Research Review Seminars

Fridays 10-11am in the theory conference room

The goals of these seminars are

- update on progress of individual research and future plans,
- disseminate this information broadly throughout the Department, and
- prepare for upcoming review of 5 year research plan of the Theory Department.

These seminars have the additional *pedagogical component* of explaining:

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

Describe **collaboration** opportunities inside the PPPL Theory Department that will benefit your project and address how you can help other relevant projects, as well as outline what the PPPL Theory Department could do to capture **future funding opportunities** in your field.

The anticipated **talk duration is 30 minutes** *plus sufficient time for questions and discussions*. Introduction and discussion above-mentioned issues should comprise at least half of the talk.

Research Review Seminars should address 5Year Plan review questions (1/3)

Scientific and/or technical merit of the project –

- *What important problem(s) in plasma or fusion science does this application address?*
- *How does the proposed research compare with other research in its field, both in terms of scientific and/or technical merit and originality?*
- *What is the likelihood that it will lead to new or fundamental advances in its field?*
- *How adequate are the proposed plans to validate, where appropriate, the theoretical predictions with experimental measurements?*

Appropriateness of the proposed method or approach –

- *Are the conceptual framework, methods, and analyses adequately developed and likely to lead to scientifically valid conclusions?*
- *Does the proposed research employ innovative concepts or methods?*
- *Does the proposed approach include elements that may be considered "high-risk / high-reward"? Please be specific.*
- *Does the applicant recognize significant potential problems and consider alternative strategies?*
-

Research Review Seminars should address 5Year Plan review questions (2/3)

Competency of the research team and adequacy of available resources

- *How well qualified are the applicant's personnel to carry out the proposed research? (If appropriate, please comment on the scientific reputation and quality of recent research by the principal investigator and other key personnel.)*
- *Please comment on the applicant's research environment and resources.*
- *Does the proposed work take advantage of unique facilities and capabilities and/or make good use of collaborative arrangements?*

Reasonableness and appropriateness of the proposed budget

- *Are the proposed budget and staffing levels adequate to carry out the proposed research?*

Research Review Seminars should address 5Year Plan review questions (3/3)

Performance under the Existing Award (if appropriate)

- *Assess the progress the applicants made during the most recent performance period and the impact of the research on the fusion program.*
- *Have the applicants disseminated the results of their research through publications in peer-reviewed journals, meeting and conference presentations, workshops, or other appropriate means?*
- *If appropriate, have the applicants attempted to validate their theoretical predictions against experimental results?*

The reviewers are also asked to comment on **Other appropriate factors**

- *What are the overall strengths and weaknesses of the application?*
- *Could the proposed research make a significant contribution to another field?*
- *If applicable, please comment on the educational benefits of the proposed activity.*

Applications from large theory groups will also be rated on the management plan and synergy of the group. With respect to synergy, the criteria are:

- *Clear evidence of collaborative work.*
- *The extent to which the group addresses difficult problems requiring a team effort.*

Tentative Schedule:

1/31 Igor Kaganovich

2/7 Nikolai Gorelenkov

2/14 Guoyong Fu

2/21- Science Bowl

2/28 Steve Jardin

3/7 CS Chang

3/14 Greg Hammett

3/21 John Krommes

Plasma-Surface Interactions

I.D. Kaganovich, A.V. Khrabrov, Y. Raitses, E. A. Startsev[(a)],
M. Campanell, E. Tokluoglu, H. Wang[(a)],
D. Sydorenko[(b)],
L. Chen, P. L. G. Ventzek[(c)],
V.I. Demidov[(d)],
J.P. Sheehan, N. Hershkowitz[(e)]
T. Sommerer[(f)]

(a) Princeton Plasma Physics Laboratory, USA
(b) Department of Physics, University of Alberta, Canada
(c) Tokyo Electron America, Austin, TX, USA
(d) West Virginia University, Morgantown, USA
(e) University of Wisconsin, Madison, USA
(f) General Electric Global Research, Niskayuna, NY

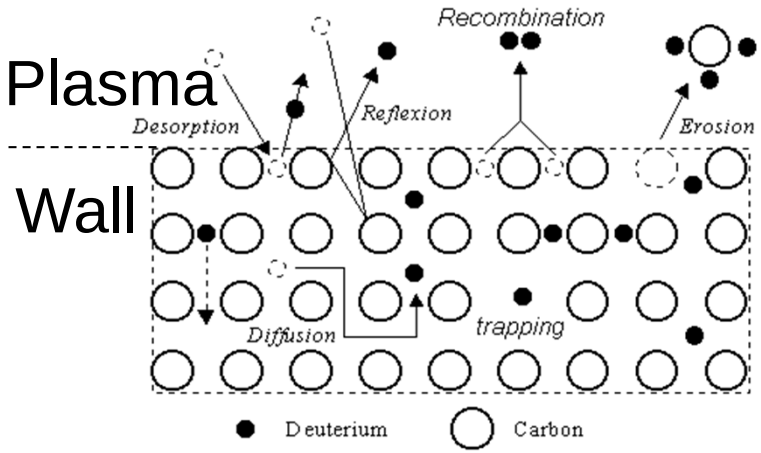
OUTLINE

- 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

PPPL
PRINCETON
PLASMA PHYSICS
LABORATORY

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.

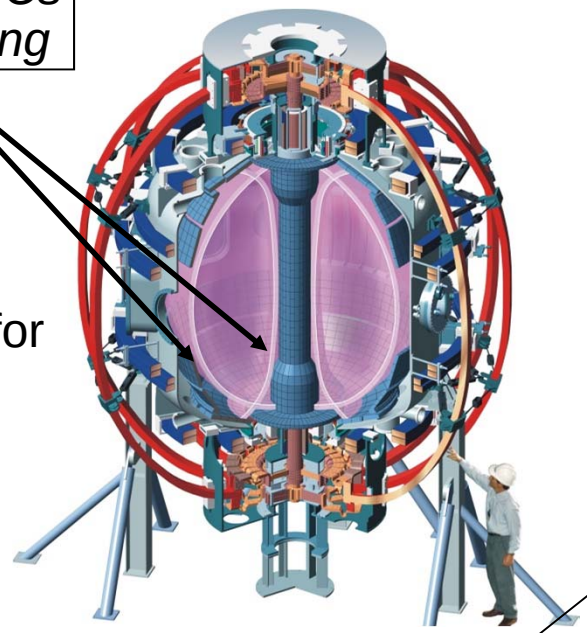
Note: Reactor must run 24/7

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

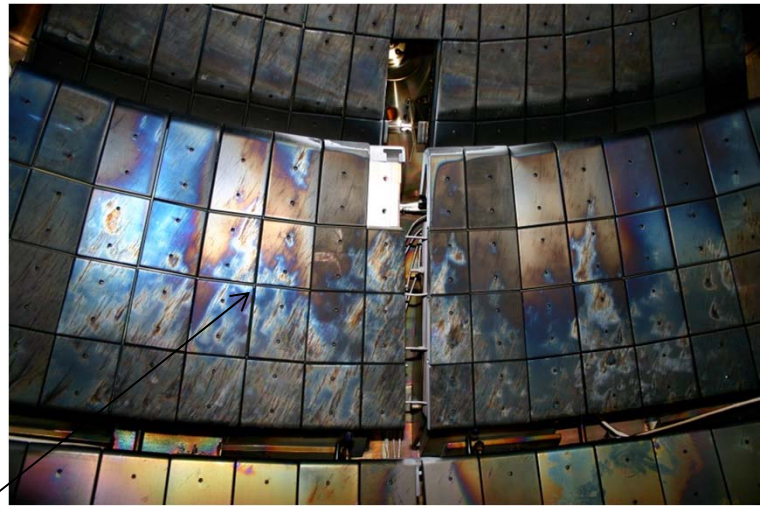
Surface coating can produce highly-localized plasma objects : *Unipolar Arcs*

Graphite/CFC PFCs with lithium coating

Confine a higher plasma pressure for a given magnetic field strength

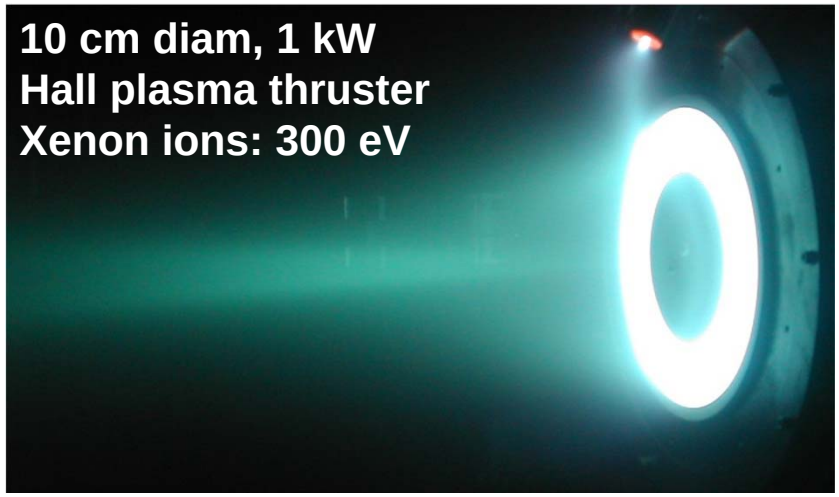


Signatures of unipolar arcs?



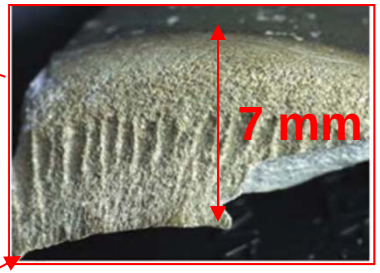
Traces of unipolar arcs

Wall erosion limits lifetime of plasma devices

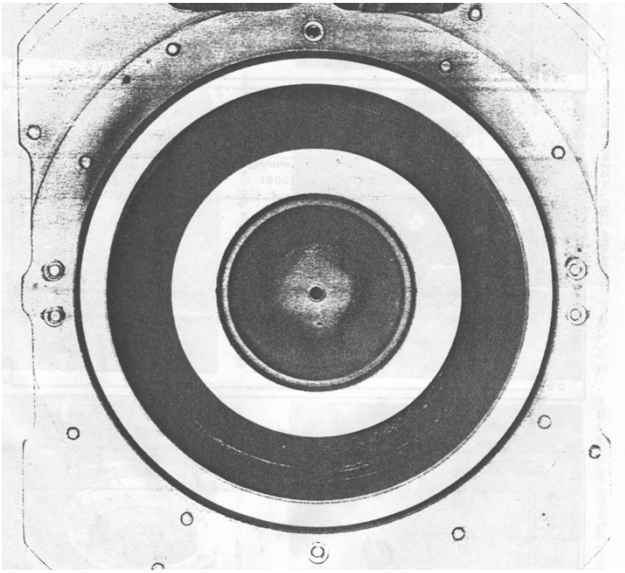


A non-uniformity of the SEE-induced near-wall electron current across B-field may explain a macroscopically inhomogeneous erosion patterns ~ $R_{Le} = mv_e/eB$

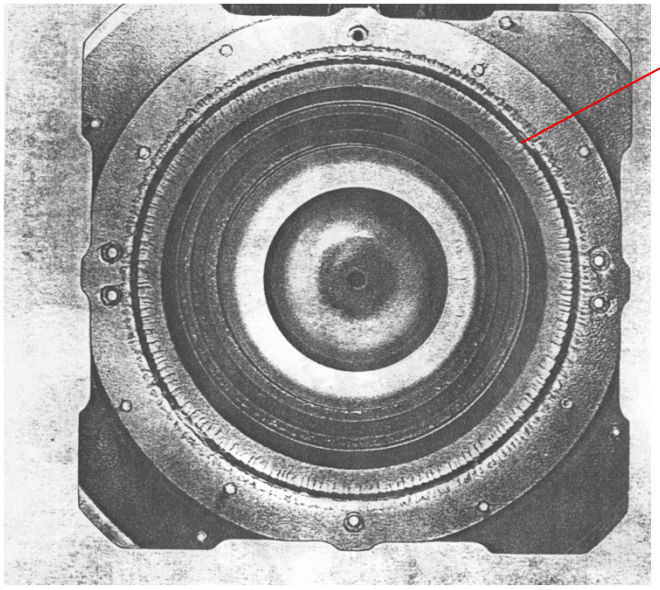
Morozov, Rev. Plasma Phys., 2000



Hall thruster (New)



Hall thruster after 6000 Hrs

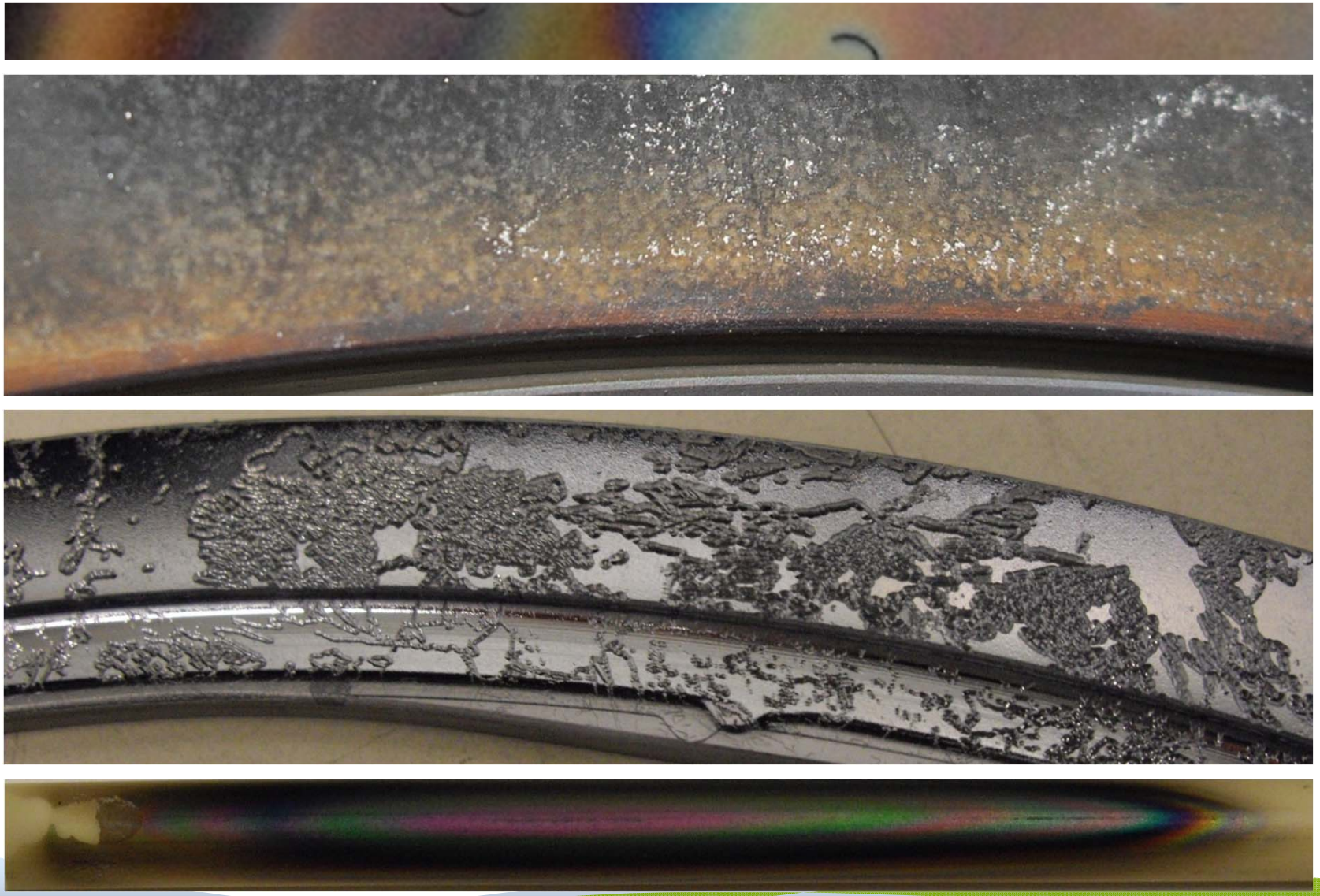


Courtesy:
L. King
F. Taccagona

MichiganTech

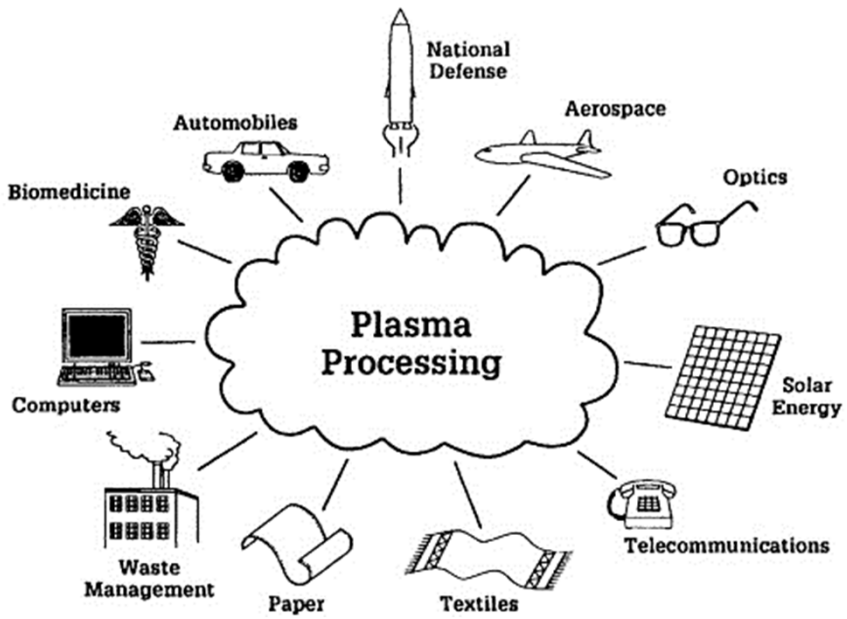
IMIP IPP

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

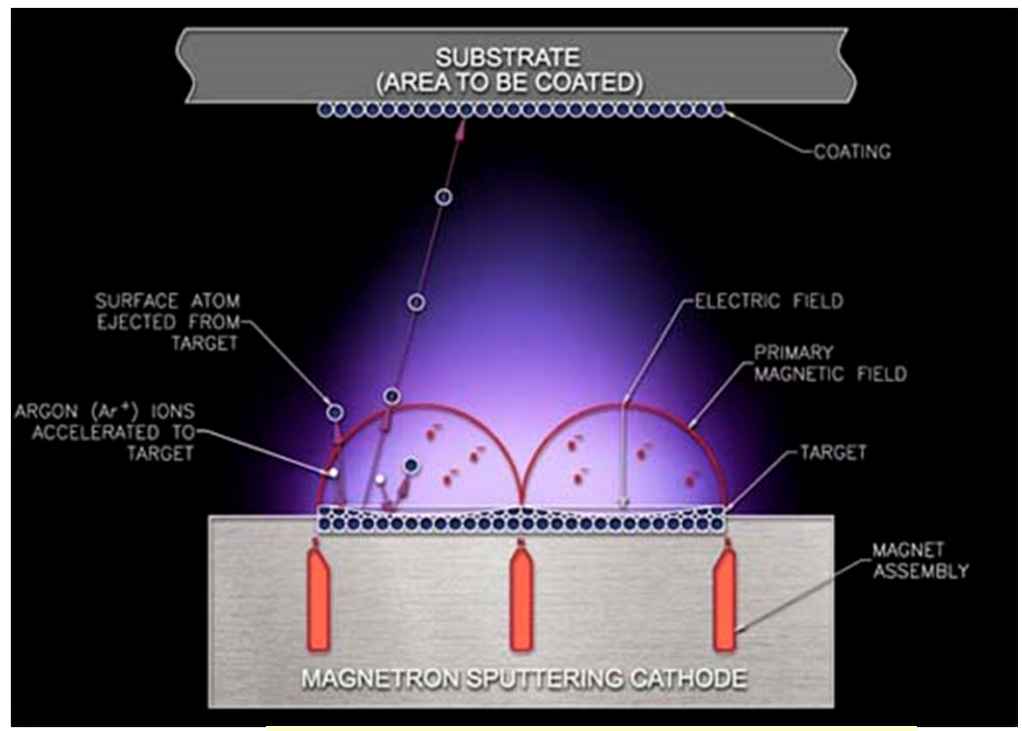


Leonid A. Dorf,
ETCH BUSINESS GROUP

In plasma processing technologies, plasma-surface interaction is everywhere



Example: deposition and coating of films by sputtering magnetron discharge

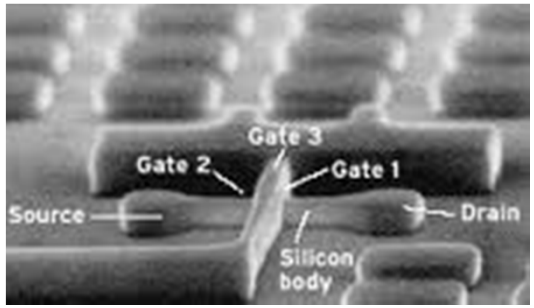


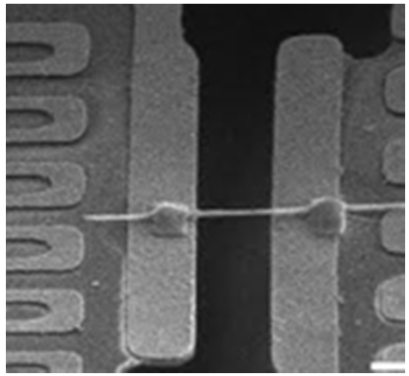
From: www.angstromsciences.com

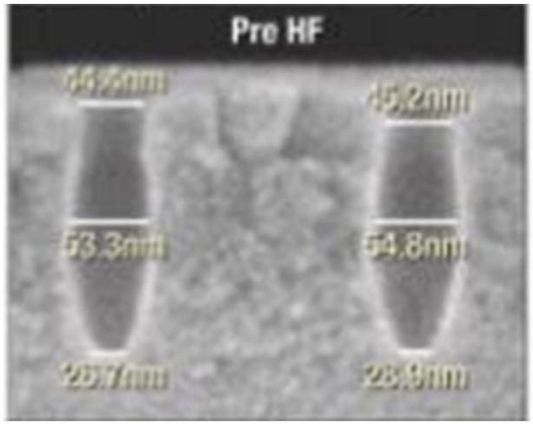
Magnetically enhanced ionization in E×B gas discharge, P ~ 3-5 mtorr

ISSUES OF SEMICONDUCTOR PRODUCTION EQUIPMENT MAKERS

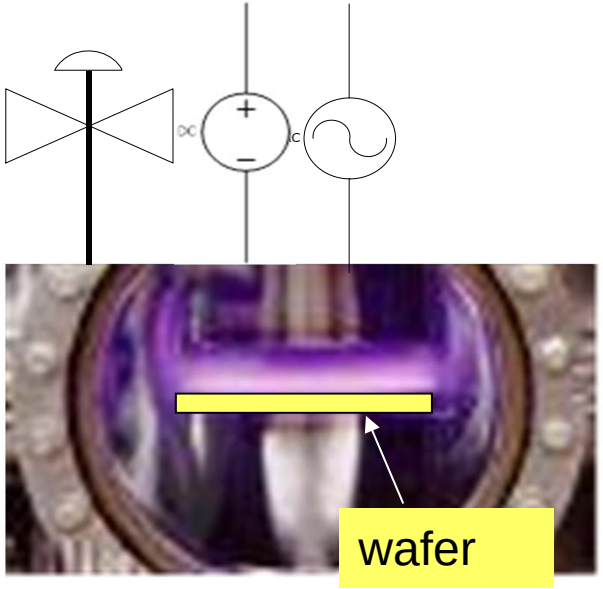
- **Processing Non-planar Features**
  - ***"Accessing dark corners and recesses"***
- **Maintaining the Integrity of Materials**
- **Selective Etching**
- **Deposition: Thinner complex materials**
- **Functionalization**







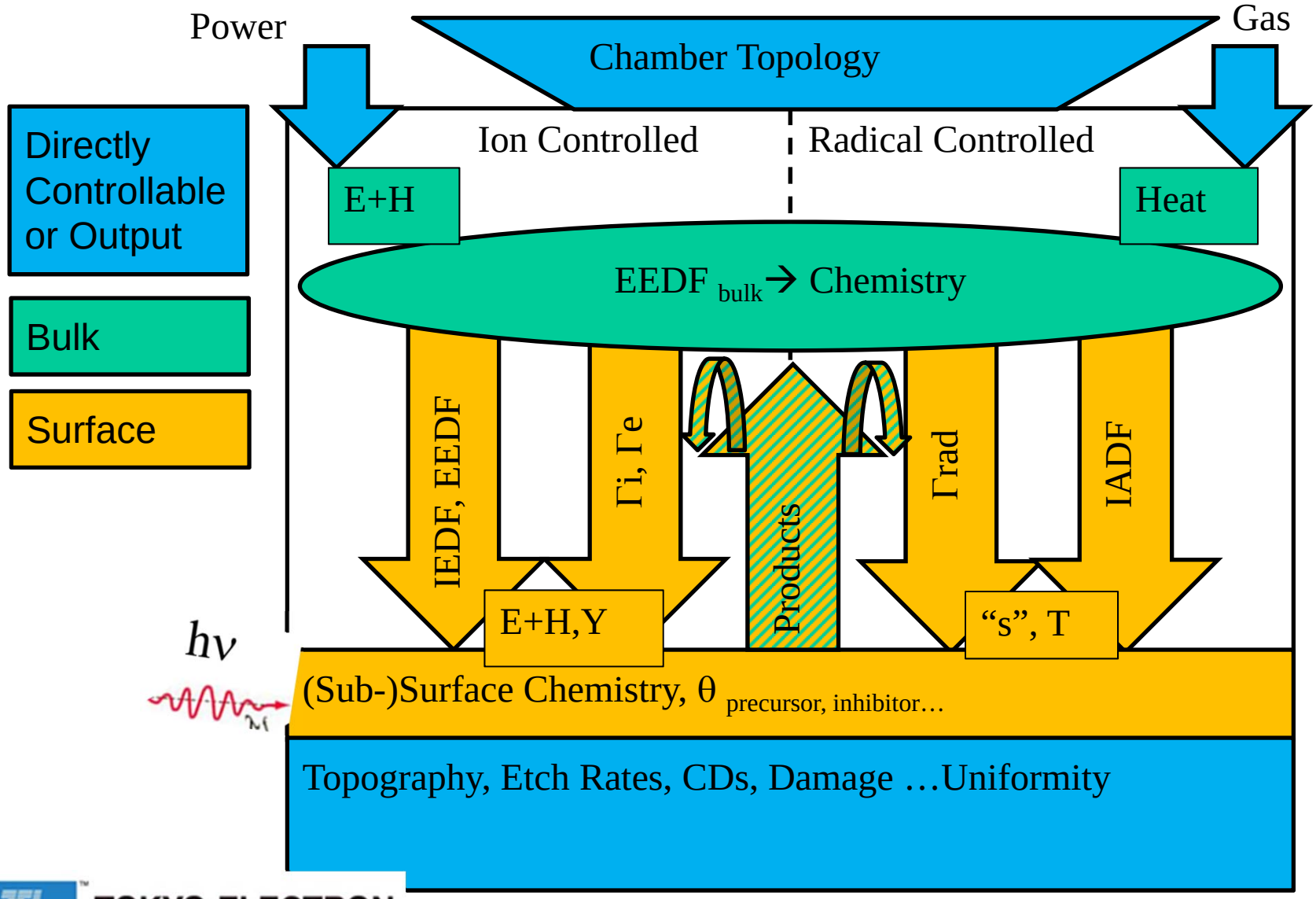
Process Settings



Courtesy of P. L. G. Ventzek

TOKYO ELECTRON

SEMICONDUCTOR EQUIPMENT REQUIRES PRECISE CONTROL OF PLASMA-SURFACE INTERACTION

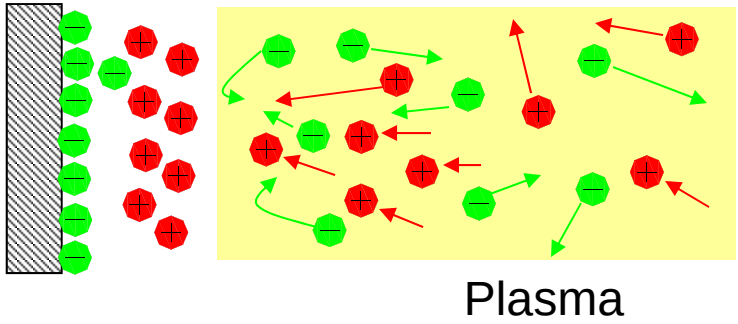


TOKYO ELECTRON

Courtesy of P. L. G. Ventzek

Sheath Insulate Wall from Electron Heat Flux

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

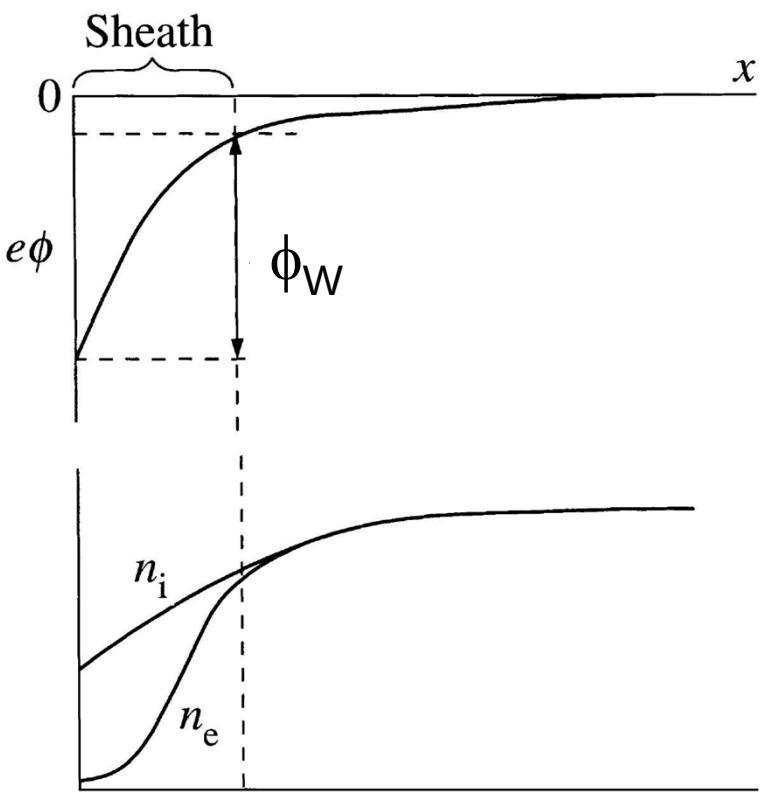


This induces an electric field to balances the flow of ions and electrons at the wall:

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

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

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



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)

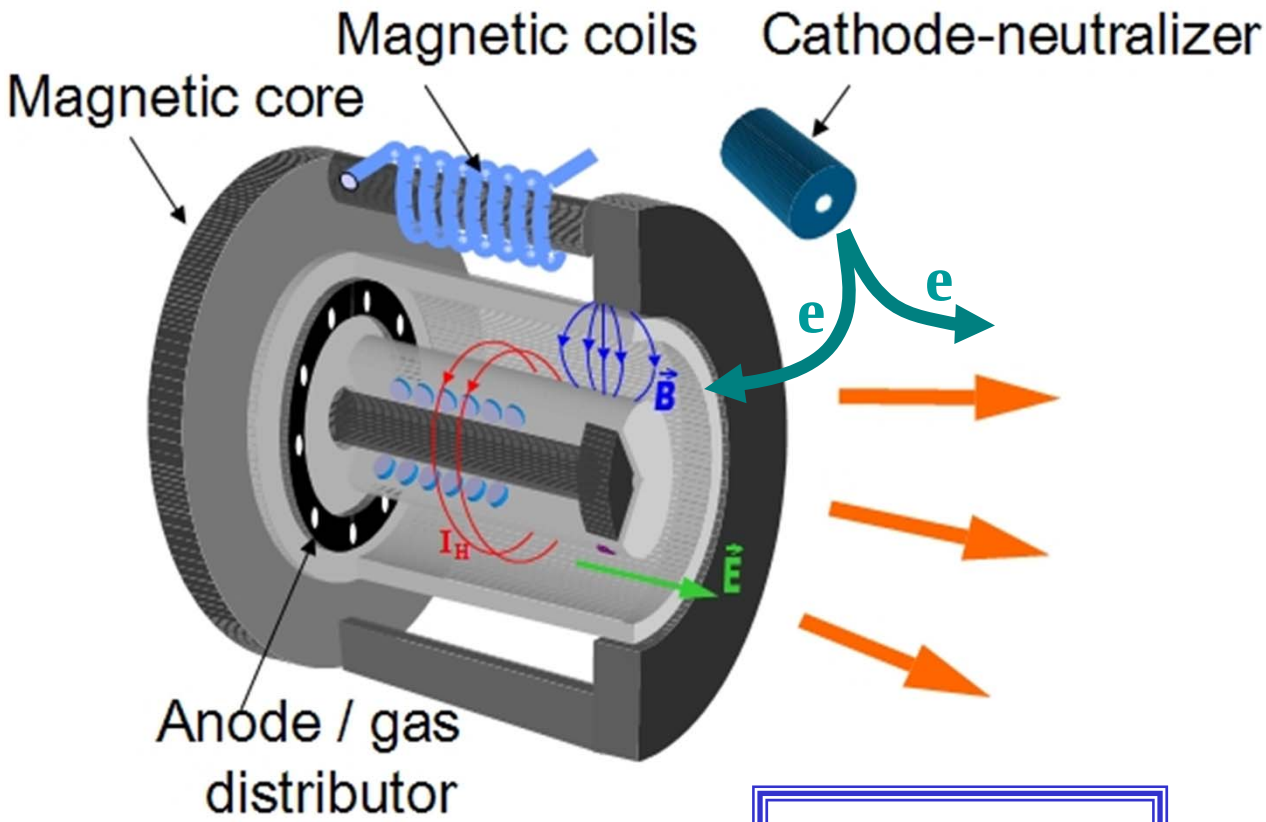
• Any plasma with electron temperatures above 20 eV for dielectric walls, and above 50-100 eV for metal walls is subject to strong secondary electron emission (SEE) effects:

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)



$\rho_e << L << \rho_i$

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

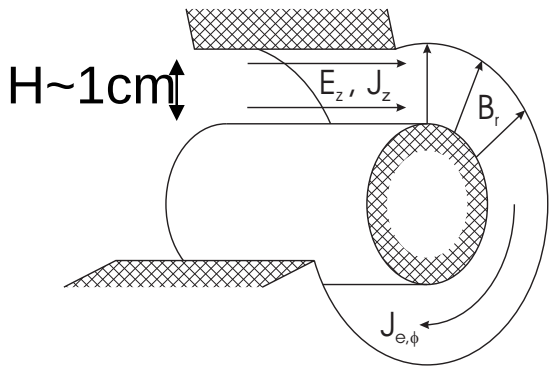
Isp ~ 1000-3000 sec

Efficiency ~ 6-70%

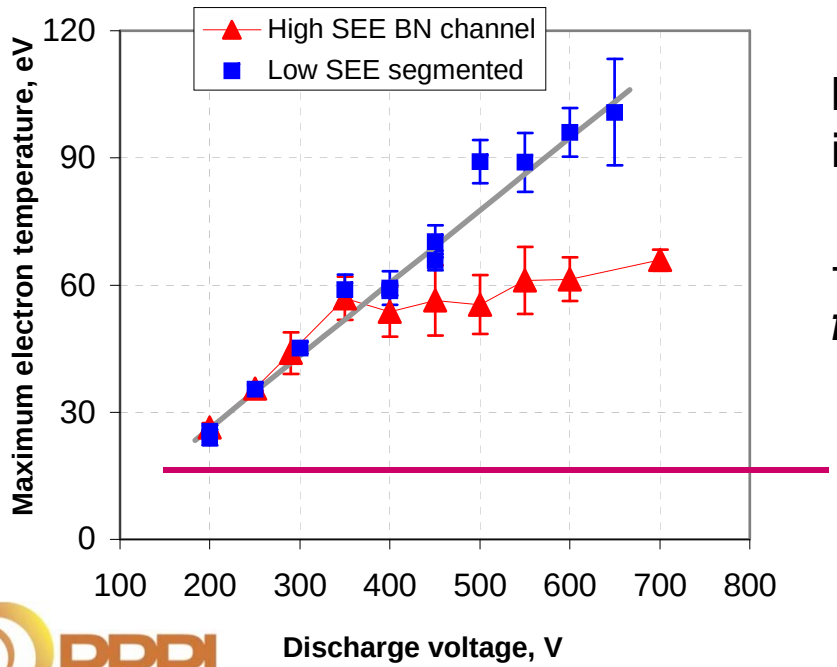
✓ HT is not space-charge limited.

✓ Higher current densities than in ion thrusters.

PLASMA-WALL INTERACTIONS IN HALL THRUSTERS



B ~ 100G, E ~ 100V/cm, T_e ~ 100eV. P=0.1-1mTorr, the plasma inside the thruster channel is collisionless, λ_{ec} (~1m) >> H (~1cm). => intense particle and heat wall losses!



High electron temperature is observed in experiments

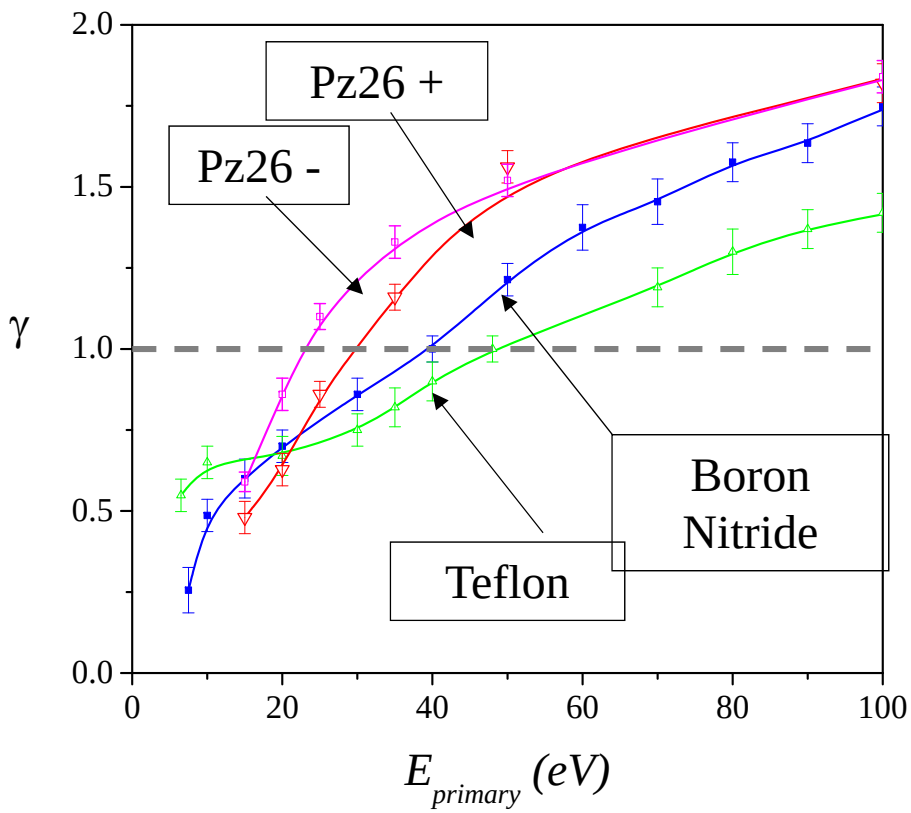
- ***Large quantitative disagreement with fluid theories.***

A fluid theory prediction.

PPPL PRINCETON PLASMA PHYSICS LABORATORY

From: Y. Raitses, *et al.*, Phys. Plasmas **13**, 014502 (2006).

Secondary electron emission yield from dielectric materials



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

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

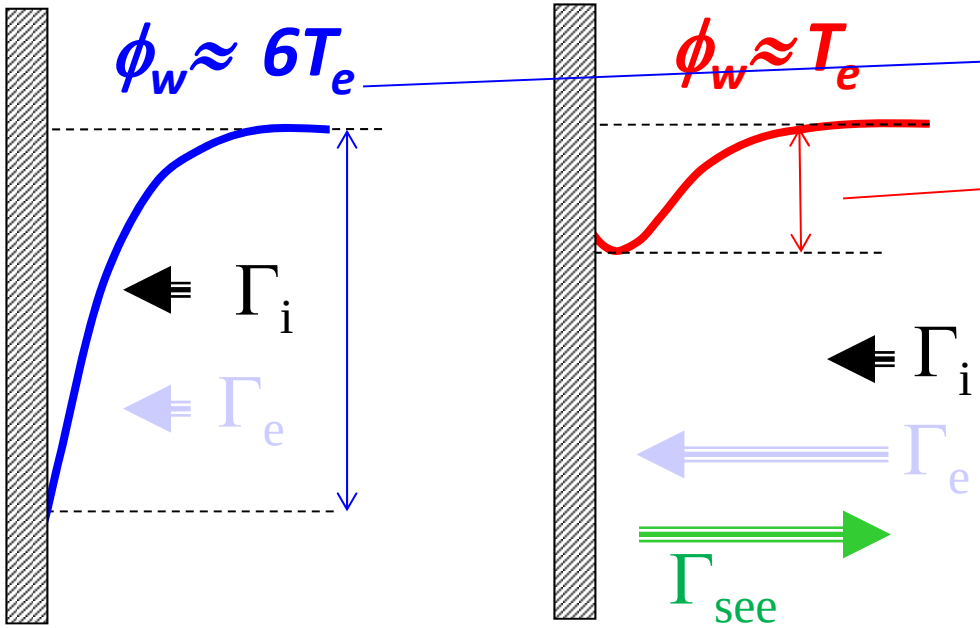
Dunaevsky et al., Phys. Plasmas, 2003

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)

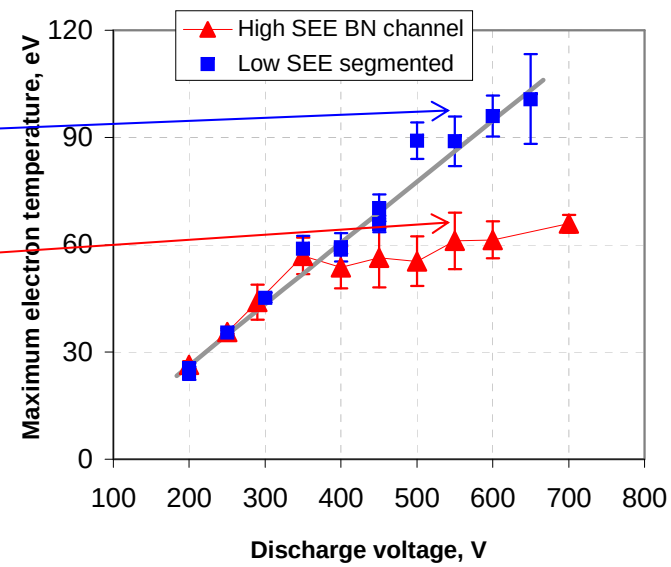
- SEE reduces the wall potential and allows large electron flux to the wall (Right Figure)

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



Wall - Sheath - Plasma

Wall – Sheath - Plasma

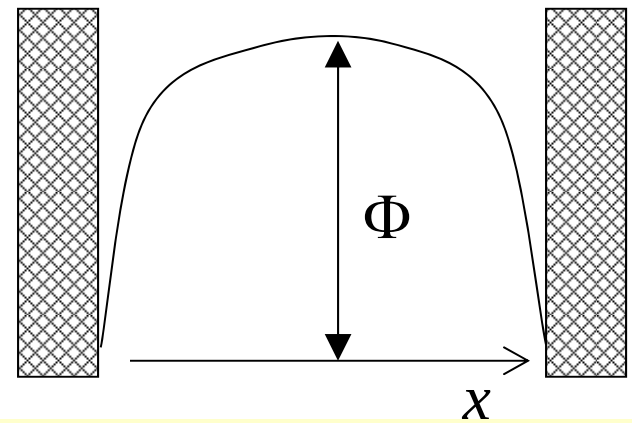


Y. Raitses et al., Phys. Plasmas 2005
Y. Raitses et al., IEEE TPS 2011

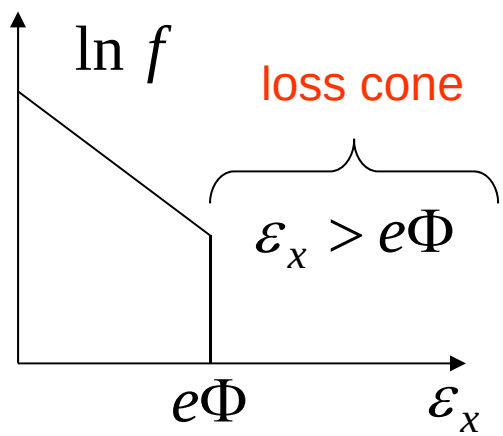
Kinetic effects may modify wall losses in collisionless plasmas

- DC discharge - EVDF is depleted in the loss cone [Tsendin, 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 >> system size

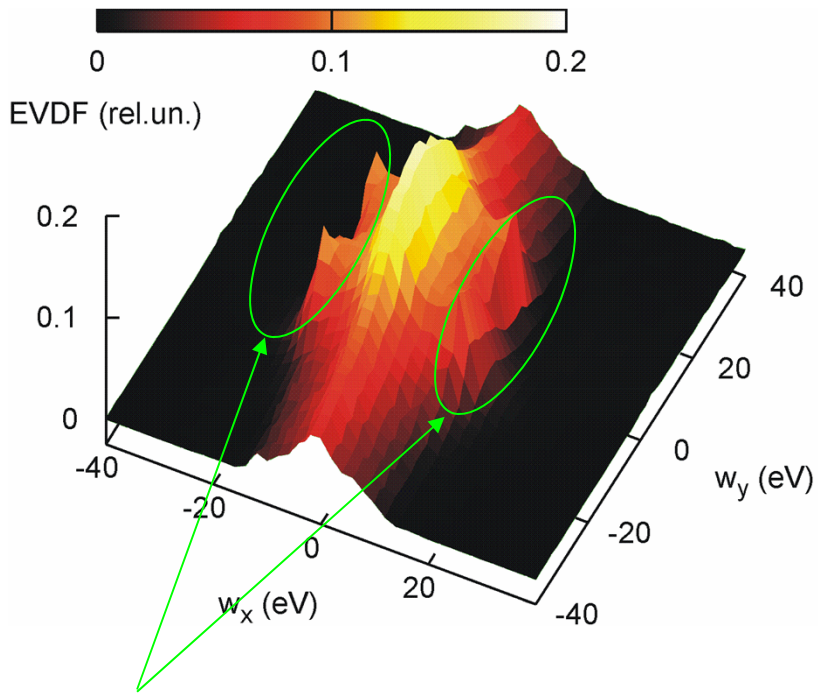


Electrons with $\varepsilon > e\phi$ leave.

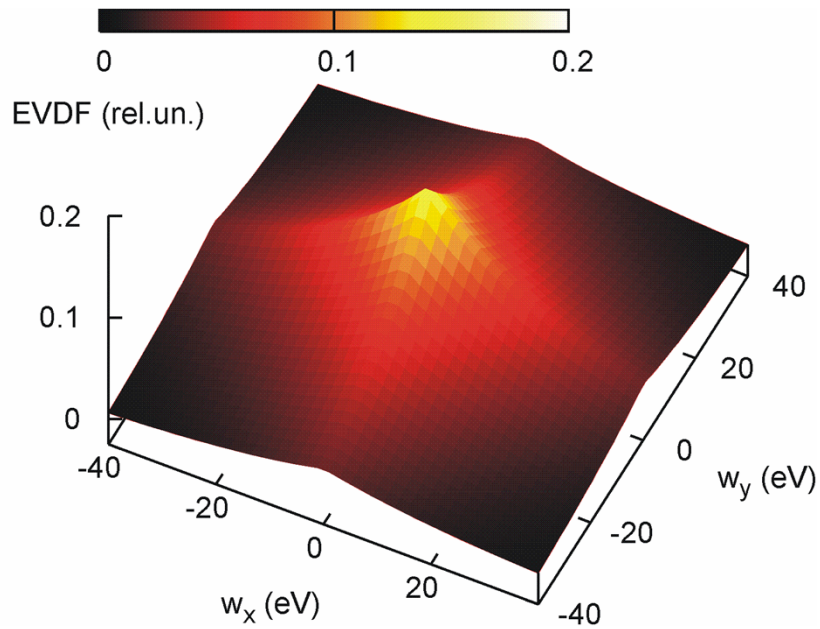


EVDF in HT is strongly anisotropic with beams of SEE electrons

Hall thruster plasma, 2D-EVDF



Isotropic Maxwellian plasma, 2D-EVDF



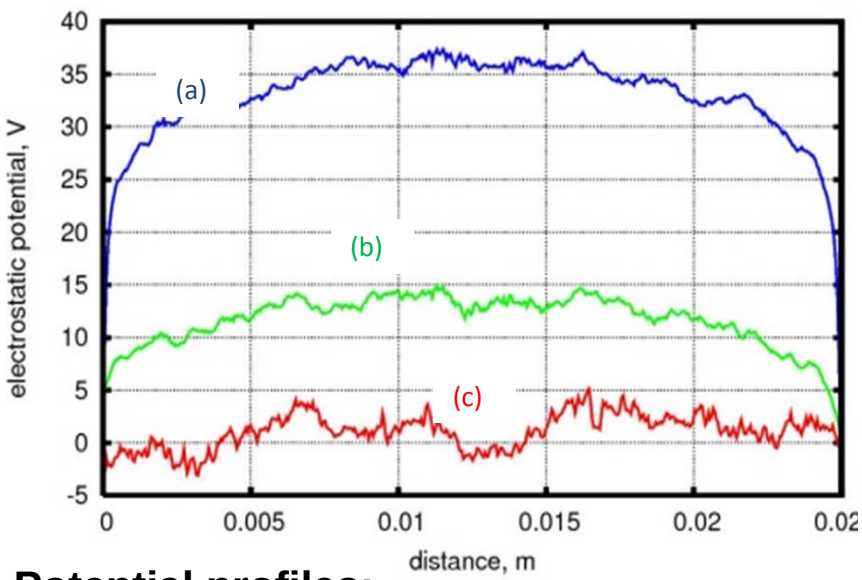
Loss cones and beams

- **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.**

Sydorenko et al, Phys. Plasmas 2006

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].**



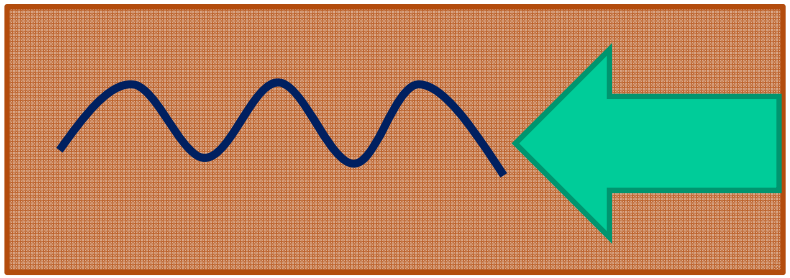
Potential profiles:
(a) E=200V/cm no emission
(b) E=200V/cm with SEE,
(c) E =250V/cm with SEE [1,3]

- **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.



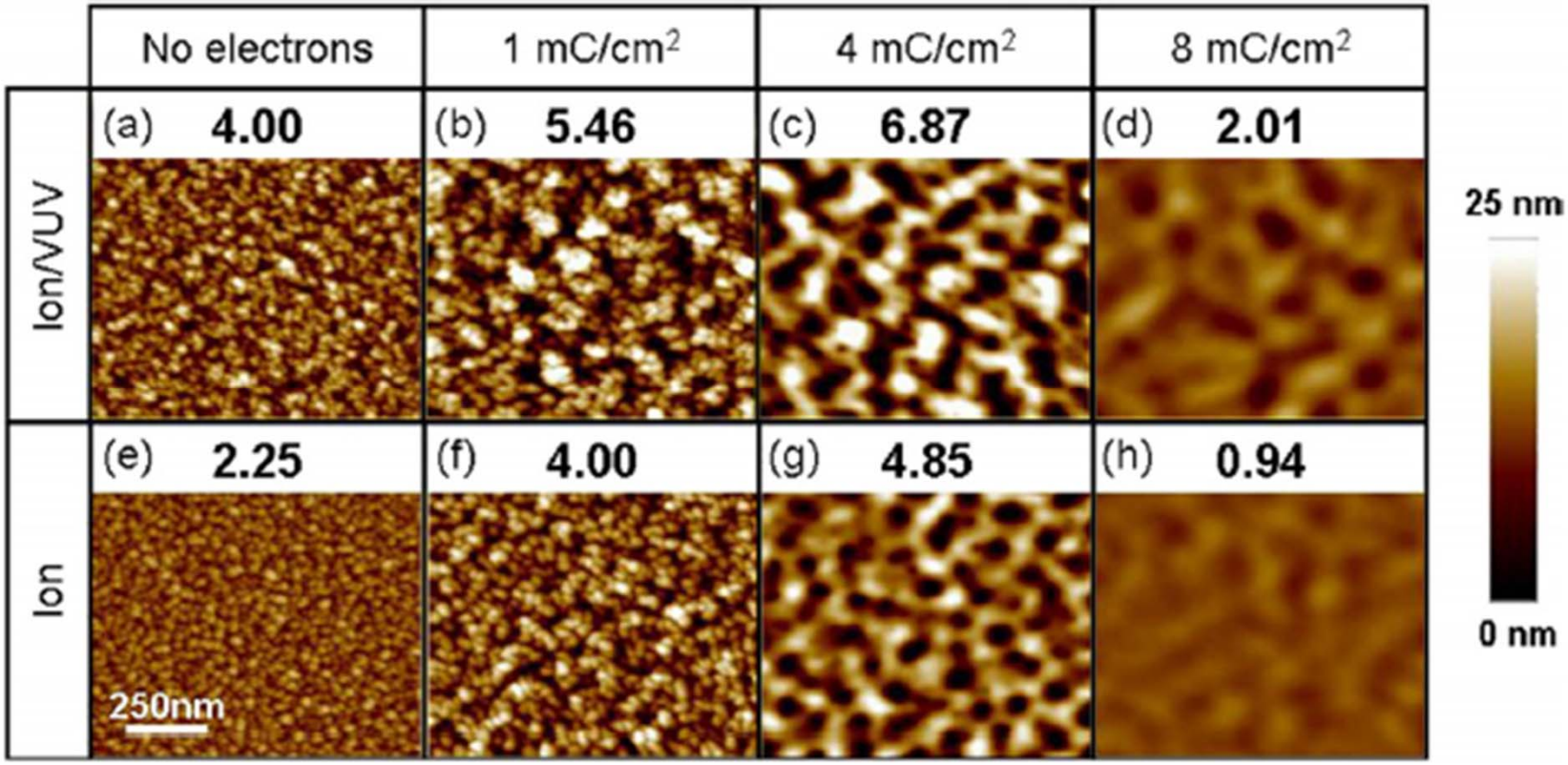
Questions:

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).**

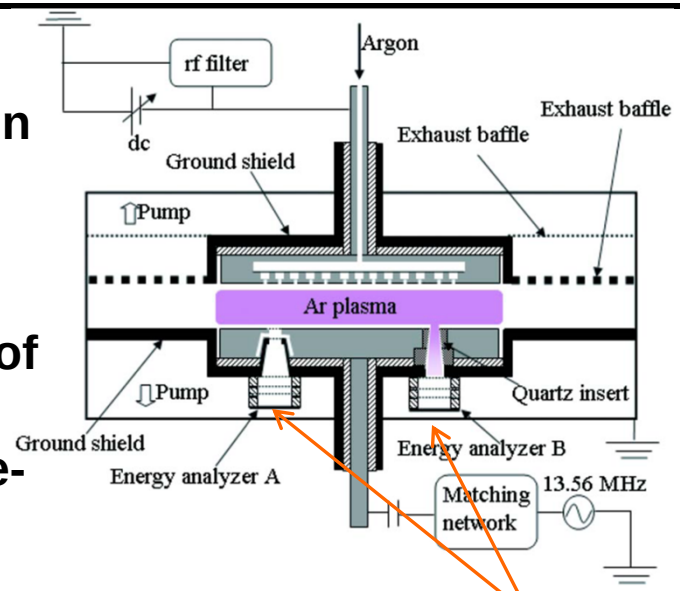


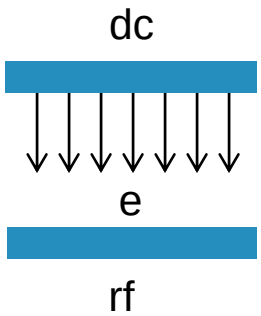
OBSERVATION OF MULTI-PEAK ELECTRON VELOCITY DISTRIBUTION FUNCTION

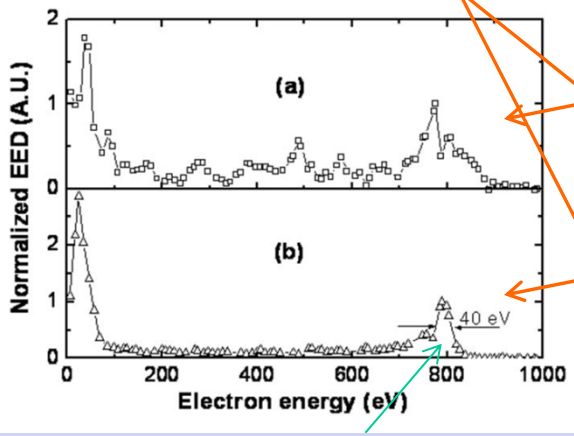
In experiments, Xu et al., APL 93 (2008) reproducible structures were observed in electron energy distributions at the RF electrode.

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 (~1kV/cm) to cause substantial direct plasma electron acceleration.







Energy analyzer A

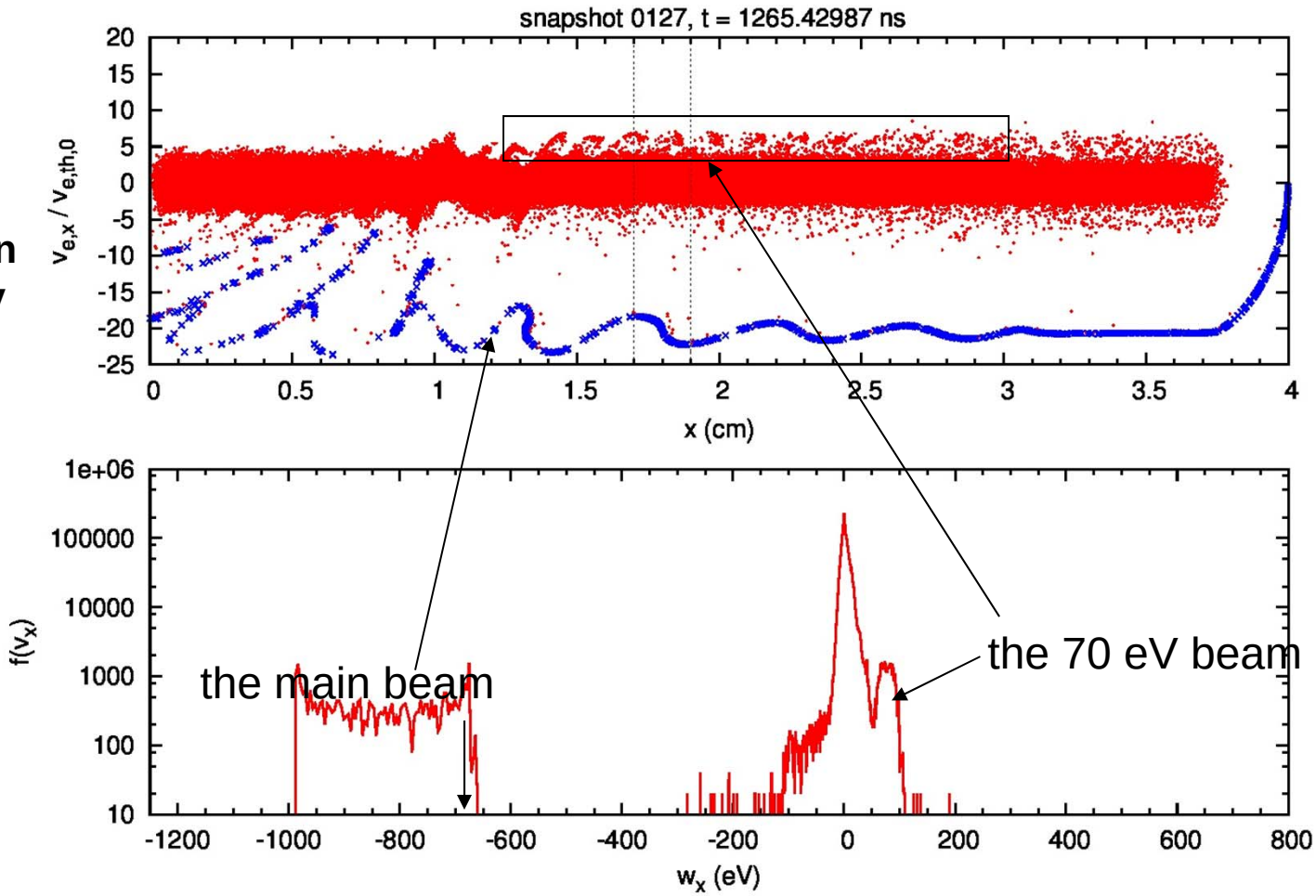
Energy analyzer B

Beam energy is given by the DC potential, 800V

TOKYO ELECTRON

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

Electron velocity



red = **bulk**

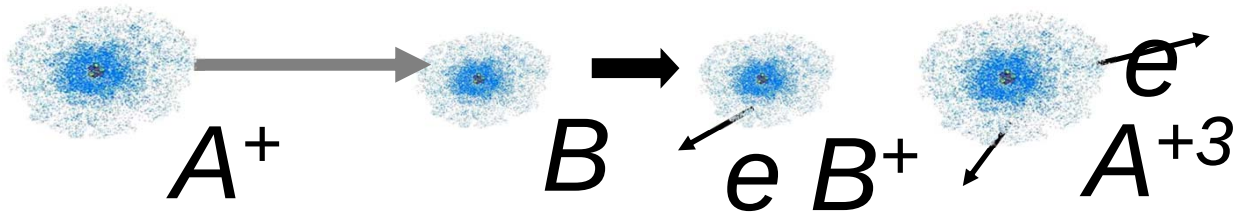
blue = **beam**

FUTURE DIRECTION AND PROGRESS

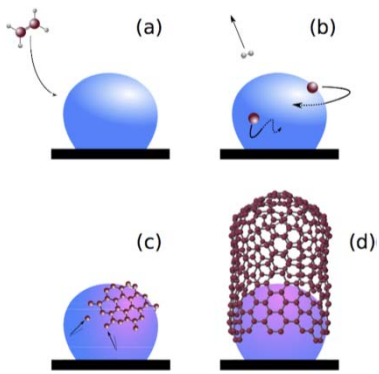
DEVELOPMENT OF SUITE OF ATOMISTIC CODES FOR FUSION, ADVANCED MATERIALS AND WARM DENSE MATTER APPLICATIONS

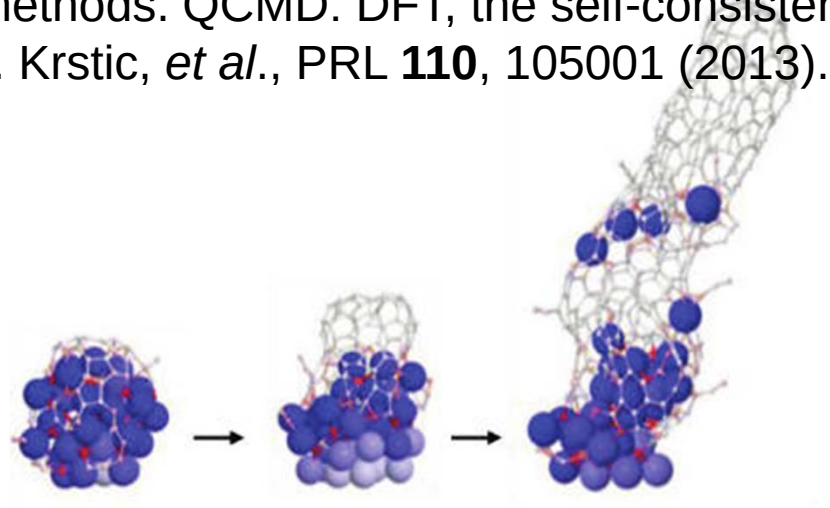
I.D. Kaganovich, E.A. Startsev, P. Krstic, R. Car, D. Stotler, R.C. Davidson

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.

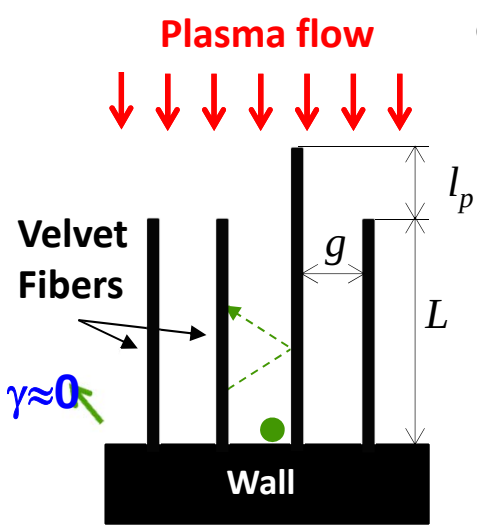
New insight: Engineered materials with surface architecture can be used to control and suppress SEE.

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

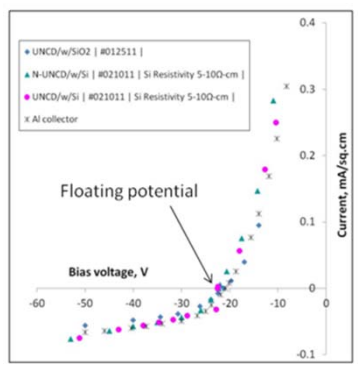
Main accomplishments

Surface architecture of engineered materials may induce undesired electron field emission

How it works:



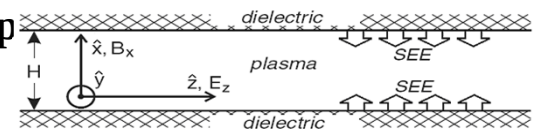
Nanocrystalline diamond coating exposed to plasma



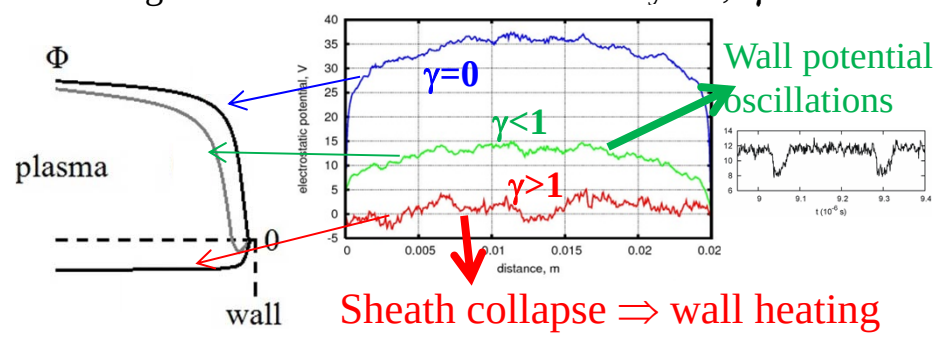
No arcing ⇒No damage to diamond coating

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

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



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

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St. Petersburg State Polytechnical University

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

Plasma Physics Laboratory, Princeton University

V. DEMIDOV

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PRINCETON PLASMA PHYSICS LABORATORY

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?

R. Cimino,[1,2] I. R. Collins,[2] M. A. Furman,[3] M. Pivi,[4] F. Ruggiero,[2] G. Rumolo,[5] and F. Zimmermann[2]
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[2]*CERN, Geneva, Switzerland*
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(Received 10 February 2004; published 29 June 2004)

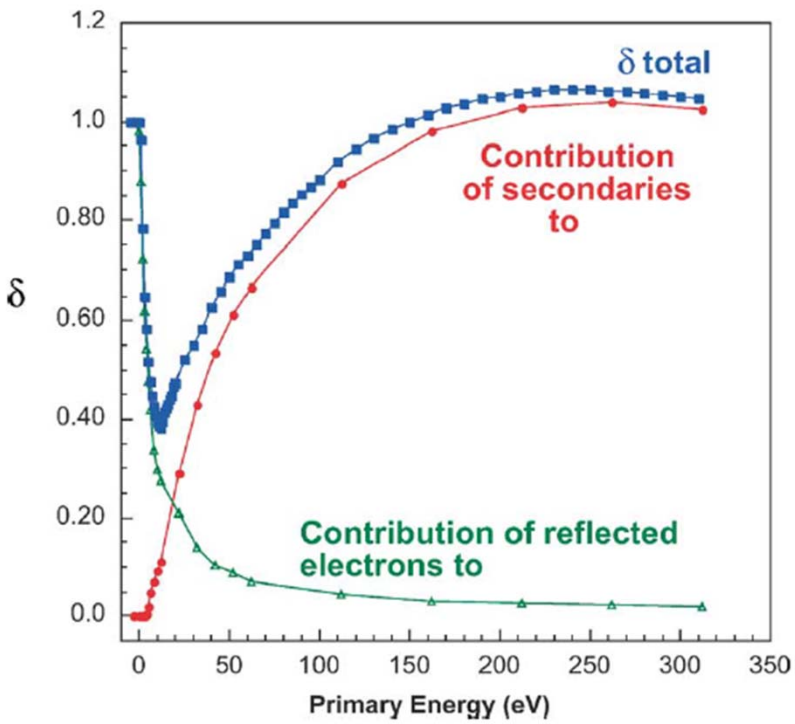
Present and future accelerators' performances may be limited by the electron cloud (EC) effect. The EC formation and evolution are determined by the wall-surface properties of the accelerator vacuum chamber. We present measurements of the total secondary electron yield (SEY) and the related energy distribution 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

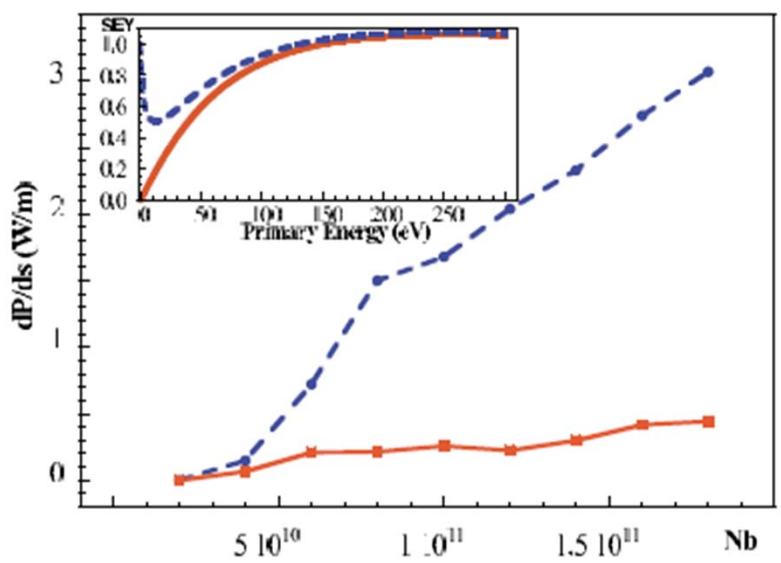
Implications of the secondary electron emission coefficient approaching unity in the limit of zero primary electron energy

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



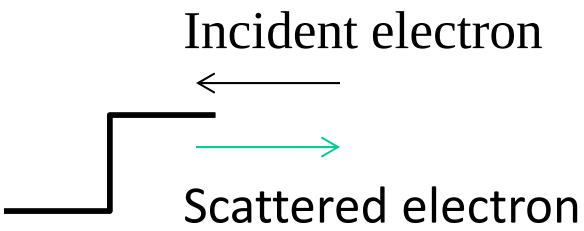
Simulated average heat load in an LHC dipole magnet as a function of proton bunch population at 0.45 TeV, for a SEY *considering the elastic reflection (dashed line)* or ignoring it (full line).



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



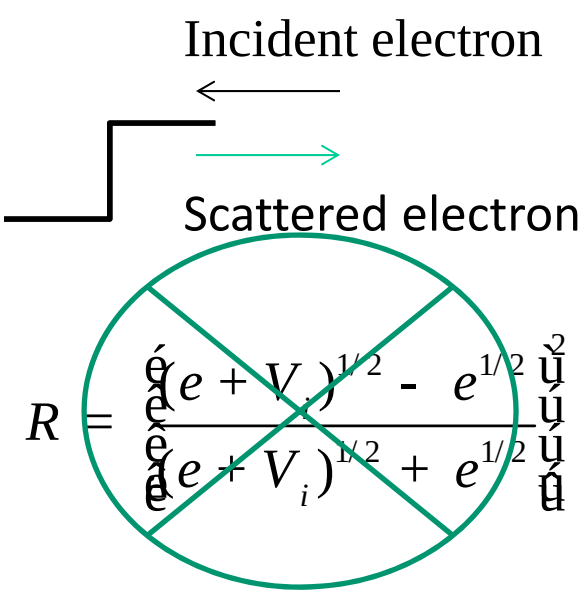
$$R = \left[\frac{(e + V_i)^{1/2} - e^{1/2}}{(e + V_i)^{1/2} + e^{1/2}}\right]^2$$

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 :

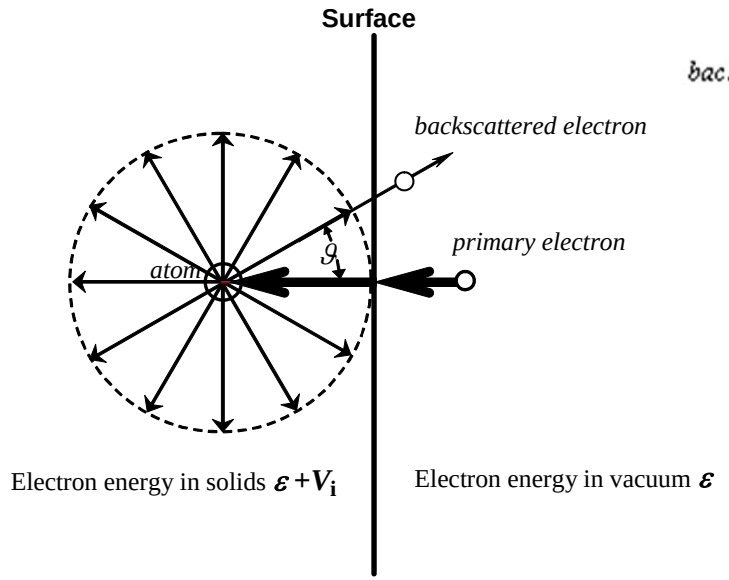
Here, V_i is the internal potential of solid, typically of 10-20 V, not 150V as mentioned in the Letter. Eq. gives R=0.67 for ε=0.01V_i, and R=0.29 for ε=0.1V_i. However, relation for the reflection coefficient does not account for electron acceleration toward the surface by the image charge in the metal. 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.

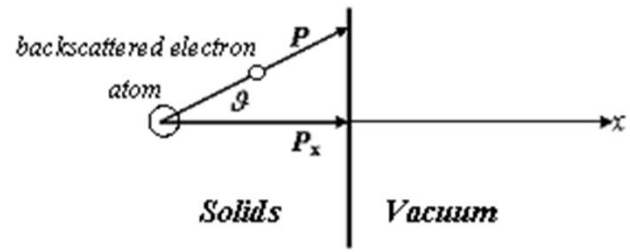
[1]. L. A. MacColl, Phys. Rev. 56, 699 (1939).

Quantum diffraction from potential barrier



$$R = \left[\frac{(e+V_i)^{1/2} - e^{1/2}}{(e+V_i)^{1/2} + e^{1/2}}\right]^2$$





$$\cos\vartheta_{max} = \sqrt{\frac{V_i}{\varepsilon + V_i}}$$

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 ε -> 0*.

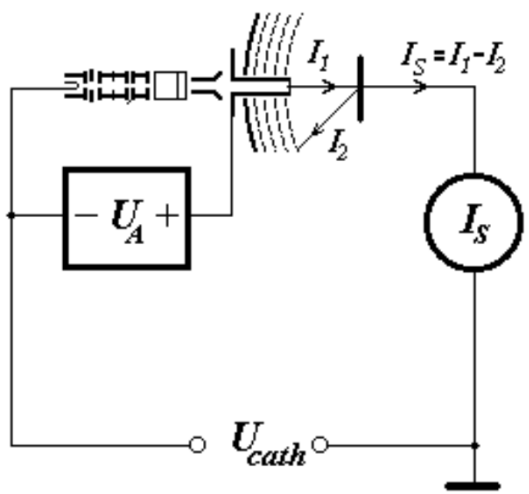
*I. M Bronshtein, B. S Fraiman. Secondary Electron Emission. Moscow, Russia: Atomizdat, p. 408 (1969).

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.

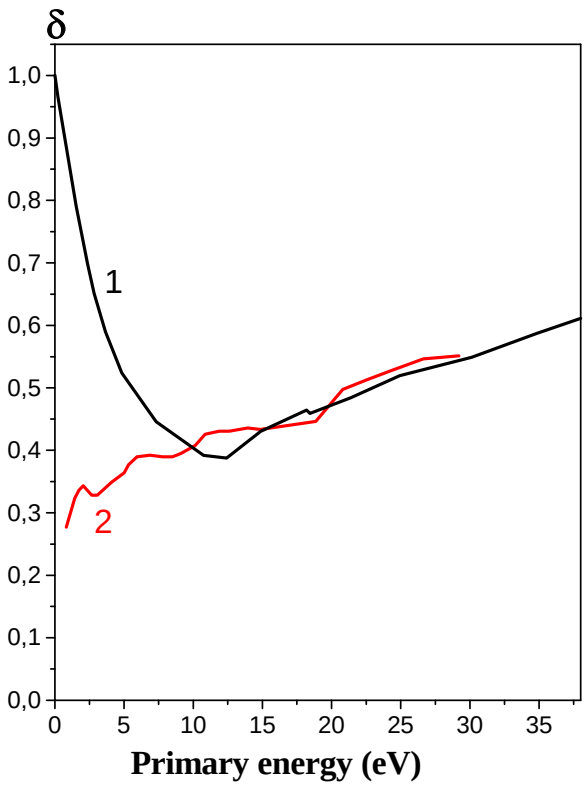


R. Cimino, I.R. Collins / Applied Surface Science 235 (2004) 231–235

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.

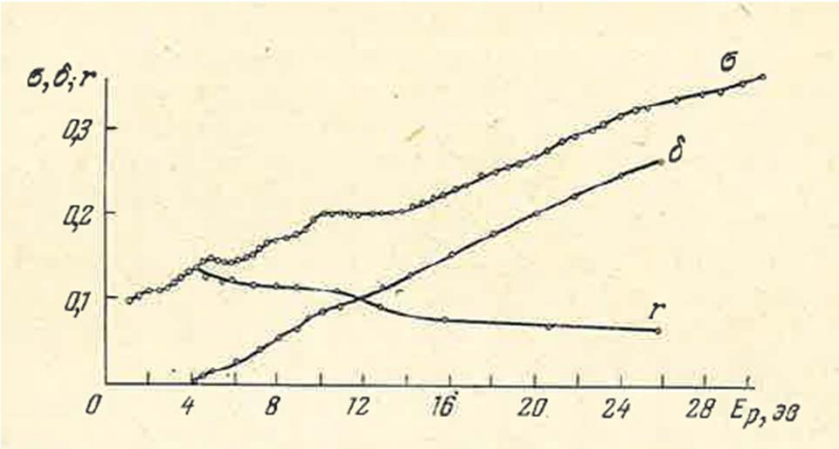
I.H. Khan, J. P. Hobson, and R.A. Armstrong, Phys. Rev. 129, 1513 (1963).

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

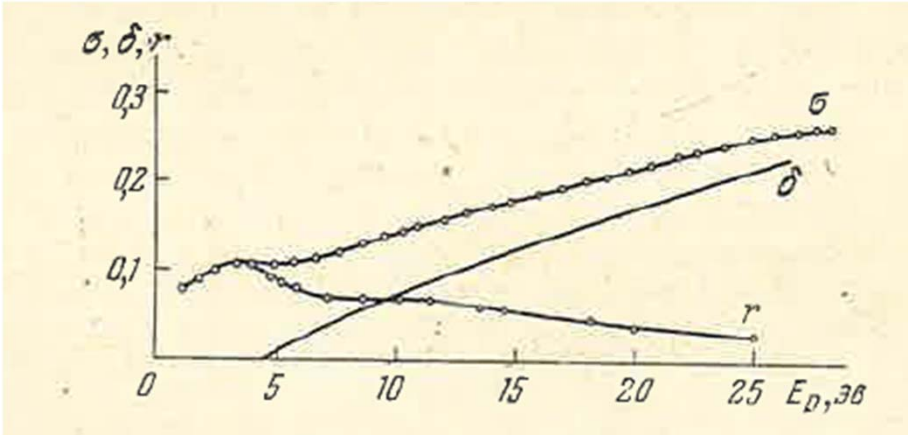
Z. Yakubova and N. A. Gorbatyi, Russian Physics Journal, 13 1477 (1970).

Previous careful measurements showing contrary observation

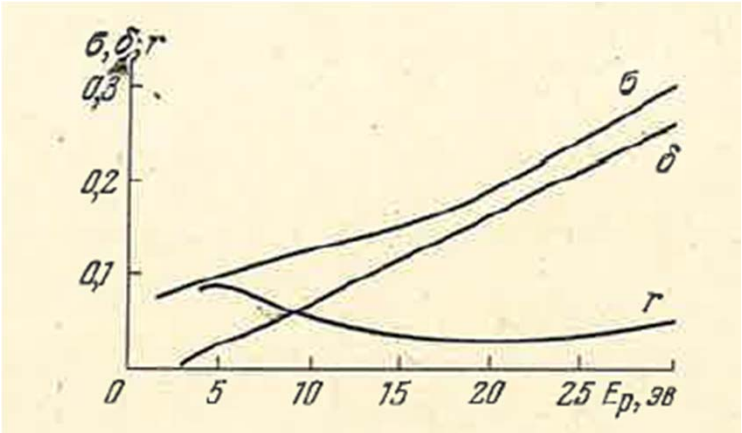
Total secondary electron yield of Al as a function of incident electron energy.



Total secondary electron yield of Ni.



Total secondary electron yield of Si.



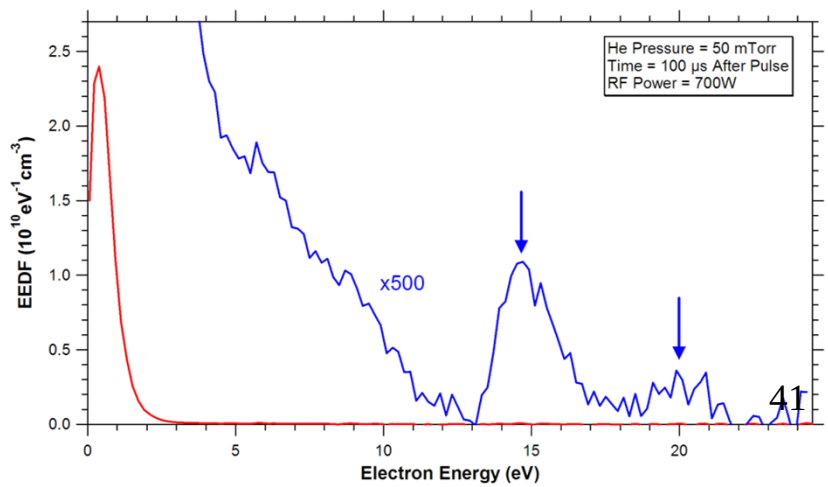
I. M Bronshtein, B. S Fraiman. Secondary Electron Emission. Moscow, Russia: Atomizdat, p. 60 (1969).

If the reflection coefficient of low energy electrons is large, the operation of probes collecting electron current will be strongly affected[1]

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

$A^* + A^* \rightarrow A + A^+ + e_f$[2].

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 form 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).

Relevant Publications and Conference Presentations in 2011-2012

J. P. Sheehan, Y. Raitses, N. Hershkowitz, I. Kaganovich, and N. J. Fisch, Phys. Plasmas **18**, 073501 (2011)

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)

M. D. Campanell, A.V. Khrabrov, and I. D. Kaganovich, Phys. Rev. Lett. **108**, 235001 (2012)

M. D. Campanell, A.V. Khrabrov, I. D. Kaganovich, Phys. Plasmas **19**, 123513 (2012)

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, ECLOUD'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.