

Plasma-Surface Interactions

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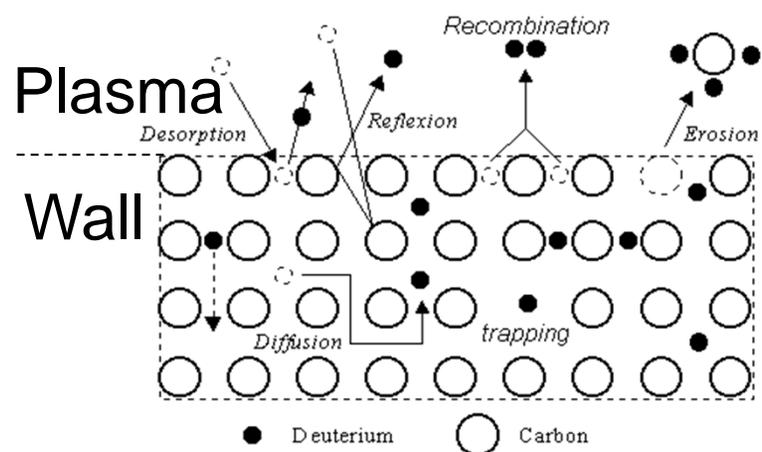


OUTLINE

- The current state-of-the art of your particular subfield
- The potential impact of this research on the plasma applications and fusion program
- Provide your vision of future direction and progress of your subfield of research

Plasma-Surface Interactions

Recombination, trapping, displacements, implantation, erosion, desorption, etc.



From: <http://www-fusion-magnetique.cea.fr>

✓ Plasma exhaust heated Mo tile “limiter” to melting temperature of 2900 K in less than 2 seconds of exposure to tokamak plasma.

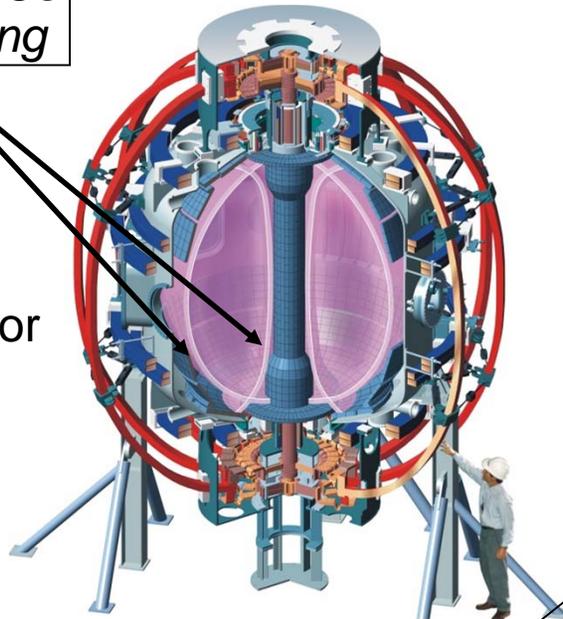
Note: Reactor must run 24/7

From: D. Whyte, MIT ANS seminar, April 2007

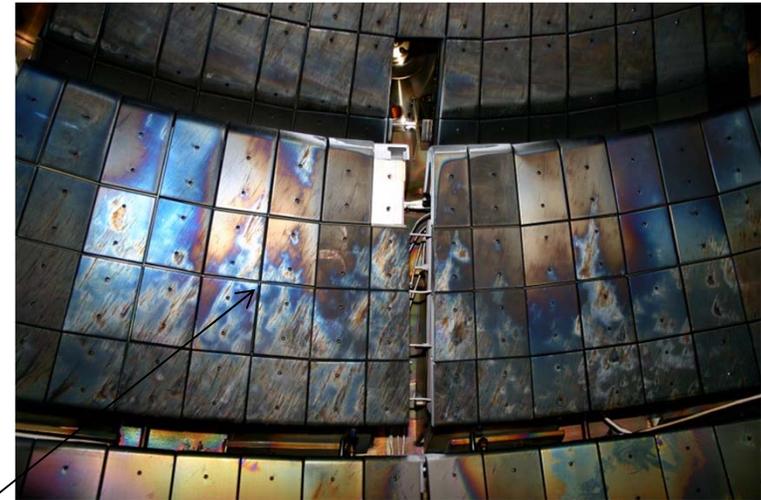
Surface coating can produce highly-localized plasma objects : *Unipolar Arcs*

Graphite/CFC PFCs
with lithium coating

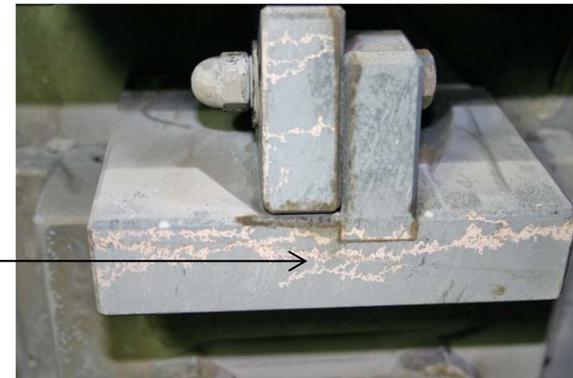
Confine a higher
plasma pressure for
a given magnetic
field strength



Signatures of unipolar arcs?

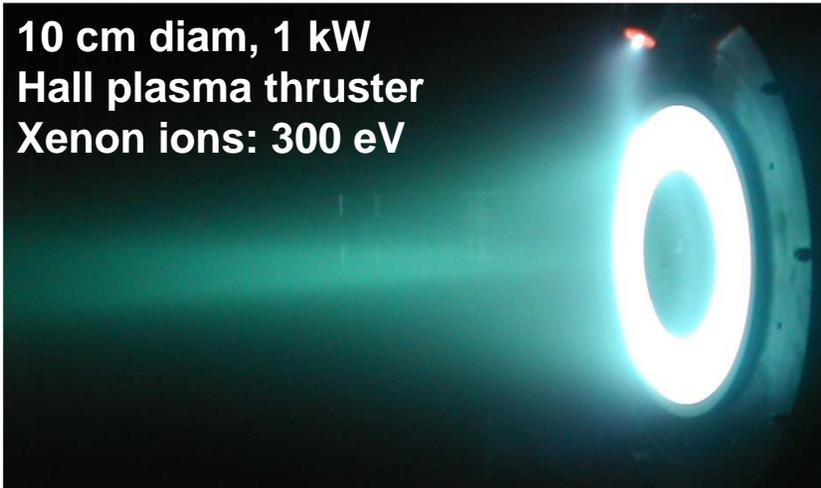


Traces of unipolar arcs



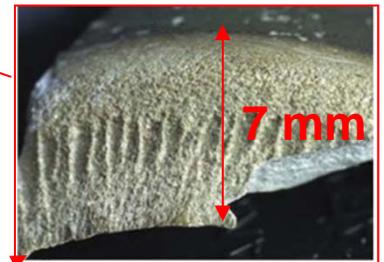
Wall erosion limits lifetime of plasma devices

10 cm diam, 1 kW
Hall plasma thruster
Xenon ions: 300 eV

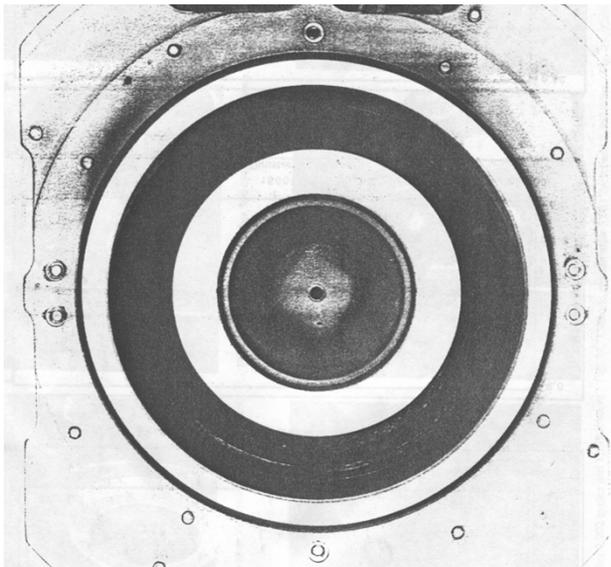


A non-uniformity of the SEE-induced near-wall electron current across B-field may explain a macroscopically inhomogeneous erosion patterns $\sim R_{Le} = mv_e/eB$

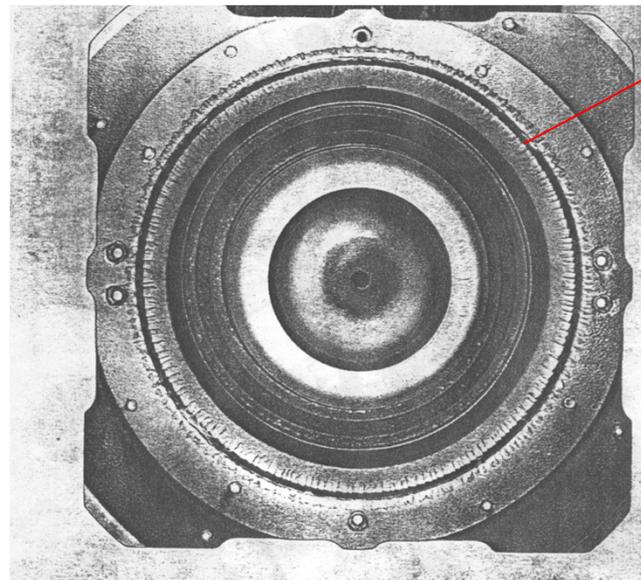
Morozov, Rev. Plasma Phys., 2000



Hall thruster (New)



Hall thruster after 6000 Hrs



*Courtesy:
L. King
F. Taccagona*

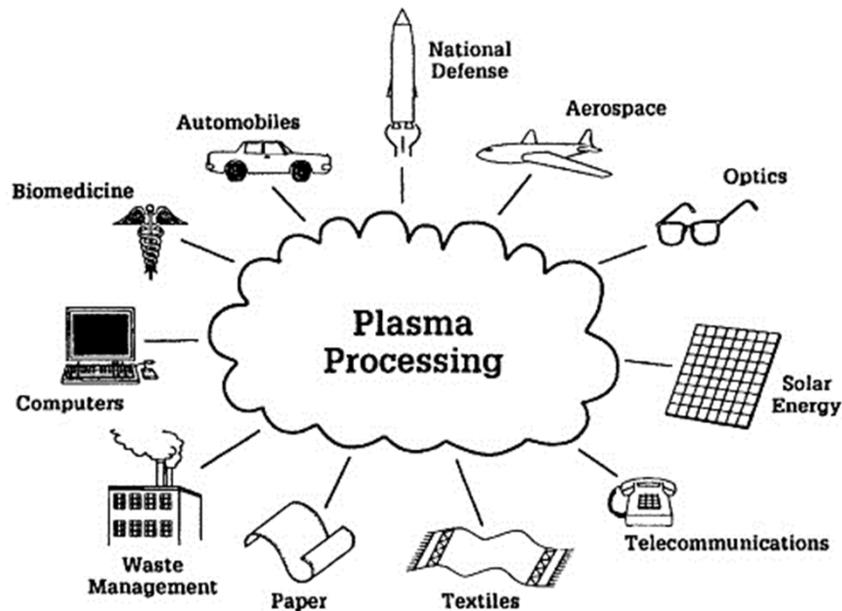
MichiganTech.

IMIP IPP 10

Surfaces discolorations and deformities due to chronic interaction with aggressive processing plasmas

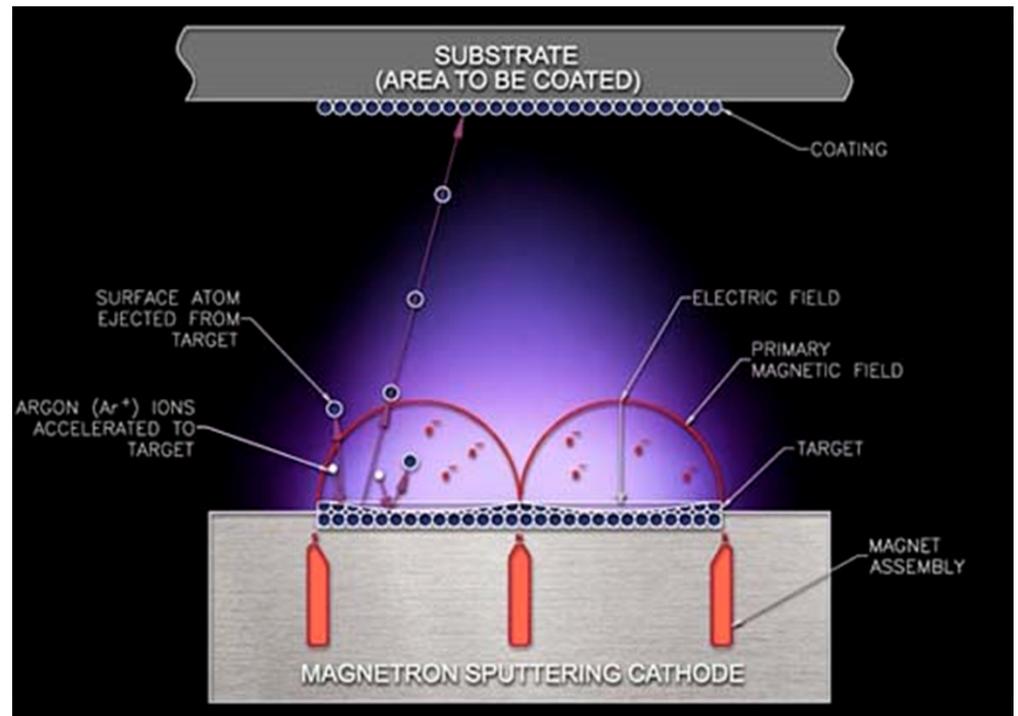


In plasma processing technologies, plasma-surface interaction is everywhere



Magnetically enhanced ionization in $E \times B$ gas discharge, $P \sim 3\text{-}5$ mtorr

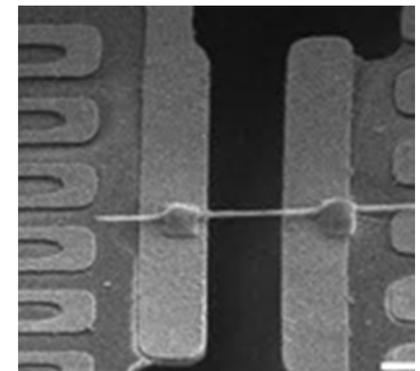
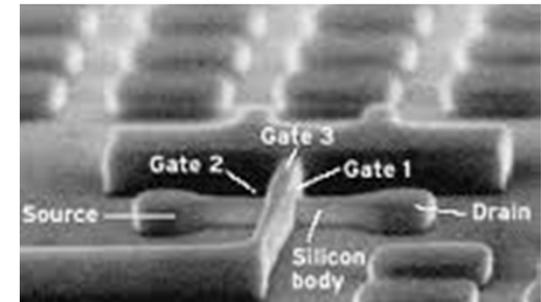
Example: deposition and coating of films by sputtering magnetron discharge



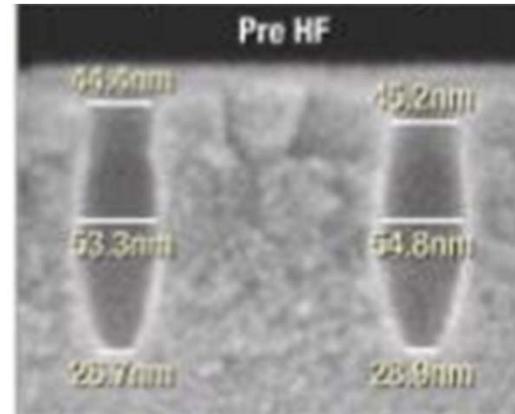
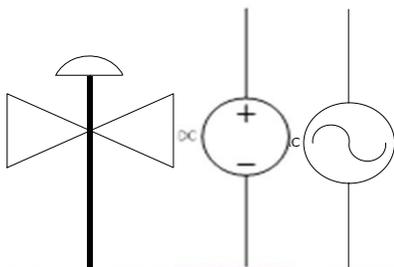
From: www.angstromsciences.com

ISSUES OF SEMICONDUCTOR PRODUCTION EQUIPMENT MAKERS

- Processing Non-planar Features
 - “Accessing dark corners and recesses”
- Maintaining the Integrity of Materials
- Selective Etching
- Deposition: Thinner complex materials
- Functionalization



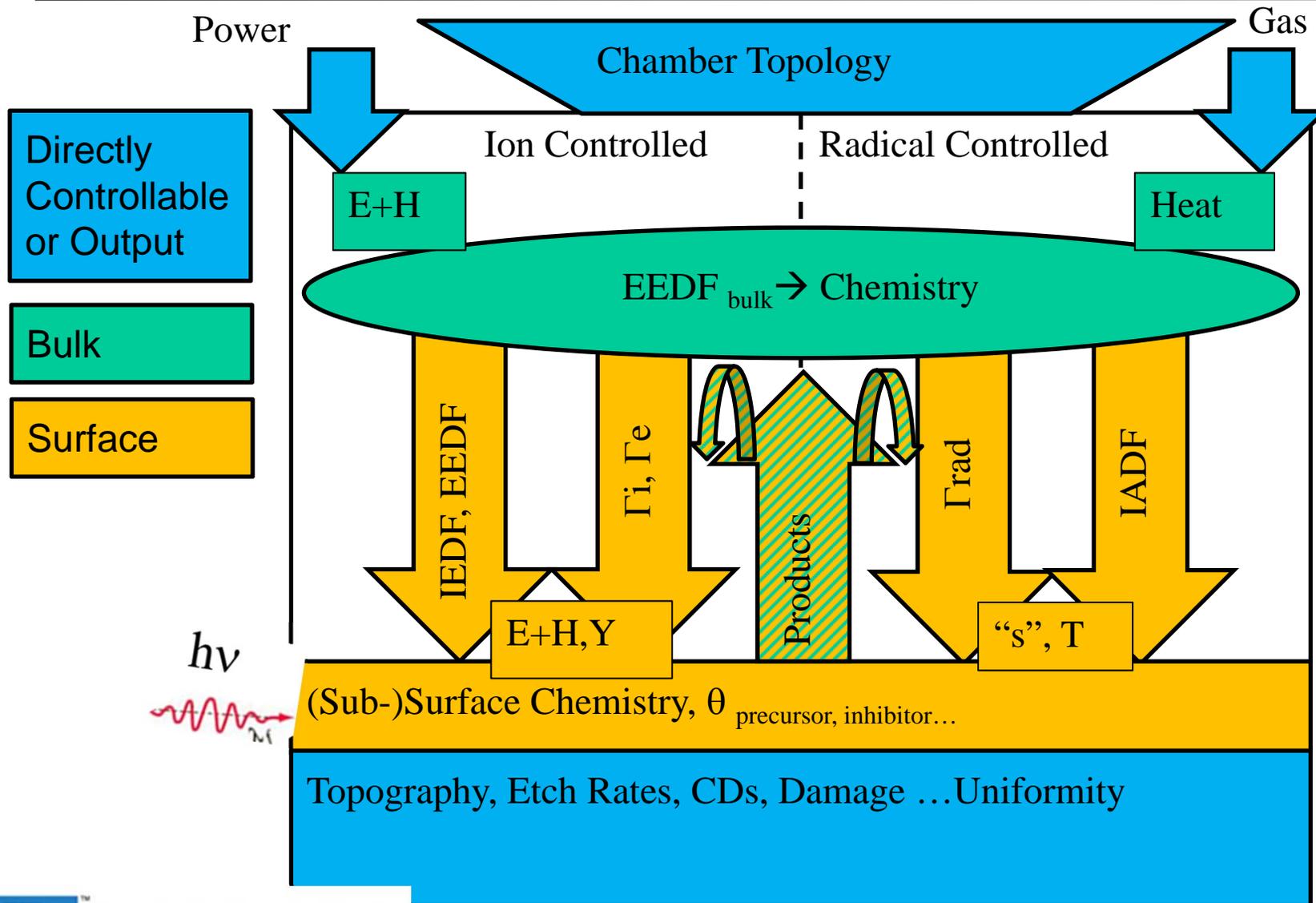
Process Settings



Courtesy of P. L. G. Ventzek



SEMICONDUCTOR EQUIPMENT REQUIRES PRECISE CONTROL OF PLASMA-SURFACE INTERACTION



Sheath Insulate Wall from Electron Heat Flux

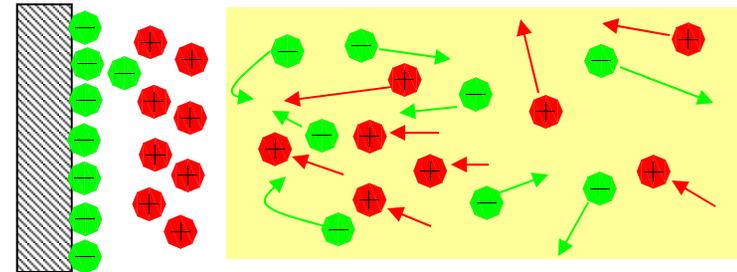
Because the electrons move faster than the ions, charge builds up on the wall surface.

This induces an electric field to balances the flow of ions and electrons at the wall:

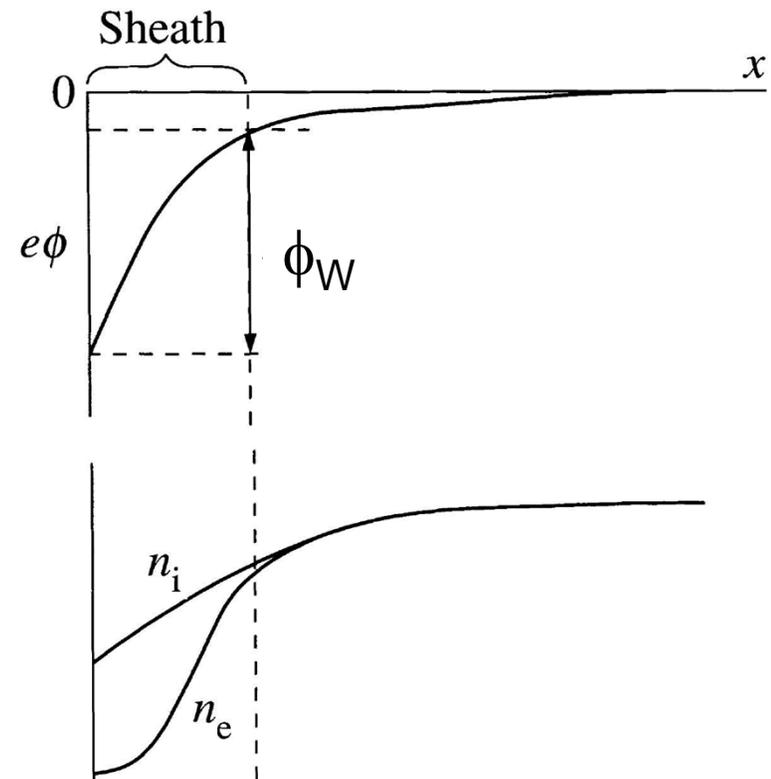
$$\Gamma_{pe} = \Gamma_{ion}$$

$$\Gamma_{pe} = \frac{1}{4} n_s \sqrt{\frac{8T_e}{\pi m}} \exp\left(-\frac{e\phi_w}{T_e}\right)$$

$$\Gamma_{ion} = n_s \sqrt{T_e/M}$$



Plasma



THE CURRENT STATE-OF-THE ART OF PLASMA SURFACE INTERACTION

Most experiment were performed in 1960-70s.

Recent resurgence in MFE due unsolved first wall problem.

Fundamental studies are often on rudimentary level well below 1970s, both in experiments and theory.

THE POTENTIAL IMPACT OF THIS RESEARCH ON THE PLASMA APPLICATIONS AND FUSION PROGRAM

MFE

Possible failure (hole in the wall) in tokamak, heat and particle fluxes to and from the walls.

Boundary conditions for MHD calculations: current flow into the walls

Plasma Thrusters

Time of Life (wall erosion due to sputtering or evaporation)

Deterioration of thrust due to anomalous electron transport due to emission or effects of wall on plasma instabilities

Plasma Processing

semiconductor equipment requires precise control of plasma-surface interaction for producing **features with designed properties on nanometer scale.**

Plasma-wall interaction in the presence of strong electron-induced secondary electron emission (SEE)

- Any plasma with electron temperatures above 20 eV for dielectric walls, and above 50-100 eV for metal walls is subject to strong secondary electron emission (SEE) effects:

Hall thrusters and Helicon thrusters

Hollow cathodes for high power microwave electronics

Multipactor breakdown and surface discharges

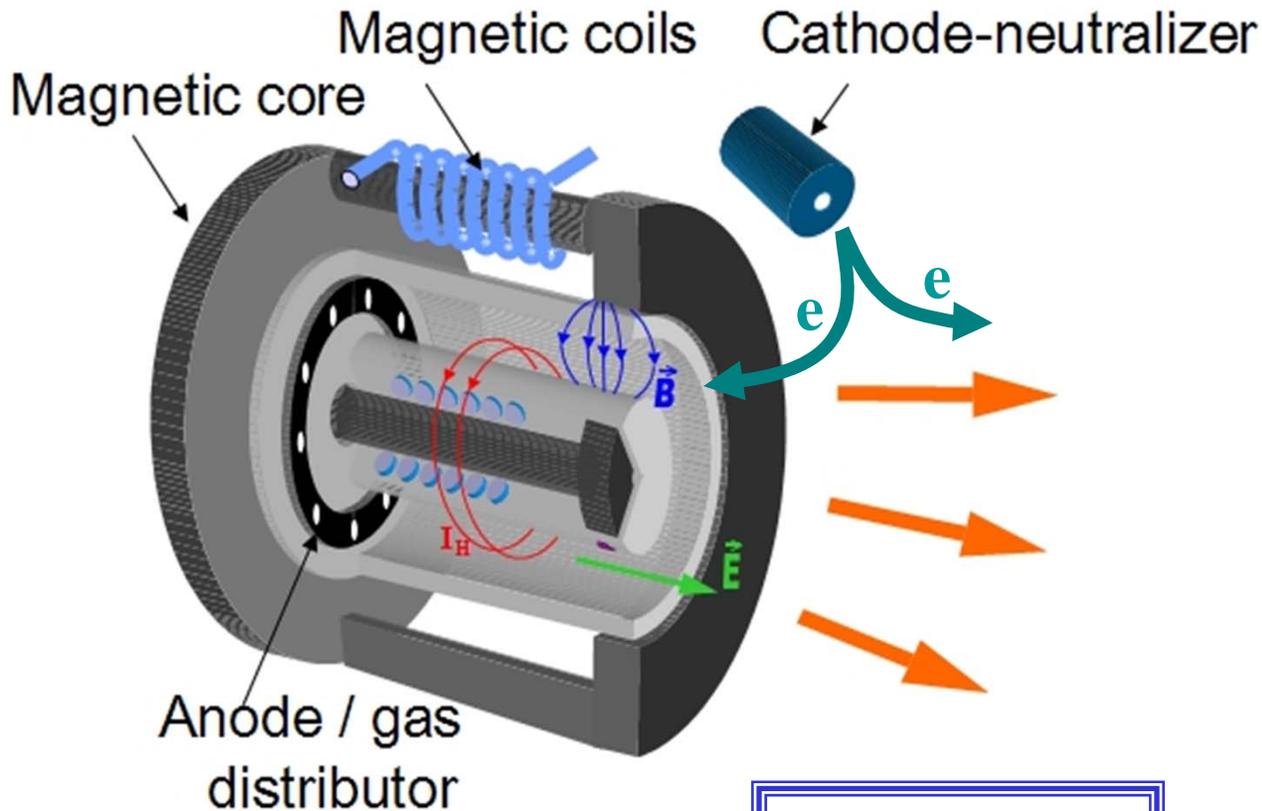
Space plasmas and dusty plasmas

Fusion plasmas

Plasma processing discharges with RF or DC bias

- Strong secondary electron emission from the floating walls can alter plasma-wall interaction and change plasma properties.
- Strong SEE can significantly increase electron heat flux from plasma to the wall leading to: 1) wall heating and evaporation and 2) plasma cooling.

Hall Thruster (HT)



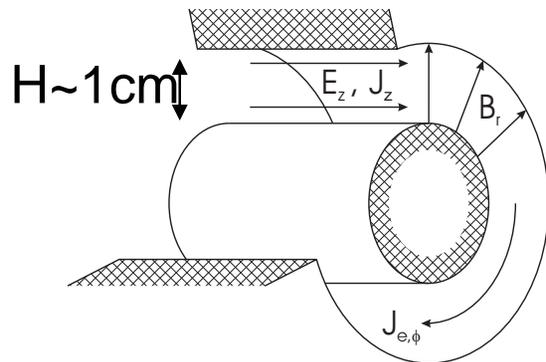
$$\rho_e \ll L \ll \rho_i$$

Diam ~ 1 -100 cm
B ~ 100 Gauss
 For propulsion: Xe, Kr
Pressure ~ 0.1-1 mtorr
V_d ~ 0.2 – 1 kV
Power ~ 0.1- 50 kW

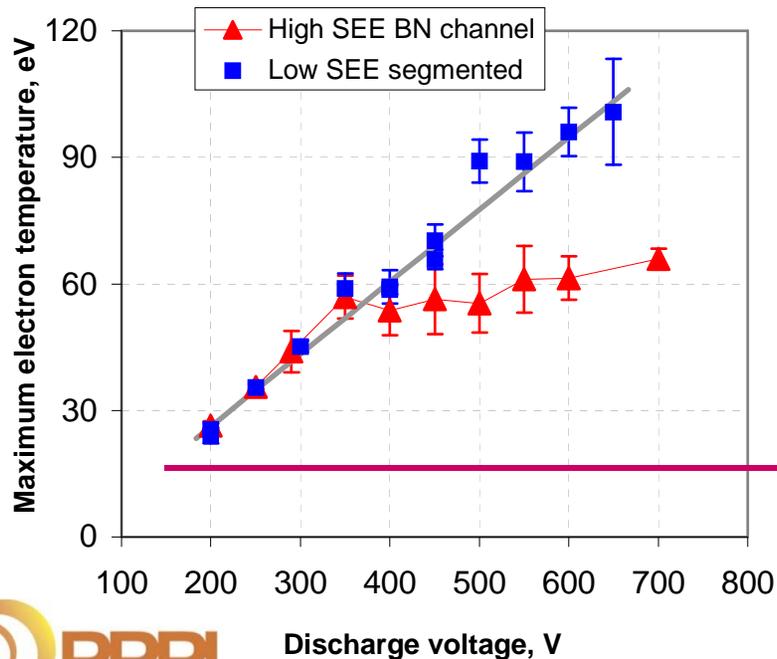
Thrust ~ 10^{-3} - 1N
Isp ~ 1000-3000 sec
Efficiency ~ 6-70%

- ✓ HT is not space-charge limited.
- ✓ Higher current densities than in ion thrusters.

PLASMA-WALL INTERACTIONS IN HALL THRUSTERS



$B \sim 100\text{G}$, $E \sim 100\text{V/cm}$, $T_e \sim 100\text{eV}$.
 $P=0.1\text{-}1\text{mTorr}$, the plasma inside the thruster channel is collisionless,
 $\lambda_{ec} (\sim 1\text{m}) \gg H (\sim 1\text{cm})$. \Rightarrow intense particle and heat wall losses!

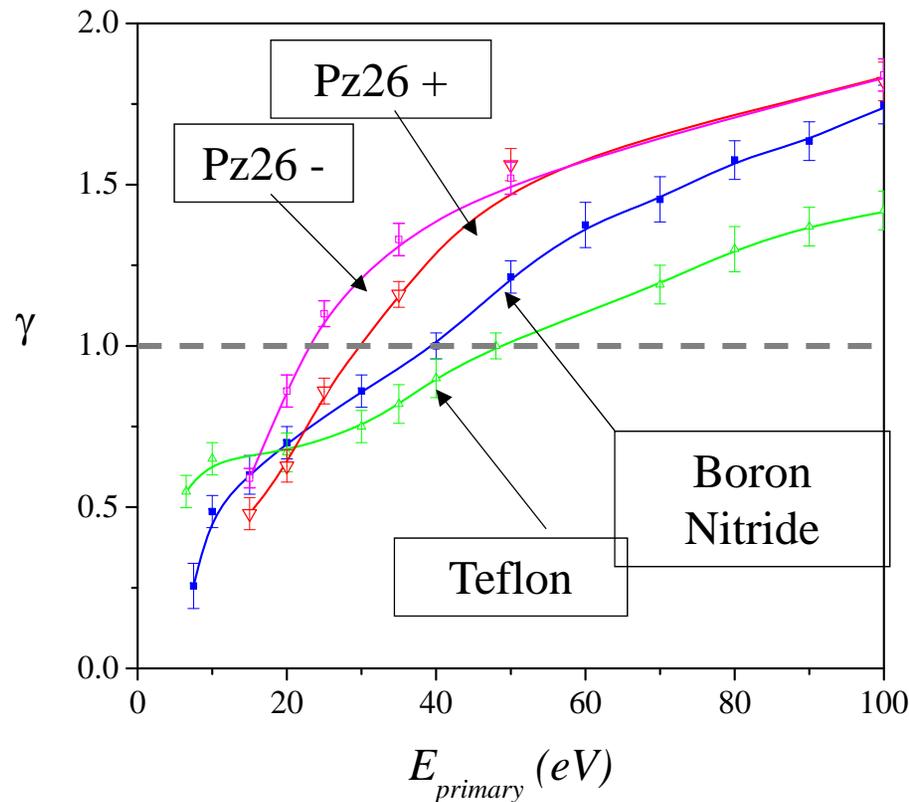


High electron temperature is observed in experiments

- *Large quantitative disagreement with fluid theories.*

A fluid theory prediction.

Secondary electron emission yield from dielectric materials



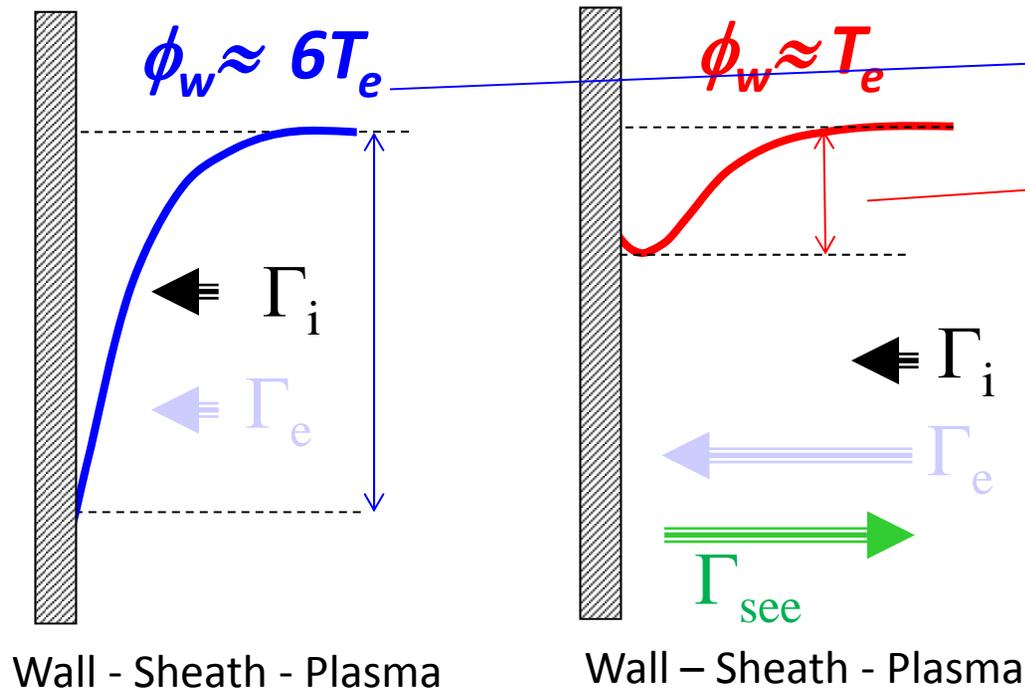
Note:

for Boron Nitride ceramic, if plasma (primary) electrons have Maxwellian electron energy distribution (EEDF):

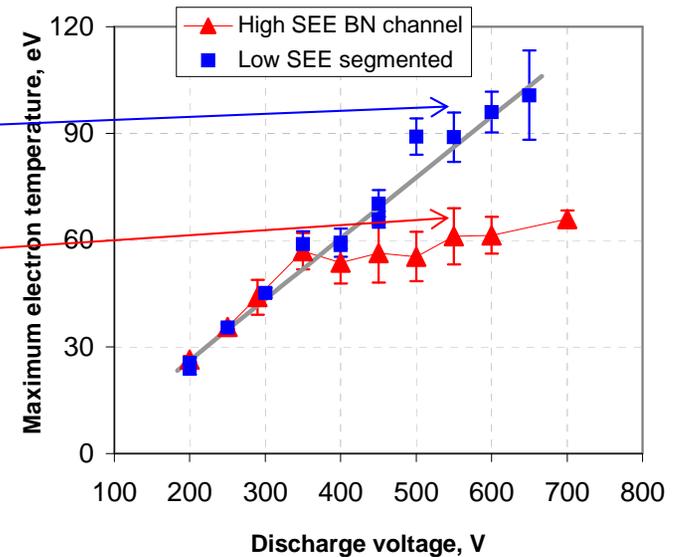
$$\chi(T_e) = 1 \text{ at } T_e = 18.3 \text{ eV}$$

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



Hall thruster experiments show very different maximum electron temperatures with high and low SEE channel wall materials

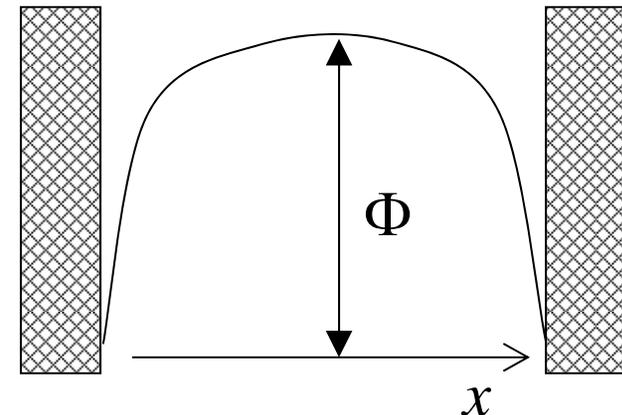


Y. Raitses et al., *Phys. Plasmas* 2005
Y. Raitses et al., *IEEE TPS* 201122

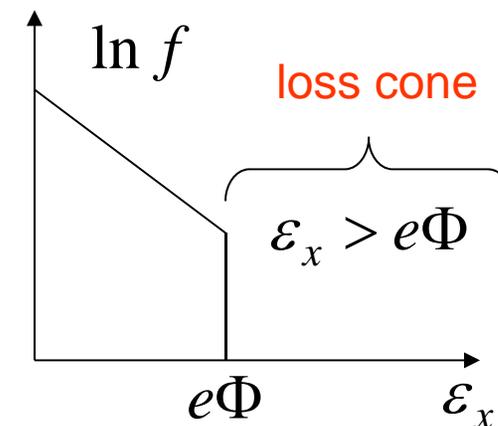
Kinetic effects may modify wall losses in collisionless plasmas

- DC discharge - EVDF is depleted in the loss cone [Tsensin, 1974].
- Tokamak (low recycling regime)- depleted, anisotropic EVDF [Wang et al., 1997]
- ECR discharge - anisotropy of EVDF in the loss cone [Kaganovich et al., 2000].
- HT - depleted high energy tail of EVDF [Meezan, Cappelli, 2002].
- HT-anisotropic, depleted EVDF with SEE beams (Sydorenko et al., 2004, Kaganovich et al., 2006)

mean free path \gg system size

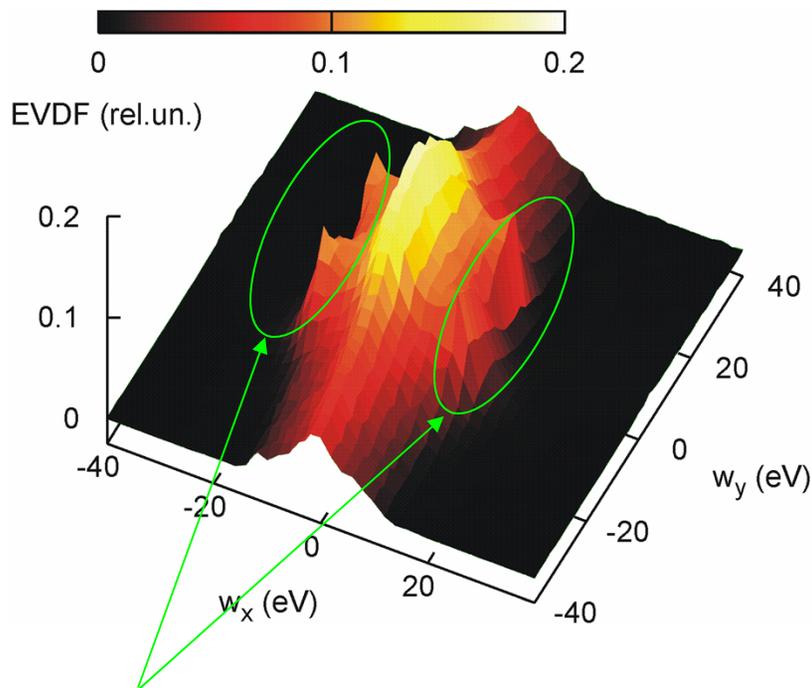


Electrons with $\varepsilon > e\phi$ leave.



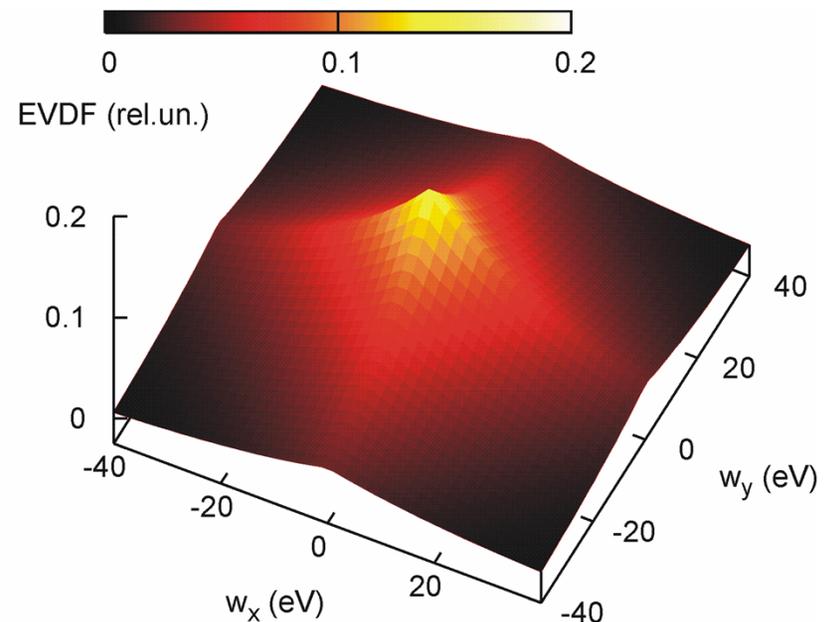
EVDF in HT is strongly anisotropic with beams of SEE electrons

Hall thruster plasma, 2D-EVDF



Loss cones
and beams

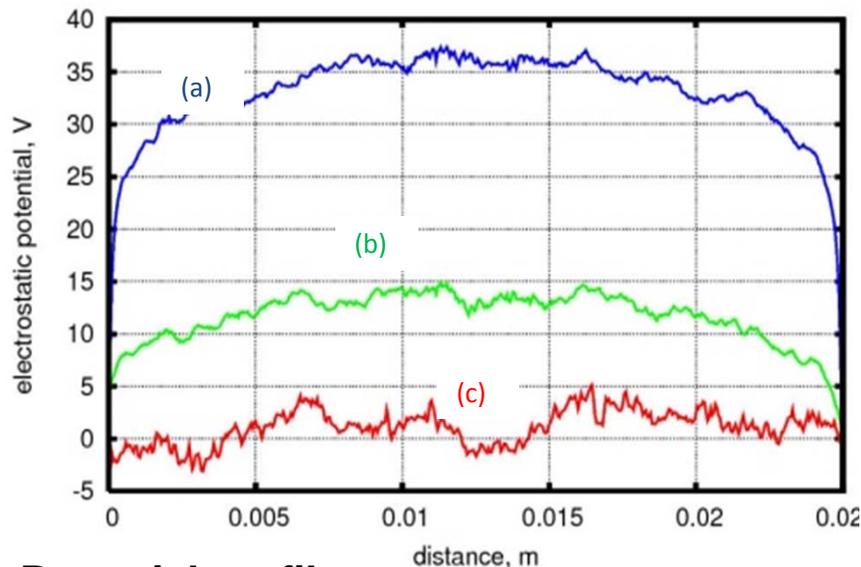
Isotropic Maxwellian plasma, 2D-EVDF



- **Electrons from the loss cone create the wall flux.**
- **In the E-direction, EVDF is not depleted and can provides a supply of high energy electrons.**

CONTROLLING PLASMA PROPERTIES: ELECTRON INDUCED SECONDARY ELECTRON EMISSION

- Kinetic studies of bounded plasmas by walls having secondary electron emission (SEE) predict a strong dependence of wall potential on SEE [1-4].
- Sheath oscillations occur due to coupling of the sheath potential and non-Maxwellian electron energy distribution functions [1,2].



Potential profiles:

- (a) $E=200\text{V/cm}$ no emission
- (b) $E=200\text{V/cm}$ with SEE,
- (c) $E=250\text{V/cm}$ with SEE [1,3]

- When electrons impacting walls produce more than one secondary on average no classical sheath exists.
- Strong dependence of wall potential on SEE allows for active control of plasma properties by judicious choice of the wall material.

[1] Phys. Rev. Lett. 103, 145004 (2009)

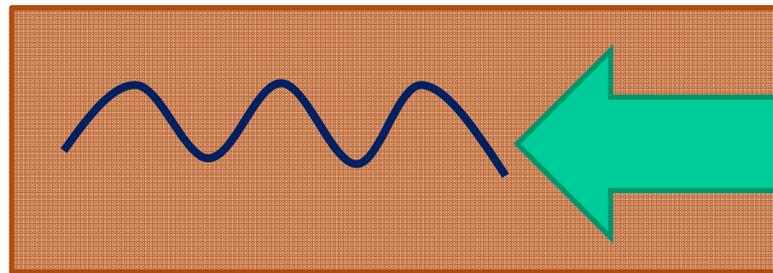
[2] Phys. Rev. Lett. 108, 235001 (2012)

[3] Phys. Rev. Lett. 108, 255001 (2012)

[4] Phys. Rev. Lett. 111, 075002 (2013)

Collisionless Electron Beam Interaction with Background Plasma

Electron beam emitted from the walls can interact with plasma and effectively transfer energy to background electrons and ions.



Questions:

How effective is this process?

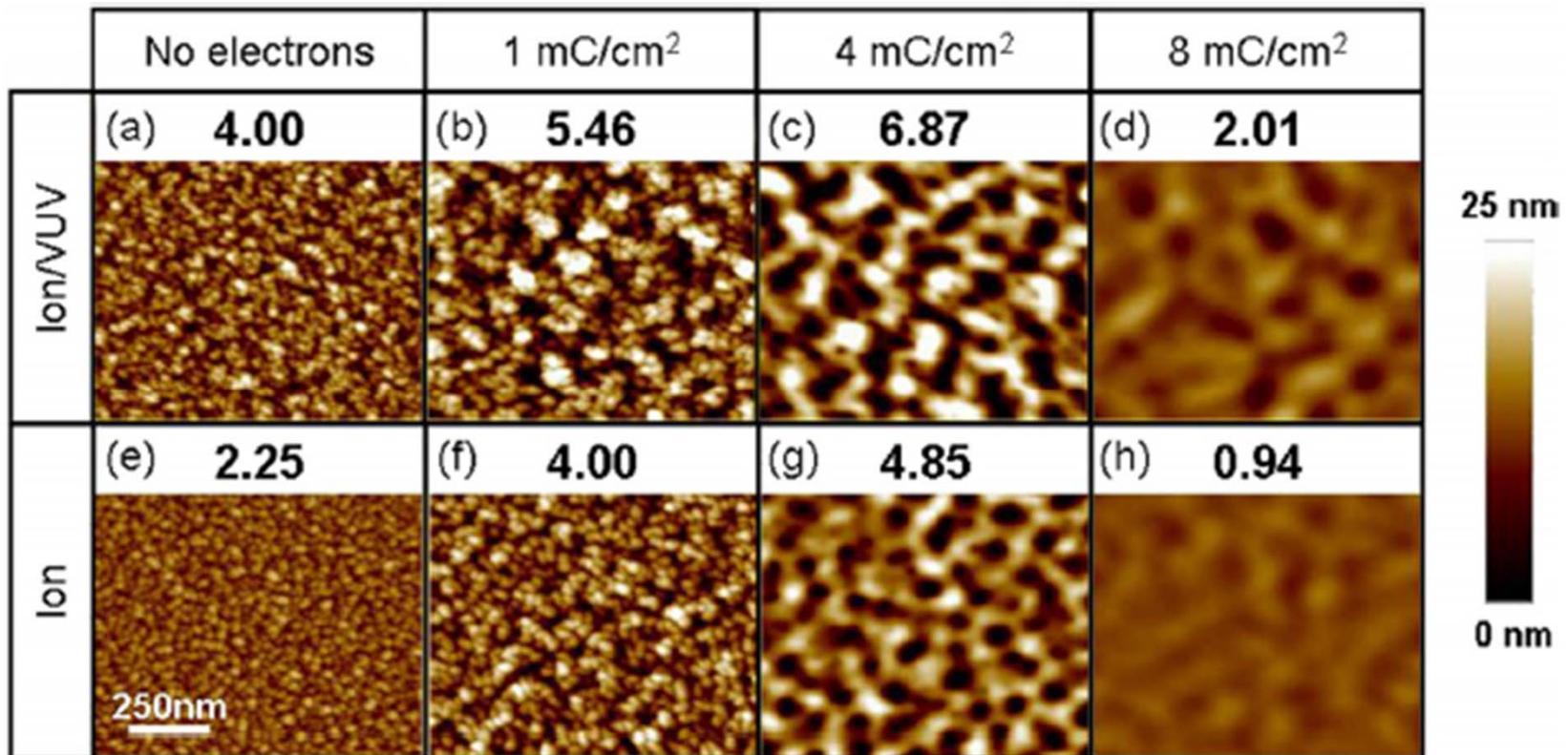
What are resulting electron and ion energy distribution functions?

Langmuir paradox and Langmuir turbulence revisited.

Still no answer in 3D and for realistic geometry!

IMPACT OF 1 KEV ELECTRONS ON PHOTO RESIST

- e-beam impact on photoresist roughness: initially roughness become worse, then surface become smoother.
- T-Y Chung, *et al*, J. Phys. D 43, 272001 (2010).

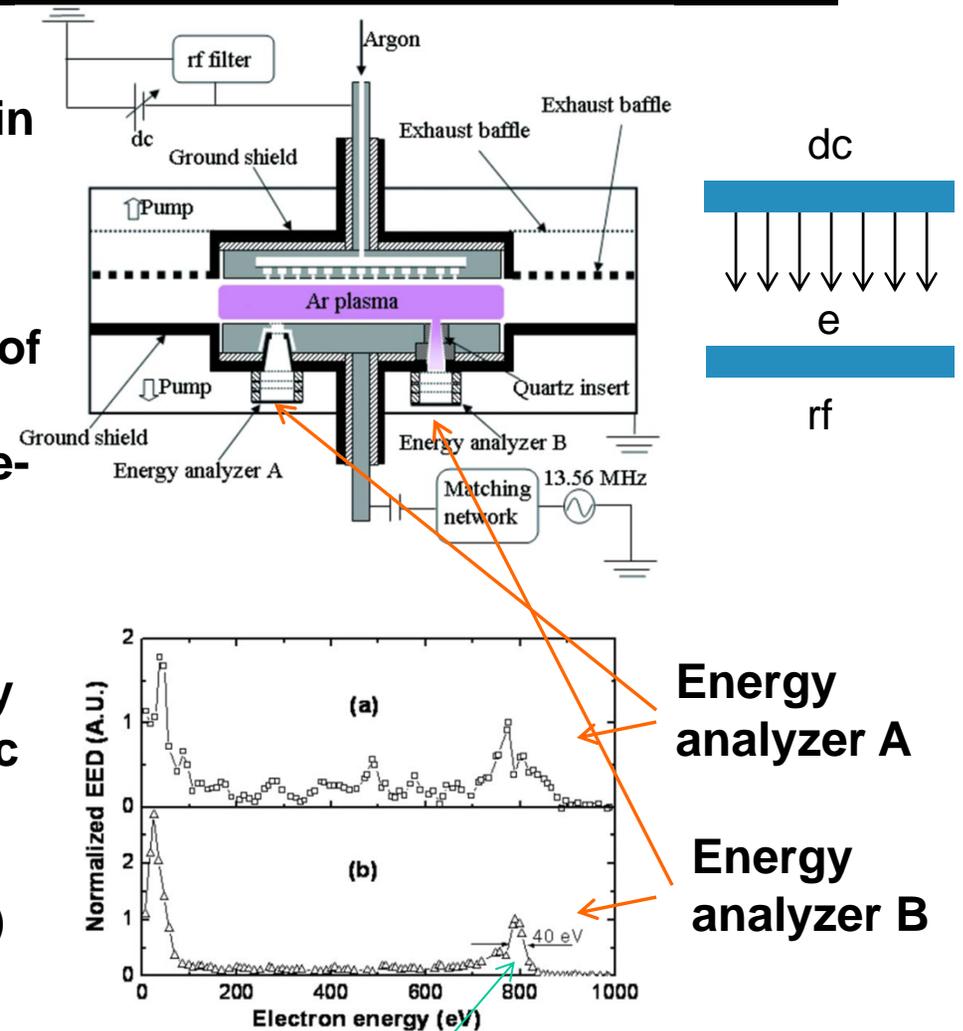


OBSERVATION OF MULTI-PEAK ELECTRON VELOCITY DISTRIBUTION FUNCTION

In experiments, Xu et al., APL 93 (2008) reproducible structures were observed in electron energy distributions at the RF electrode.

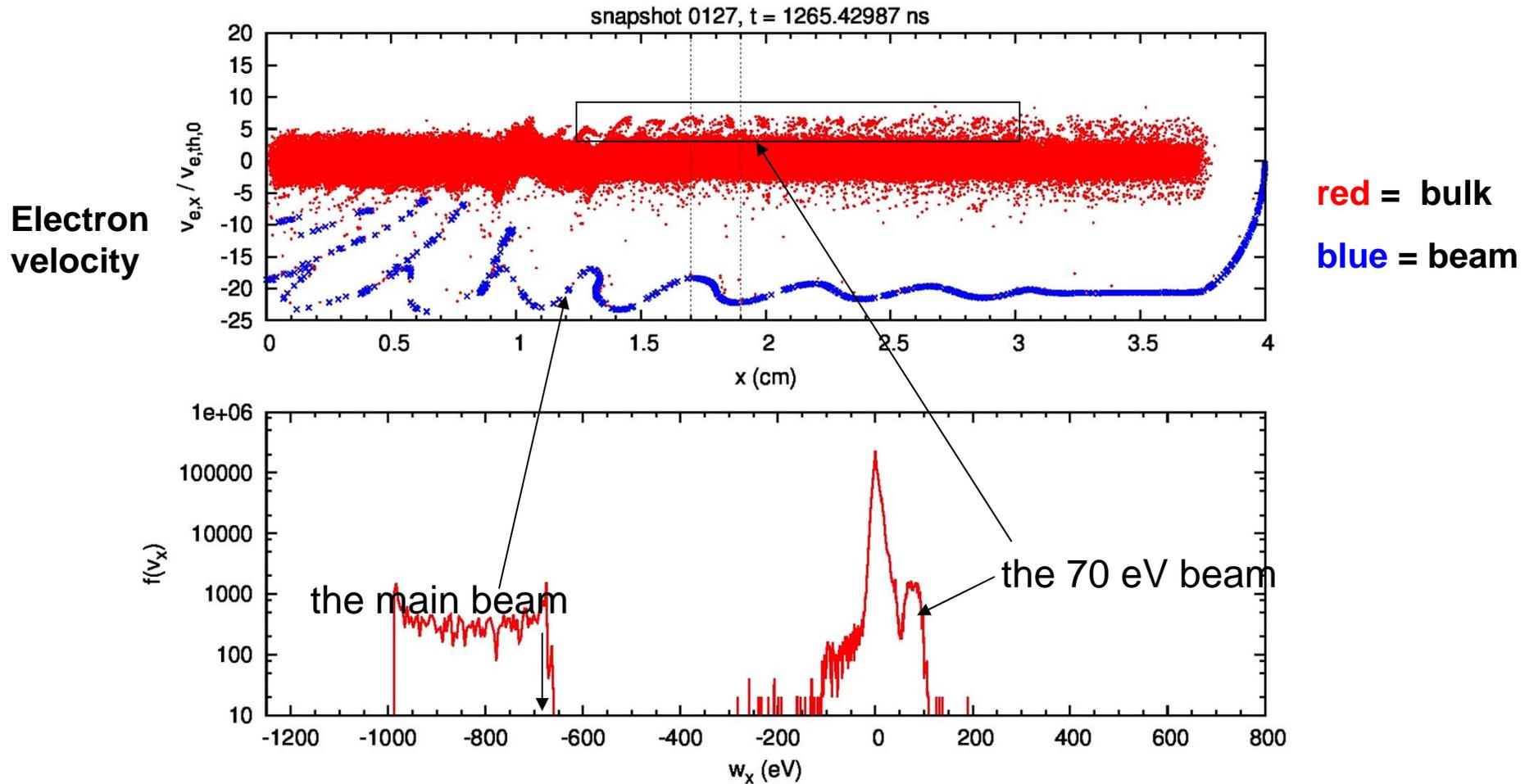
We performed large scaled simulations of this system millions of particles: 1000 spatial cells, 1000s particle per cell, time-averaging diagnostics for fine EVDF velocity and spatial resolution.

Observed excitation of plasma waves by the beam, then excitation of ion acoustic waves and intermittency of plasma turbulence. The electric field in plasma waves may be strong enough ($\sim 1\text{kV/cm}$) to cause substantial direct plasma electron acceleration.



Beam energy is given by the DC potential, 800V

INTENSE LOCALIZED HF ELECTRIC FIELDS MAY BE A SOURCE OF MEDIUM-ENERGY ELECTRONS

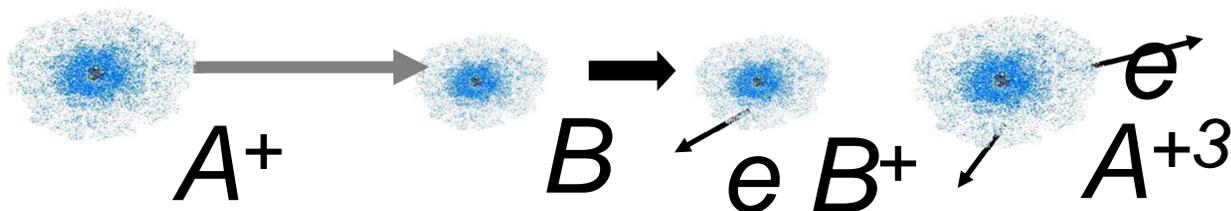


FUTURE DIRECTION AND PROGRESS

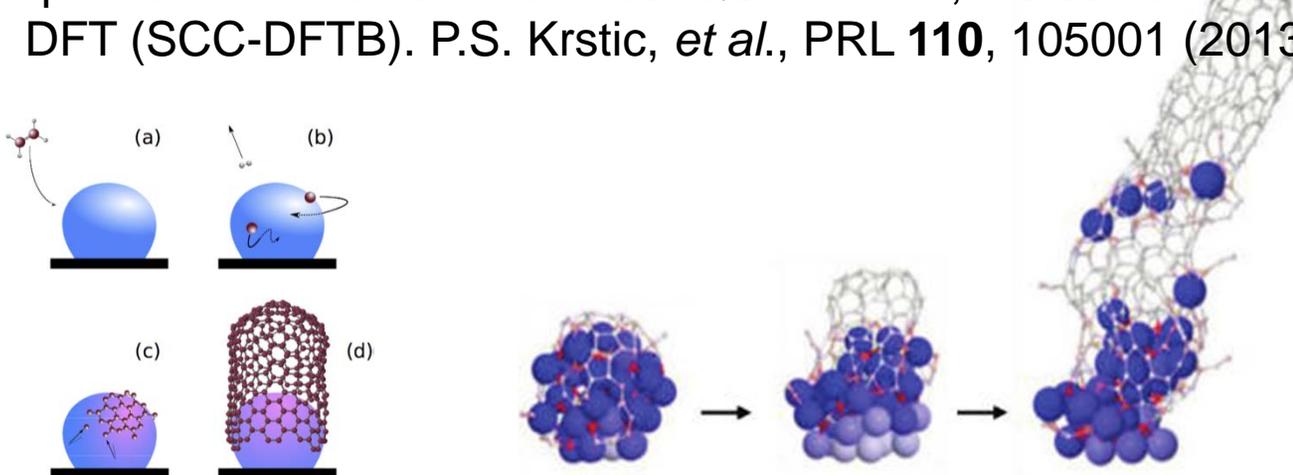
DEVELOPMENT OF SUITE OF ATOMISTIC CODES FOR FUSION, ADVANCED MATERIALS AND WARM DENSE MATTER APPLICATIONS

I.D. Kaganovich, E.A. Startsev, P. Krstic, R. Car, D. Stotler, R.C. Davidson

Developed models of charge-changing collisions. NJ. Phys. (2006), PRA (2003), NIMA (2009).



For simulations of *in situ* dynamics of complex systems like a plasma-material interface and nanomaterial growth, we plan to use combination of classical molecular and quantum-mechanical methods. QCMD: DFT, the self-consistent-charge tight-binding DFT (SCC-DFTB). P.S. Krstic, *et al.*, PRL **110**, 105001 (2013).



Effects of Electron-Induced Secondary Electron Emission (SEE) on Plasma-Wall Interactions

Yevgeny Raitses and Igor Kaganovich

Status quo: Plasma with a strong SEE is relevant to plasma thrusters, high power MW devices, etc. Strong SEE can significantly alter plasma-wall interaction affecting thruster performance and lifetime. The observed SEE effects in thrusters requires fully kinetic modeling of plasma-wall interaction.

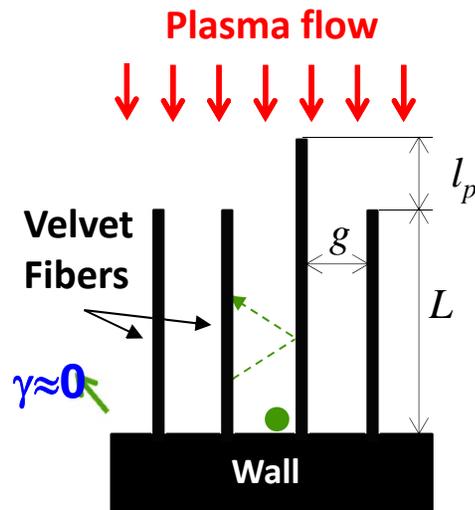
New insight: Engineered materials with surface architecture can be used to control and suppress SEE.

Project goal: Characterize effects of surface architecture on SEE and plasma-wall interaction

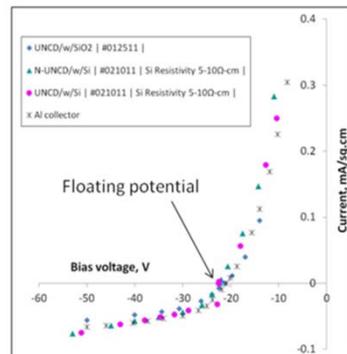
Main accomplishments

Surface architecture of engineered materials may induce undesired electron field emission

How it works:



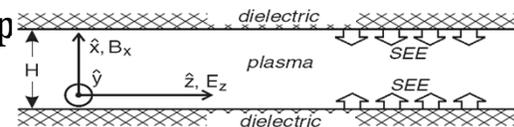
Nanocrystalline diamond coating exposed to plasma



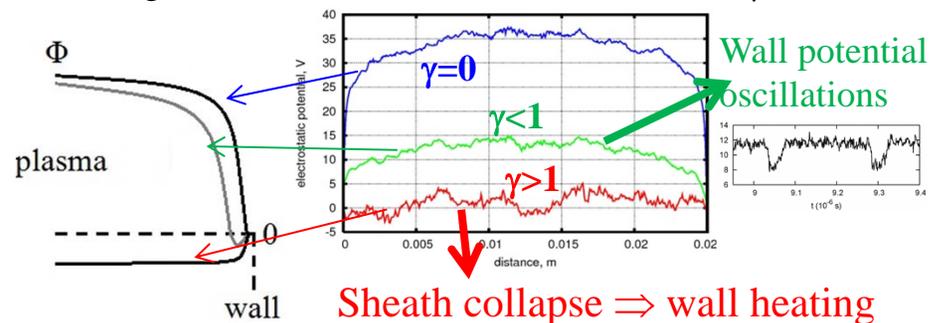
No arcing \Rightarrow No damage to diamond coating

To avoid field emission $g, l_p < \lambda_D$, Debye length

Kinetic modeling predict new plasma regimes with strong SEE: unstable sheath, sheath collapse



Three regimes for different effective SEE yield, γ



Key publications in 2012

Phys. Rev. Lett. **108**, 255001; Phys. Rev. Lett. **108**, 235001
 Phys. Plasmas **19**, 123513; Rev. Sci. Instr. **83**, 103502;
 Phys. Plasmas **19**, 093511

Secondary Electron Emission in the Limit of Low Energy and its Effect on High Energy Physics Accelerators

A. N. ANDRONOV, A. S. SMIRNOV,

St. Petersburg State Polytechnical University

I. D. KAGANOVICH, E. A. STARTSEV, Y. RAITSES, R. C.
DAVIDSON

Plasma Physics Laboratory, Princeton University

V. DEMIDOV

West Virginia University

Is the secondary electron emission coefficient approaches unity in the limit of zero primary electron energy?

VOLUME 93, NUMBER 1

PHYSICAL REVIEW LETTERS

week ending
2 JULY 2004

Can Low-Energy Electrons Affect High-Energy Physics Accelerators?

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¹*LNF-INFN, Frascati, Italy*

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(Received 10 February 2004; published 29 June 2004)

Present and future accelerators' performances may be limited by the electron cloud (EC) effect. The EC formation and evolution are determined by the wall-surface properties of the accelerator vacuum chamber. We present measurements of the total secondary electron yield (SEY) and the related energy distribution curves of the secondary electrons as a function of incident-electron energy. Particular attention has been paid to the emission process due to very low-energy primary electrons (<20 eV). It is shown that the SEY approaches unity and the reflected electron component is predominant in the limit of zero primary incident electron energy. Motivated by these measurements, we have used state-of-the-art EC simulation codes to predict how these results may impact the production of the electron cloud in the Large Hadron Collider, under construction at CERN, and the related surface heat load.

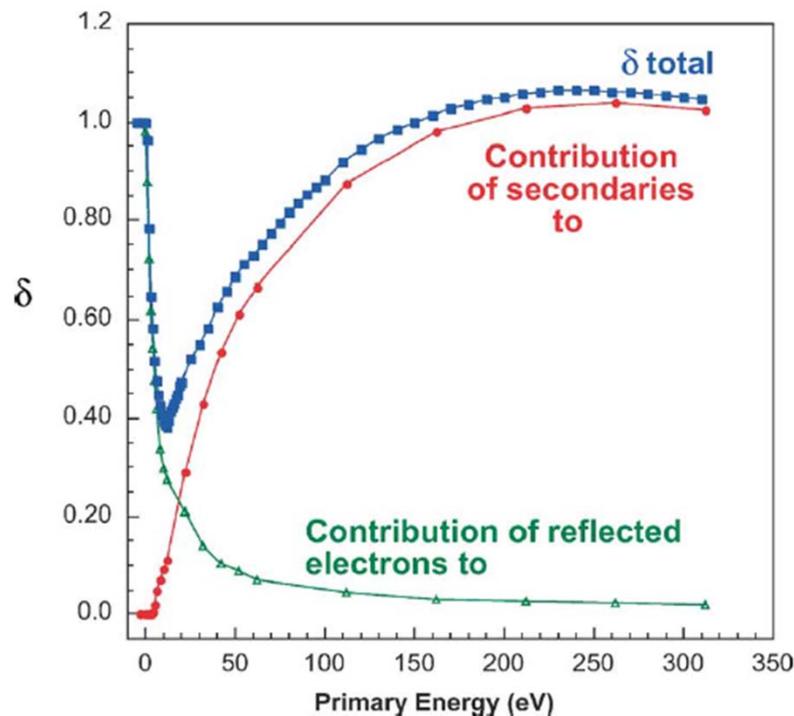
DOI: 10.1103/PhysRevLett.93.014801

PACS numbers: 29.27.Bd, 41.75.Lx, 79.20.Hx

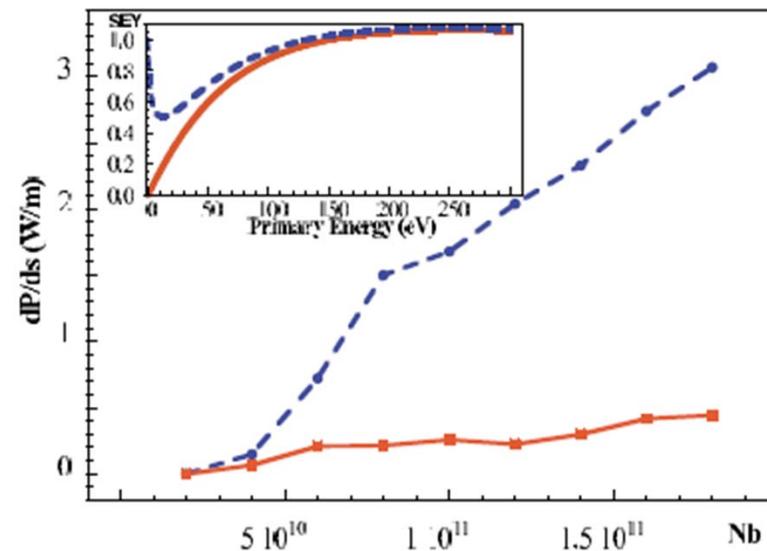
Implications of the secondary electron emission coefficient approaching unity in the limit of zero primary electron energy

Total secondary electron emission coefficient (δ) and contribution to it of secondaries and reflected electrons from a fully scrubbed Cu surface at 9 K as a function of primary electron energy.

R. Cimino, I.R. Collins/Applied Surface Science 235 (2004) 231–235



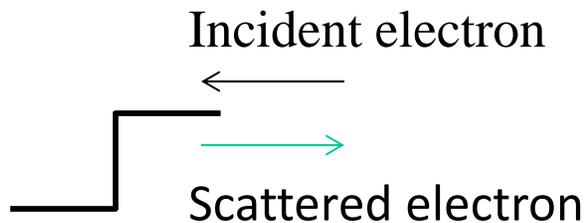
Simulated average heat load in an LHC dipole magnet as a function of proton bunch population at 0.45 TeV, for a SEY *considering the elastic reflection (dashed line) or ignoring it (full line).*



Long (forgotten) history of secondary electron emission studies suggests otherwise.

- Theoretical
 - Quantum diffraction from potential barrier
- Experimental
 - Difficulties of measurements at low incident electron energy
 - Previous careful measurements showing contrary observation
 - Probe measurements in plasma will not work

Quantum diffraction from potential barrier



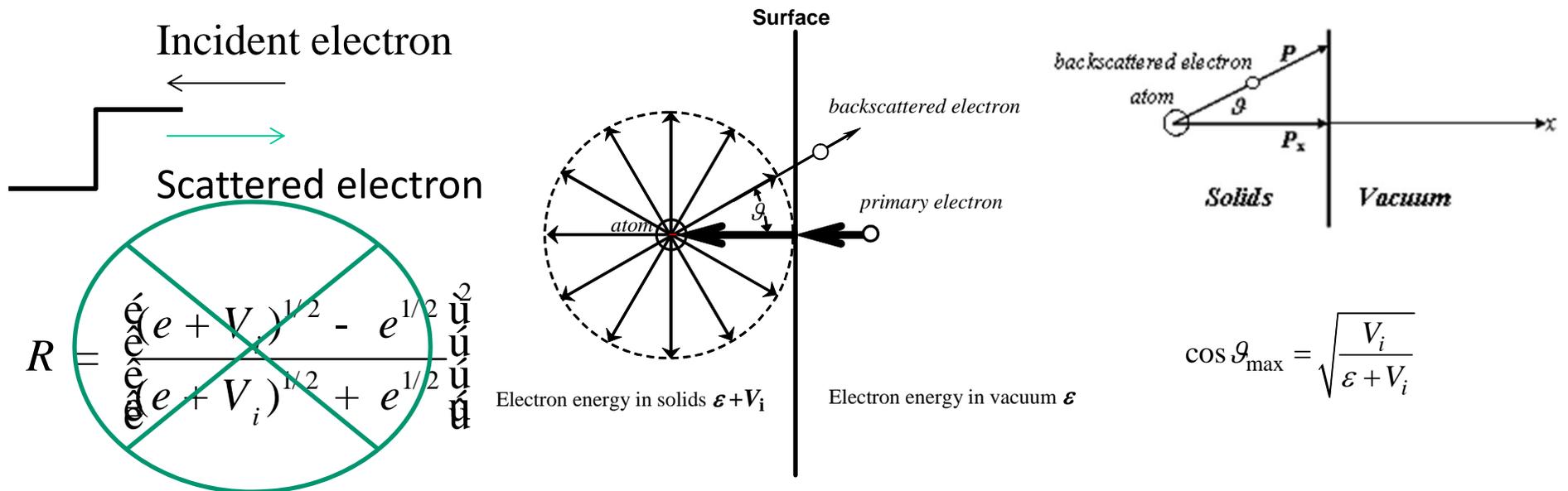
$$R = \frac{\epsilon(e + V_i)^{1/2} - e^{1/2} \hbar^2 u^2}{\epsilon(e + V_i)^{1/2} + e^{1/2} \hbar^2 u^2}$$

Quantum-mechanical effect due to electron diffraction off a simple negative potential step at the surface. The electron reflection coefficient, R , which is the ratio of the electron reflected and incident fluxes, for an electron with energy, ϵ , from a simple negative potential step (well) of amplitude V_i :

Here, V_i is the internal potential of solid, typically of 10-20 V, not 150V as mentioned in the Letter. Eq. gives $R=0.67$ for $\epsilon=0.01V_i$, and $R=0.29$ for $\epsilon=0.1V_i$. However, relation for the reflection coefficient does not account for electron acceleration toward the surface by the image charge in the metal. Due to image charge, an electron with negligible initial energy approaches the surface with energy of the order internal potential of solid. Detail calculation taking the image charge force into account [1] gives $R=2-4\%$, for typical values of the internal potential of solid 10 eV.

[1]. L. A. MacColl, Phys. Rev. 56, 699 (1939).

Quantum diffraction from potential barrier



Due to image charge, an electron with negligible initial energy approaches the surface with energy of the order internal potential of solid. Electrons are scatter in collisions with atoms and cannot overcome barrier due to smaller normal to the surface velocity. Therefore, the escape angle and, as a result, escape probability and R go to zero when $\epsilon \rightarrow 0^*$.

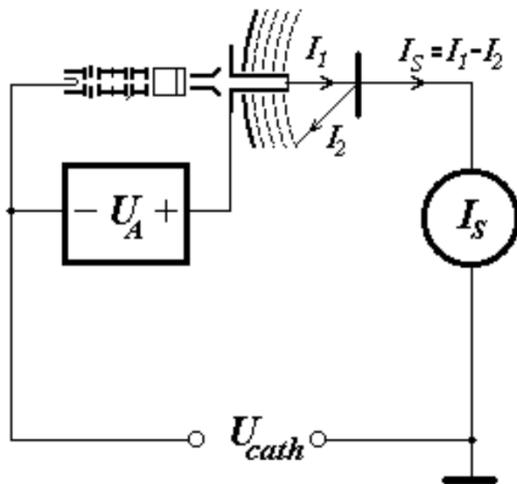
*I. M Bronshtein, B. S Fraiman. Secondary Electron Emission. Moscow, Russia: Atomizdat, p. 408 (1969).

It is very difficult to produce collimated electron beam with few eV energy for measurements of secondary electron emission coefficient at low incident electron energy.

An electron gun is at fixed energy.

Electrons are decelerated with a retarding potential at the target. =>

The energy spectrum of electrons arriving at the target is not known sufficiently, and many of returning electrons are reflected from a retarding electric field without any interaction with the target.

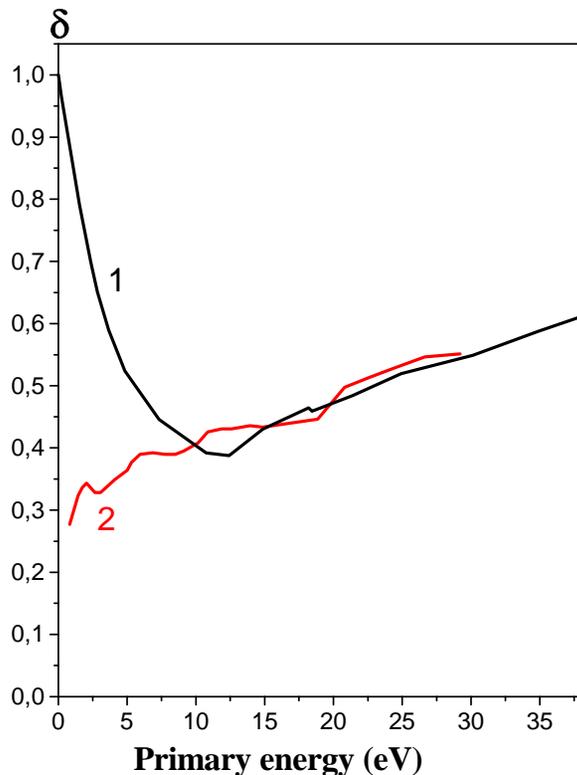


R. Cimino, I.R. Collins / Applied Surface Science 235 (2004) 231–235

machine. To measure low-energy impinging primary electrons, a negative bias voltage was applied on the sample. Such a bias allows one to work at very low primary energy (close to 0 eV) while keeping the gun in a region where it is stable and focused, as measured by a line profile on a 1 mm slot Faraday cup. The

Previous careful measurements showing contrary observation

Total secondary electron yield of Cu as a function of incident electron energy.
1. from the letter for fully scrubbed Cu ($T=10$ K). 2. Experimental data for bulk Cu after heating in vacuum (room temperature).



1. R. Cimino, et al, Phys. Rev. Lett. **93**, 014801 (2004).
2. I. M Bronshtein, B. S Fraiman. Secondary Electron Emission. Moscow, Russia: Atomizdat, p. 408 (1969).

Other measurements reported the reflection coefficient of about 7% for incident electron energy below few electron volts for most pure metals.

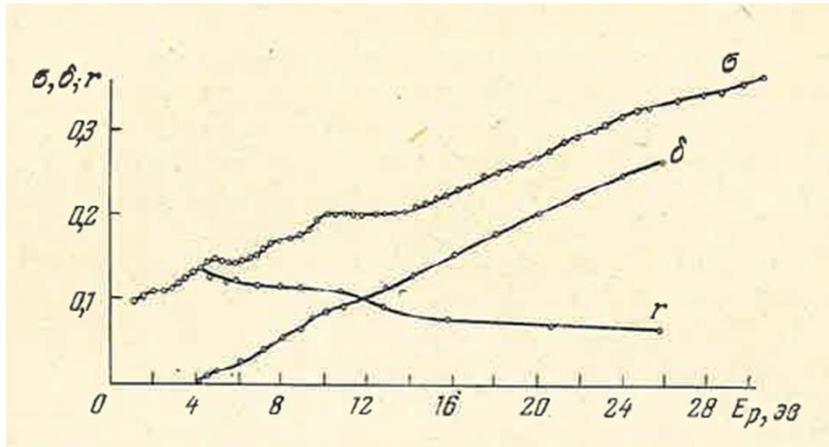
I.H. Khan, J. P. Hobson, and R.A. Armstrong, Phys. Rev. 129, 1513 (1963).

H. Heil, Phys. Rev. **164**, 887, (1967).

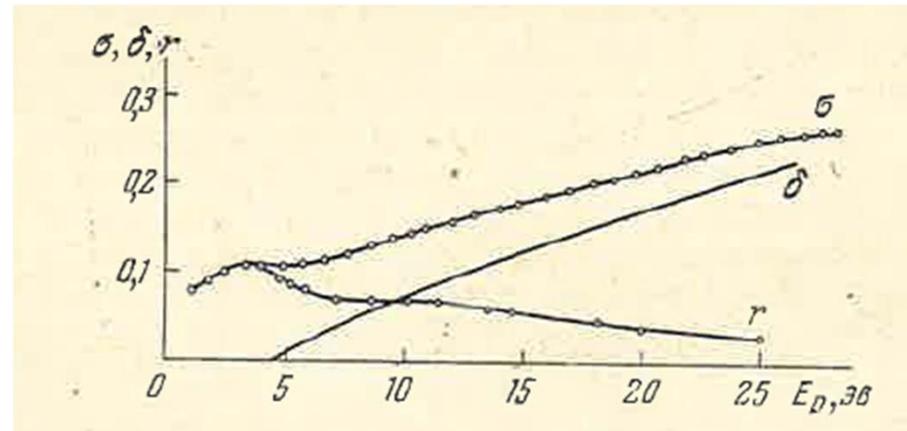
Z. Yakubova and N. A. Gorbatyi, Russian Physics Journal, 13 1477 (1970).

Previous careful measurements showing contrary observation

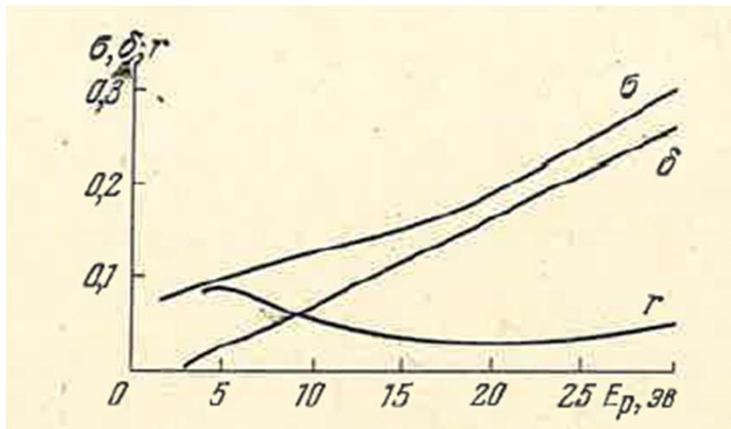
Total secondary electron yield of Al as a function of incident electron energy.



Total secondary electron yield of Ni.



Total secondary electron yield of Si.



I. M Bronshtein, B. S Fraiman. Secondary Electron Emission. Moscow, Russia: Atomizdat, p. 60 (1969).

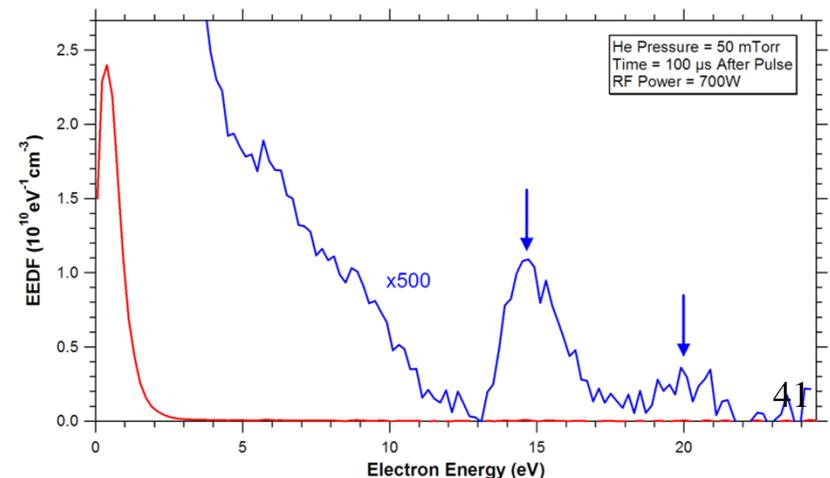
If the reflection coefficient of low energy electrons is large, the operation of probes collecting electron current will be strongly affected¹

This has not been observed. In the afterglow, electrons cool rapidly to $T_e \sim 0.2$ eV. A small amount of fast electrons with well defined energy arise from the Penning ionization



By measuring probe characteristic it is possible to determine if the peak on probe characteristic is widen or shifted relative to the value due to electron reflection from the probe surface. It was shown that there is no change in probe characteristics for clean probe within accuracy 0.16eV^2 .

1. K. Wiesemann, Ann. Phys. *Lpz* **27** 303 (1971).
2. V. I. Demidov, N. B. Kolokolov, and O. G. Toronov, Sov. Phys. Tech. Phys. **29**, 230 (1984).



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Y. Raitses, I. D. Kaganovich, A. Khrabrov, D. Sydorenko, N. J. Fisch, and A. Smolyakov, IEEE Transactions on Plasma Science **39**, 995 (2011)

M. D. Campanell, A.V. Khrabrov, and I. D. Kaganovich, Phys. Rev. Lett. **108**, 255001 (2012)

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A.N. Andronov, A.S. Smirnov, I.D. Kaganovich, E.A. Startsev, Y. Raitses, R.C Davidson, and V. Demidov, "SEE in the Limit of Low Energy and its Effect on High Energy Physics Accelerators", the 5th Electron-Cloud Workshop, ELOUD'12, La Biodola, Italy, June 2012

Y. Raitses and A. V. Sumant, "Plasma interactions with ultrananocrystalline diamond coating", XXI International Material Research Congress, Cancun, Mexico, August 2012

Conclusions

New study usually starts 20 years after old facts are forgotten.