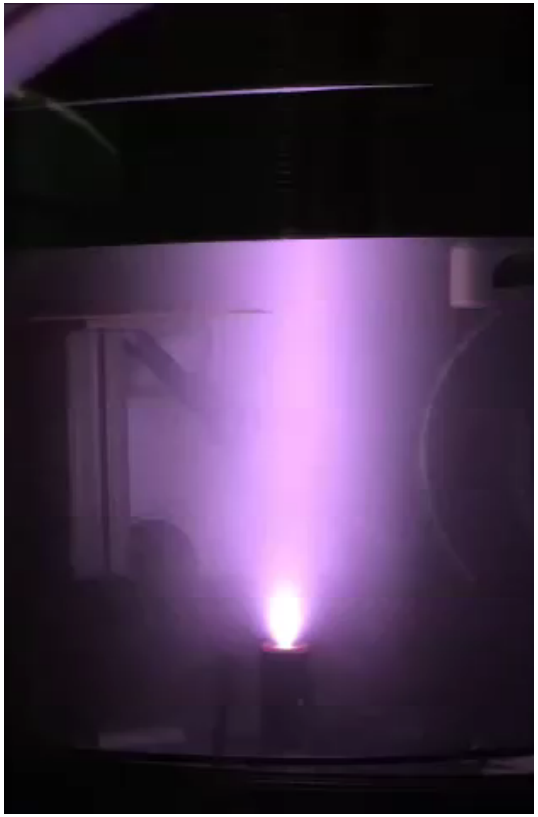
UCLA "Open Plasma" Experiment



Functionalized Microstrip Concept Product

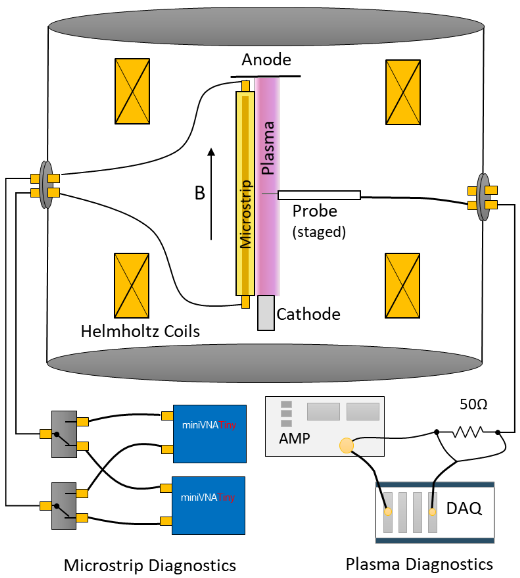


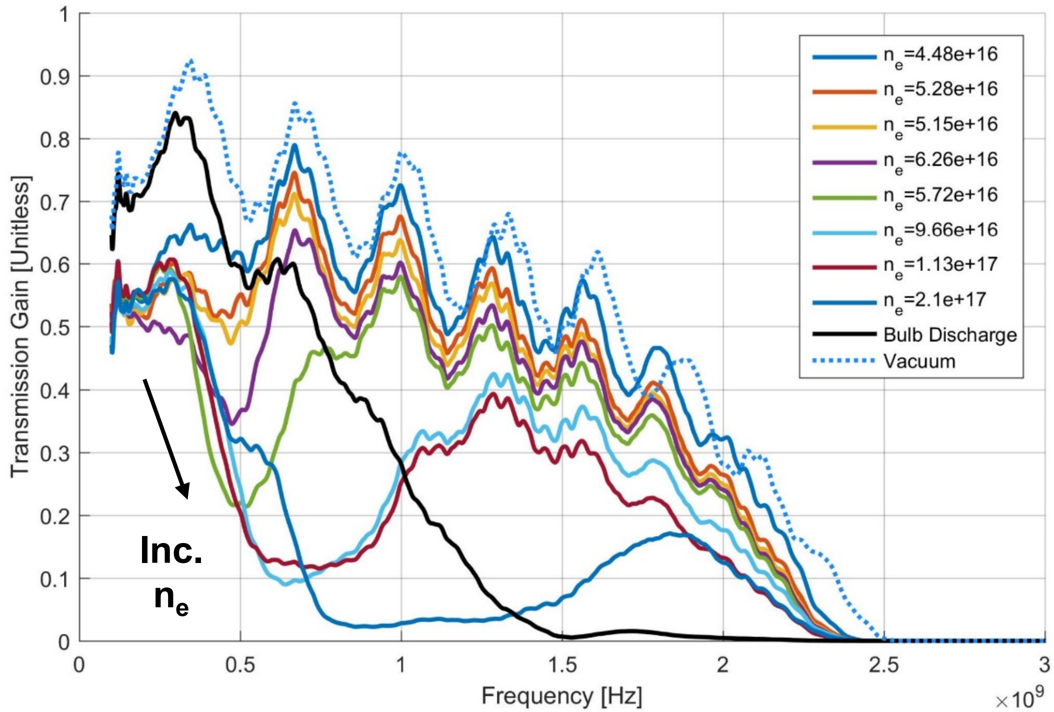
Microstrip with Tungsten Filament Cathode



Microstrip with Small Hollow Cathode

Plasma-Surface Plasmon Polaritons





Plasma frequency

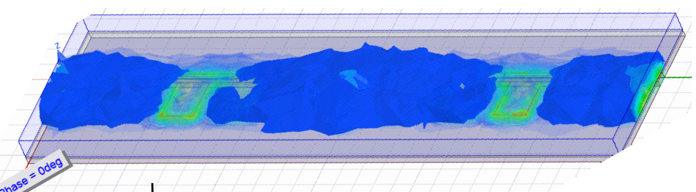
$$\omega_p = \sqrt{\frac{\boldsymbol{n_e} e^2}{m \varepsilon_0}}$$

Plasma "Drude" permittivity

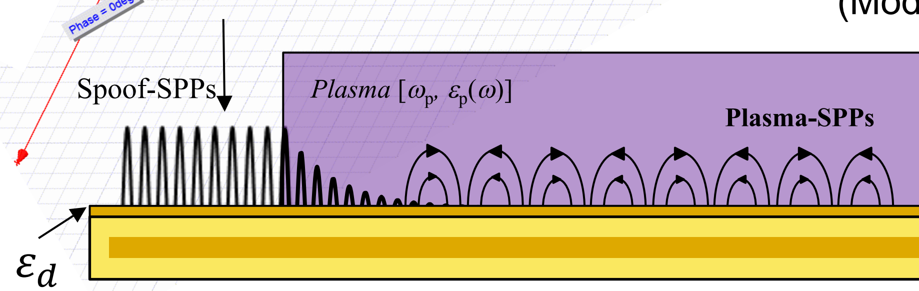
$$\varepsilon_p(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\omega\gamma}$$

SP resonance

$$\omega_{sp} = \frac{\omega_p}{\sqrt{1 + \varepsilon_d}}$$

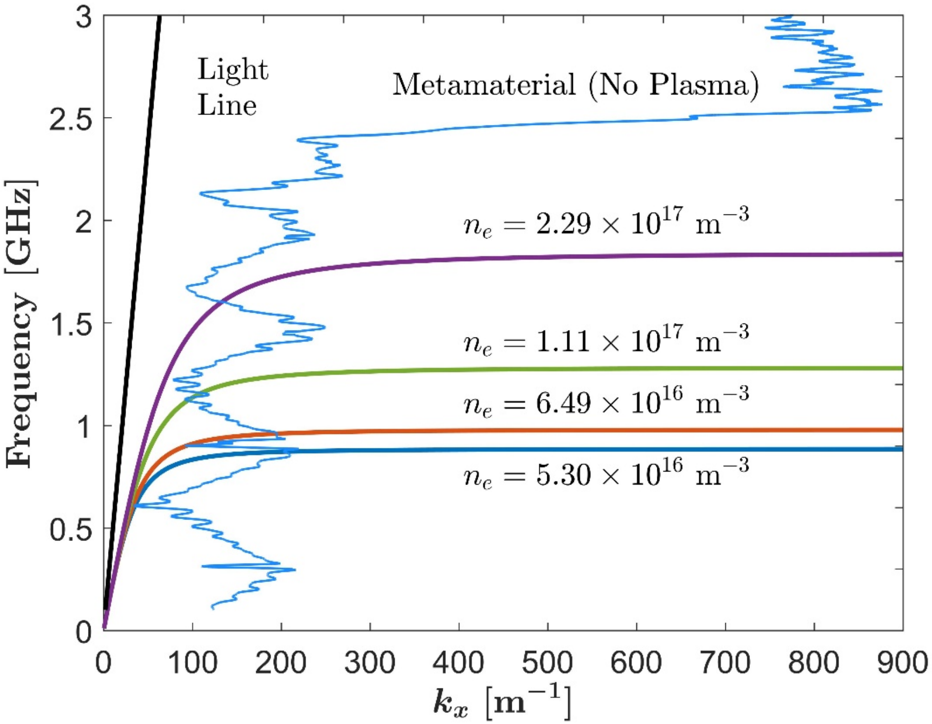


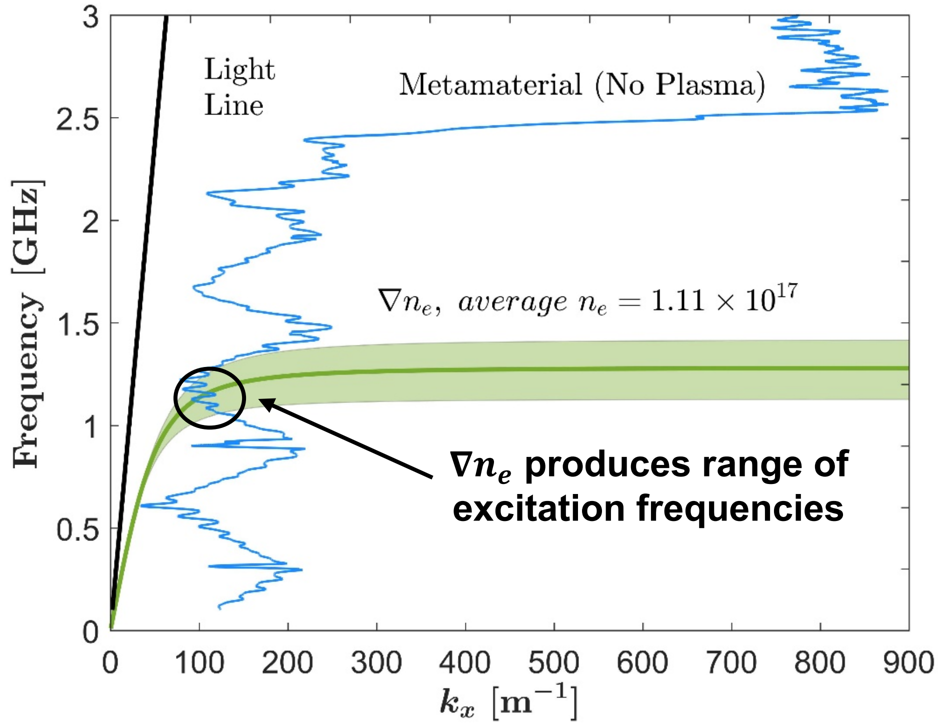
Microstrip-induced SSPs (Model)

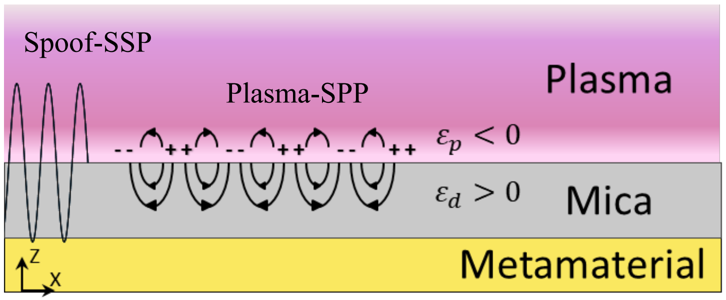


Tunable microstrip response

Frequency-tunable microstrip via SSP/Plasma-SPP interaction



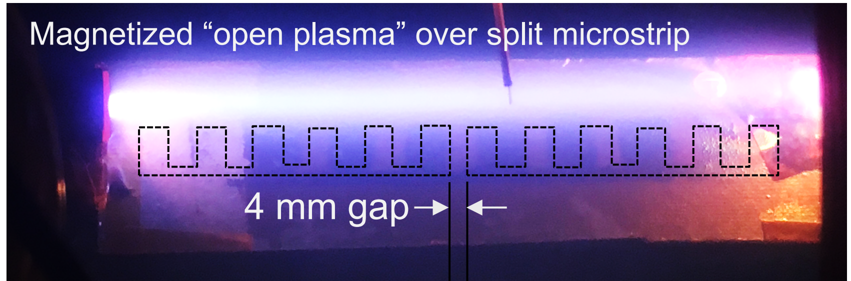


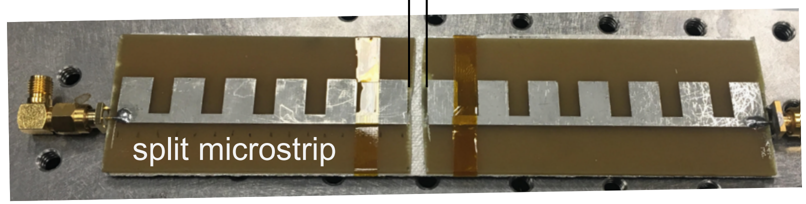


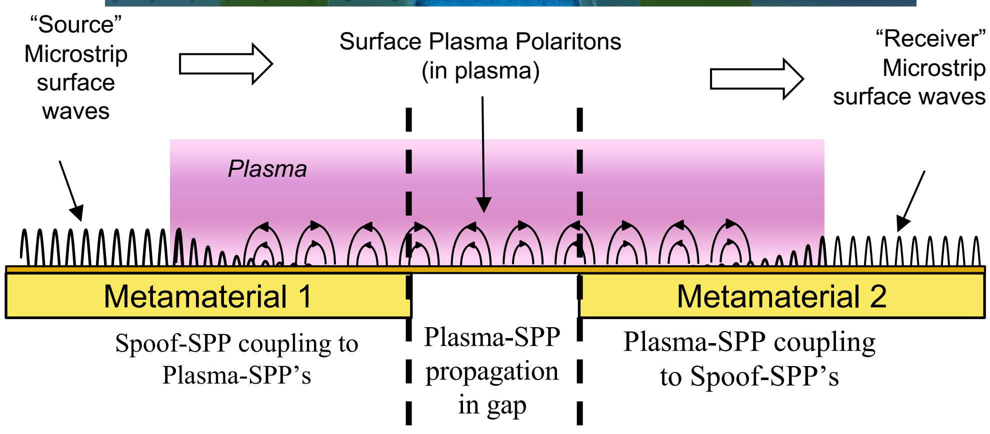
$$k_{x,plasma} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_p\,\varepsilon_d}{\varepsilon_p + \varepsilon_d}}$$

$$k_{x,microstrip} = \frac{1}{\mathrm{d}}\cos^{-1}\frac{1 - S_{11}S_{22} + S_{21}S_{12}}{S_{21}}$$

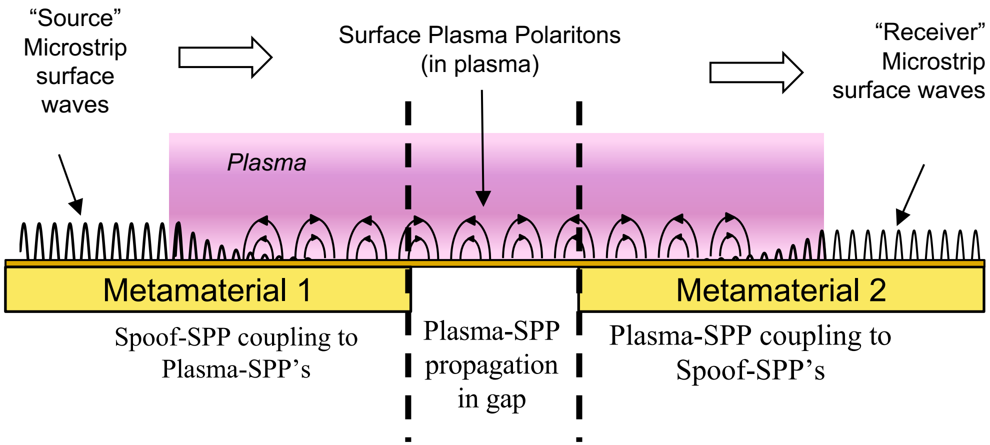
Plasma-Metamaterial "Reciprocal-Coupling"?





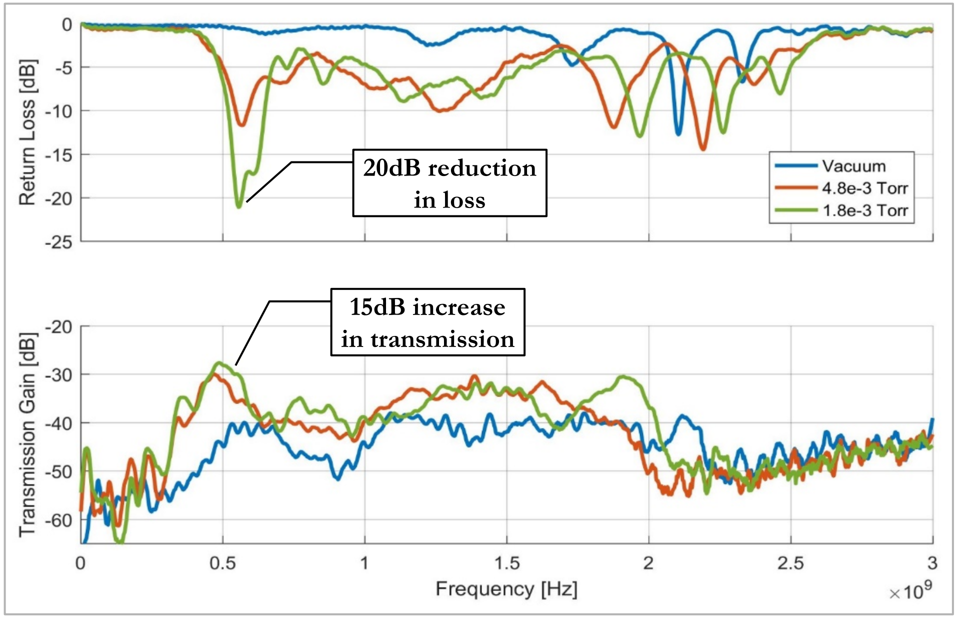


Plasma-Metamaterial "Reciprocal-Coupling"? Yes!



Microstrip reflection loss (S_{11})

Transmission gain (S_{21})



Uchizono, Wirz, "Reciprocal coupling of surface plasmon polaritons using overdense plasma," in prep PoP

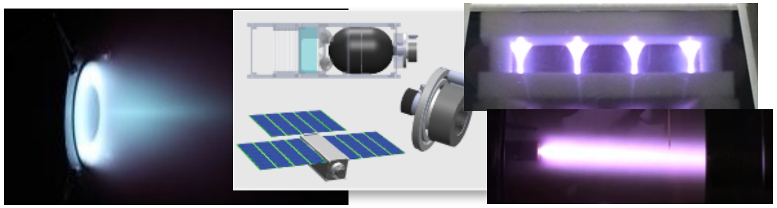
UCLA Plasma & Space Propulsion

Plasma Technology

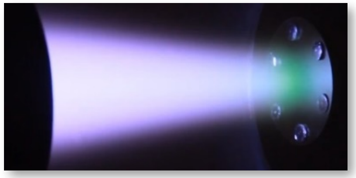
Applied Plasma Science

Plasma Physics

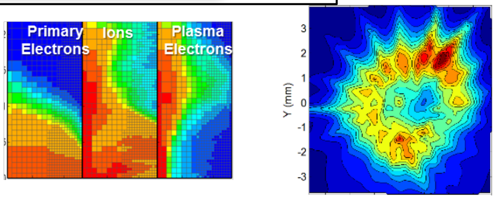
Electric Propulsion, Plasma Devices, Cathodes



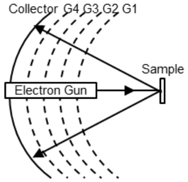
Plasma-Material Interactions



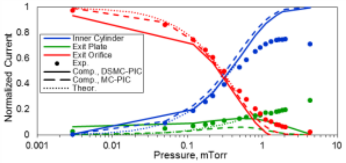
Plasma Confinement



i-SEE
e-SEE
i-n



Canonical Experiments for Plasma Model Validation



Funding & Collaborations

Funding | **Collaborations**

Plasma Technology

Applied Plasma Science

Plasma Physics

Researchers / Major Funding

NASA AFOSR AIR FORCE OFFICE OF SCIENTIFIC RESEARCH U.S. DEPARTMENT OF ENERGY arpa·e NSF Southern California Gas Company A Sempra Energy company AFRL THE AIR FORCE RESEARCH LABORATORY LEAD | DISCOVER | DEVELOP | DELIVER JPL STATE OF CALIFORNIA ENERGY COMMISSION

Thank You!
Questions?

www.WirzResearchGroup.com

wirz@ucla.com