Kinetic Effects of Electron-Induced Secondary Electron Emission on Plasma-Wall Interactions

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

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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.

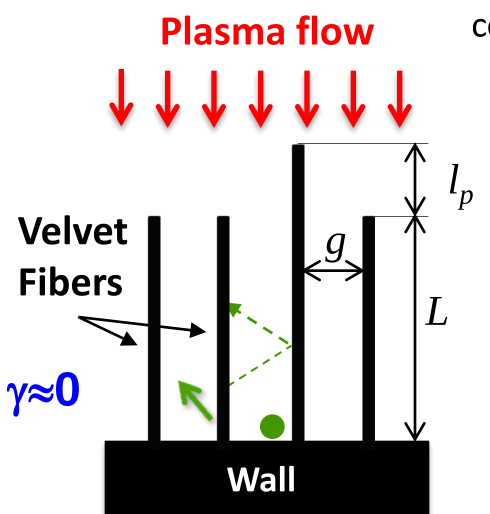
New insight: Engineered materials with surface architecture can be used to control and suppress SEE.

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

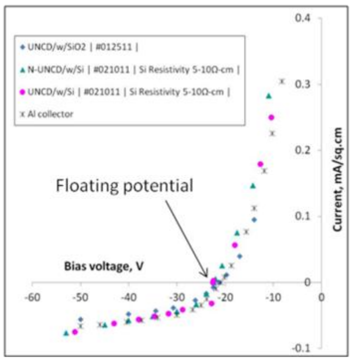
Main accomplishments

Surface architecture of engineered materials may induce undesired electron field emission

How it works:



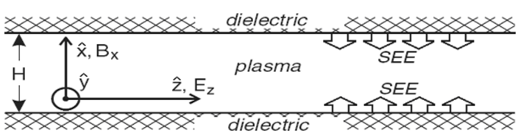
Nanocrystalline diamond coating exposed to plasma



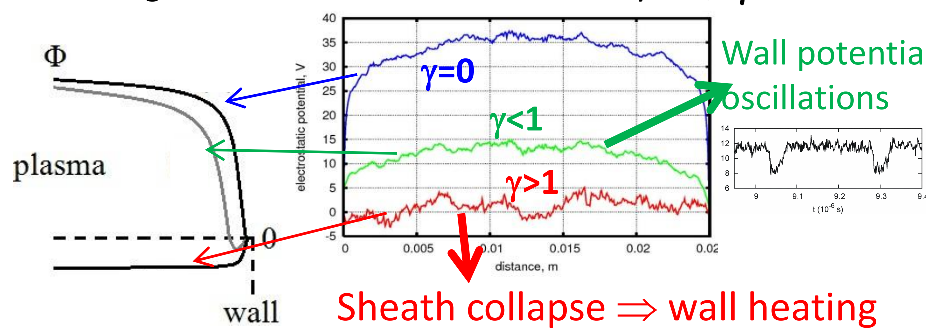
No arcing ⇒No damage to diamond coating

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

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



Three regimes for different effective SEE yield, γ



Sheath collapse ⇒ wall heating

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

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

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• 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.

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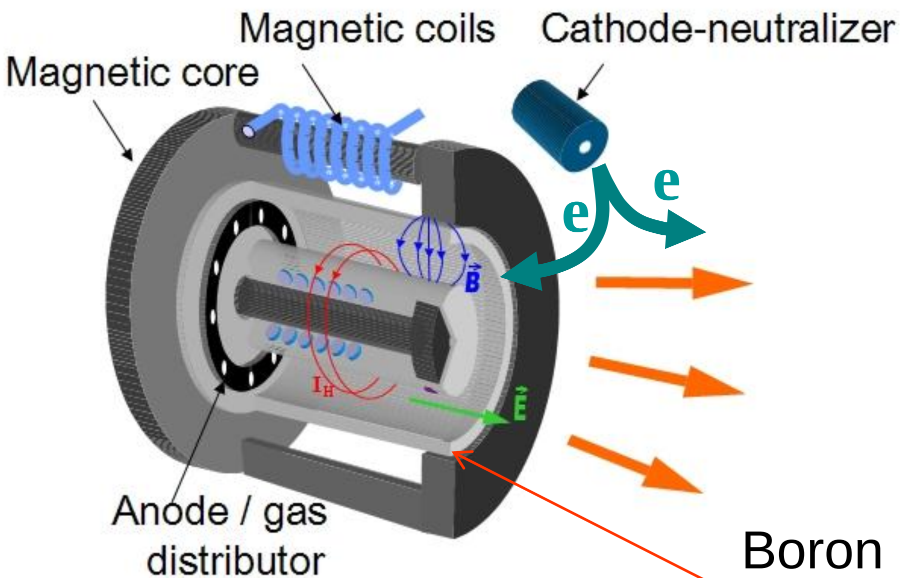
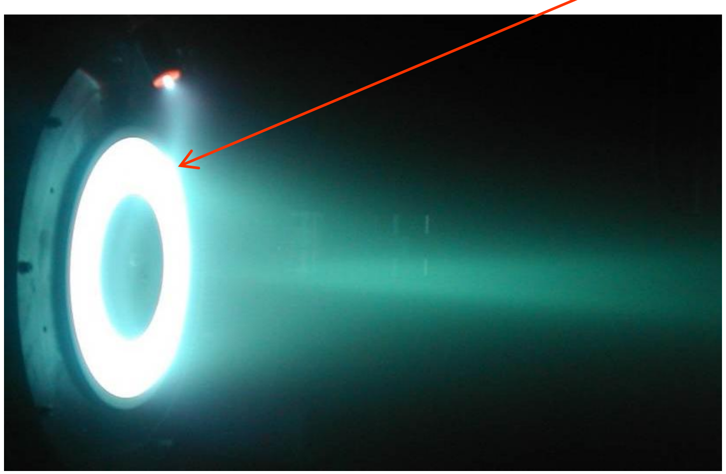
Hall Thruster (HT) – fuel-efficient plasma propulsion device for space applications



Boron nitride ceramic channel



Diameter ~ 1 -100 cm

Working gases: Xe, Kr

Pressure ~ 10^{-4} torr

Power ~ 0.1- 50 kW

Thrust ~ 10^{-3} - 1N

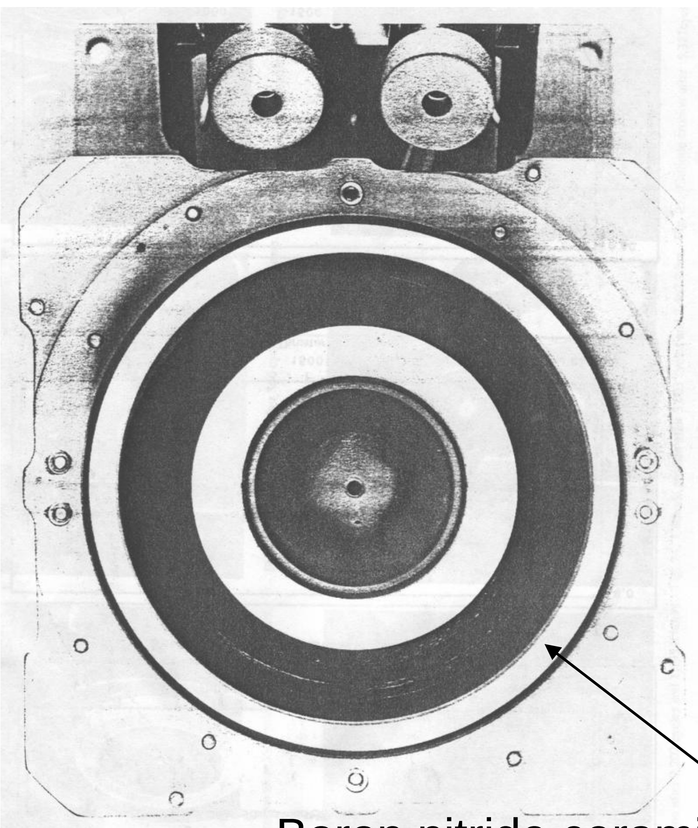
Isp ~ 1000-3000 sec

Efficiency up to 70%

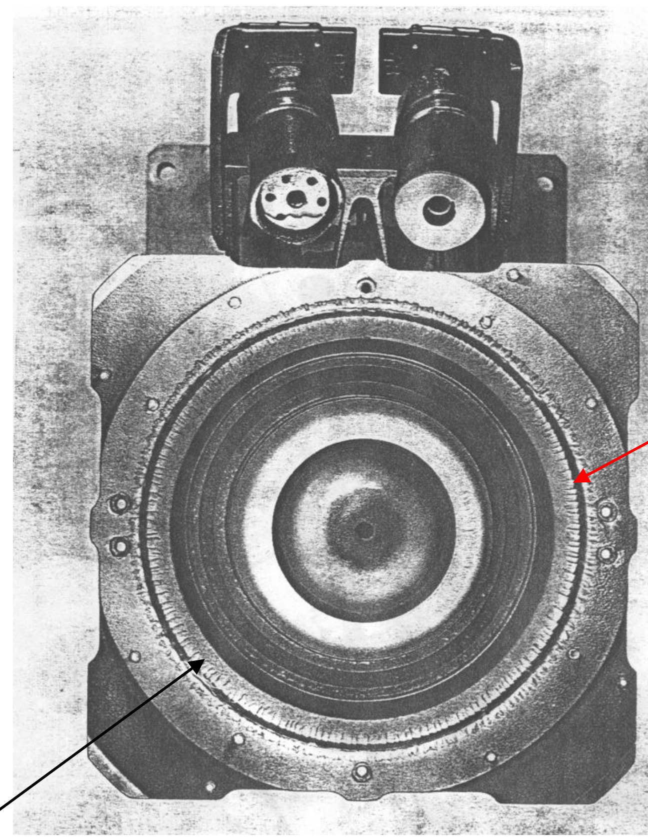
✓ Hall thrusters can produce much higher thrust densities than ion thrusters

Plasma-wall interaction can deteriorate thruster performance and reduce thruster lifetime

1.35-kW SPT-100 New



1.35-kW SPT-100 5,700 Hrs



Courtesy:
L. King
F. Taccagona

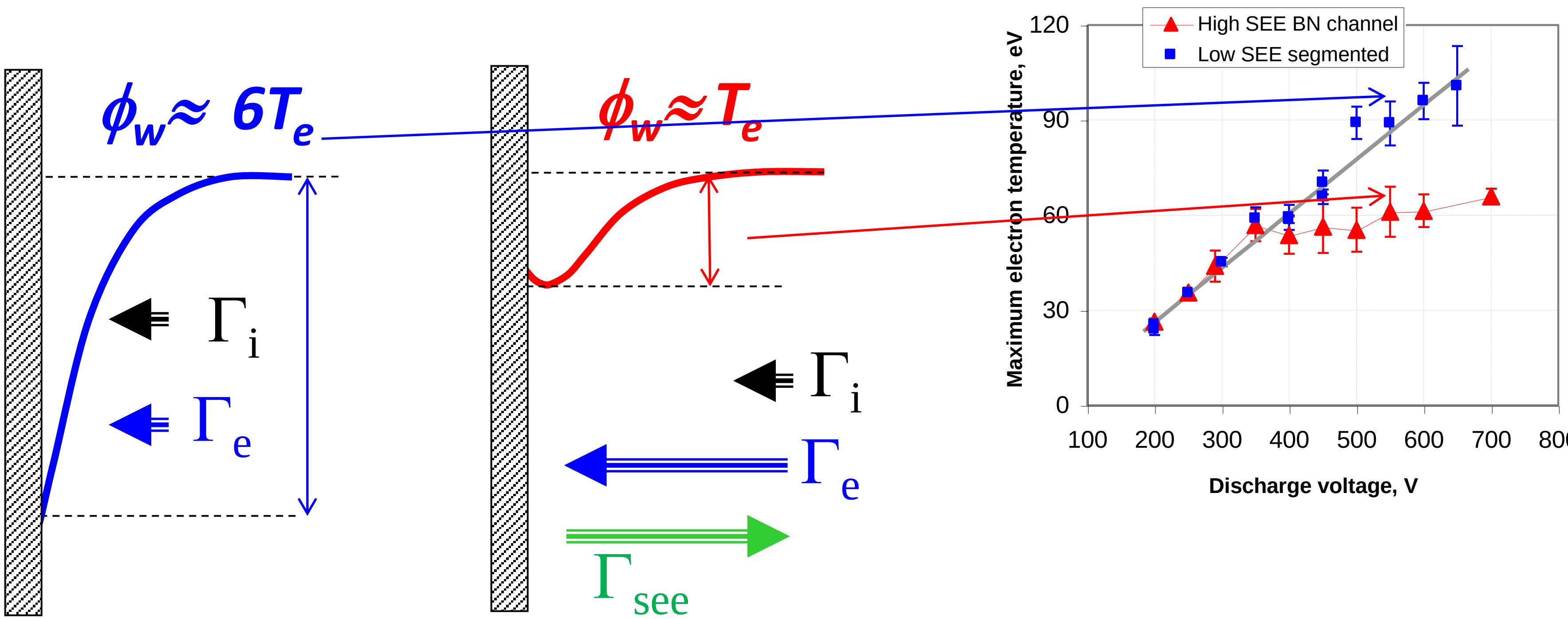
Boron nitride ceramic channel, 10 cm OD diameter

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



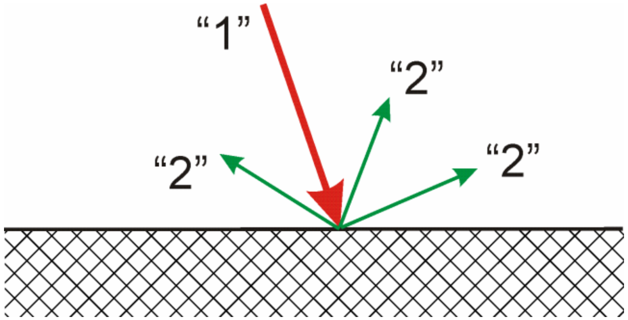
Wall - Sheath - Plasma

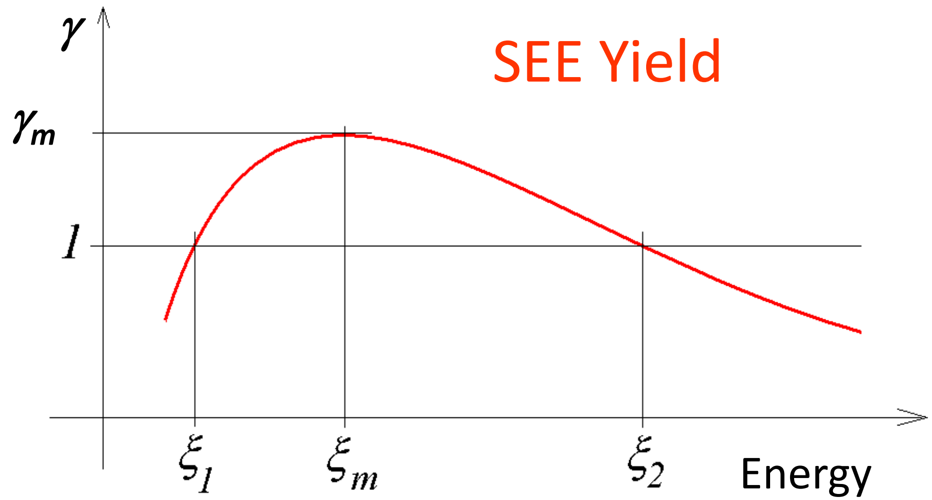
Wall – Sheath - Plasma

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

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Electron-induced secondary electron emission (SEE)

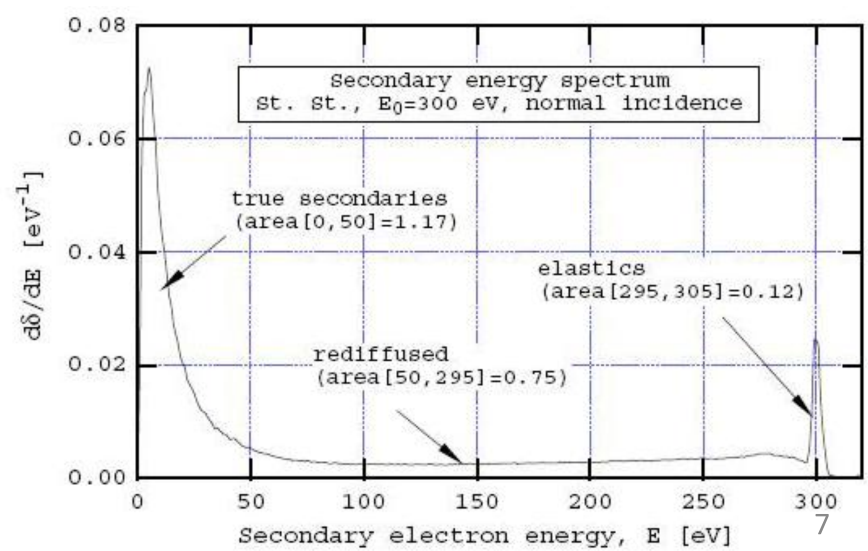




SEE yield $$\gamma = \frac{\text{Secondaries}}{\text{Primaries}}$$

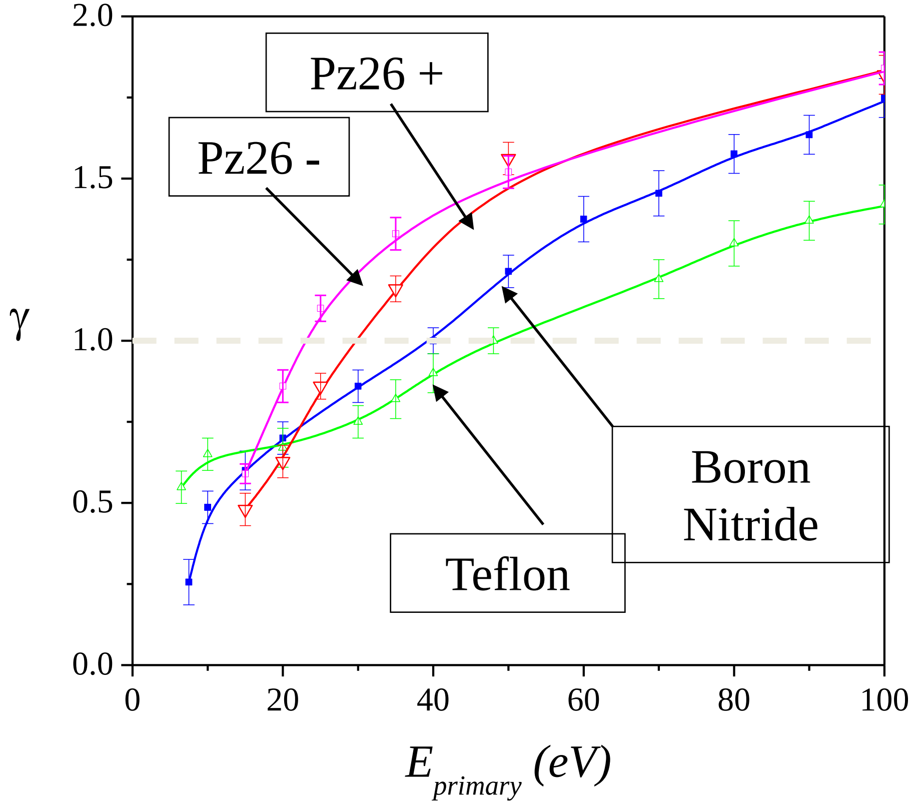
$$\gamma = \gamma(E_e)$$

Example of energy spectrum (for steel)



Furman and Pivi, LBNL 52807, 2003

Secondary electron emission yield from dielectric materials

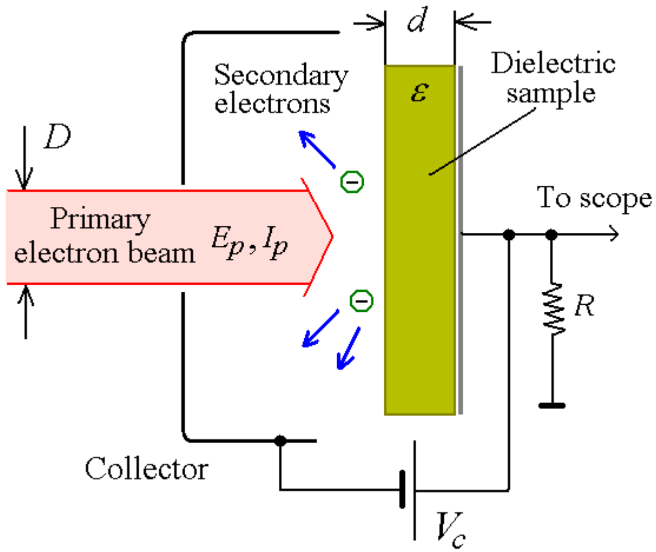


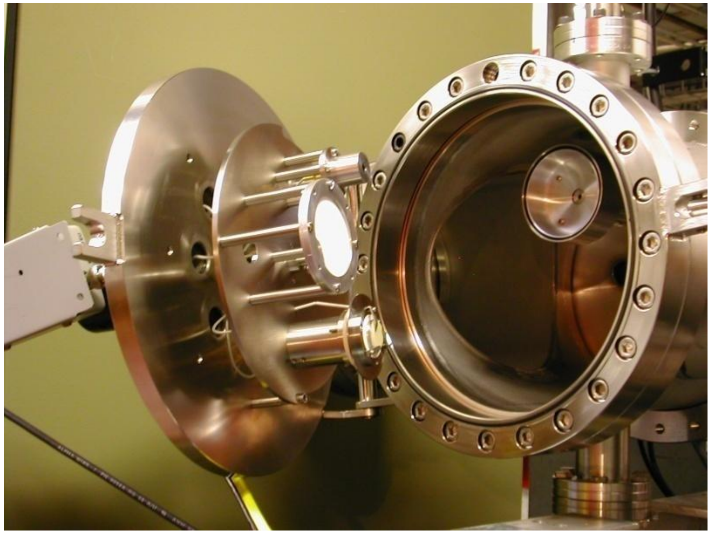
Note:
for Boron Nitride ceramic, if plasma (primary) electrons have Maxwellian electron energy distribution function (EEDF):

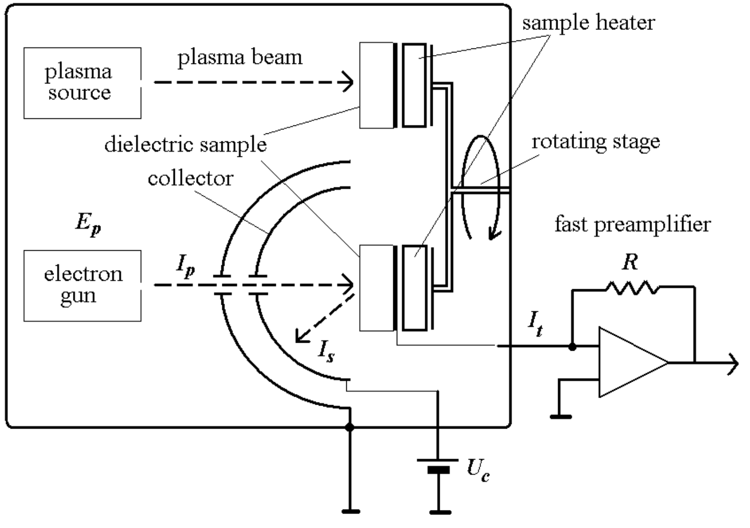
$\gamma(T_e) = 1$ at T_e = 18.3 eV

Dunaevsky et al., Phys. Plasmas, 2003

Upgraded setup for measurements of SEE yield from micro-engineered materials







- Cryogenic system to maintain better vacuum ($<10^{-8}$ torr) during SEE measurements
- Ion source to remove surface charges
- The upgrade allows to minimize, outgassing, surface , contamination, etc.

Plasma properties can be changed by applying engineered materials to the surface

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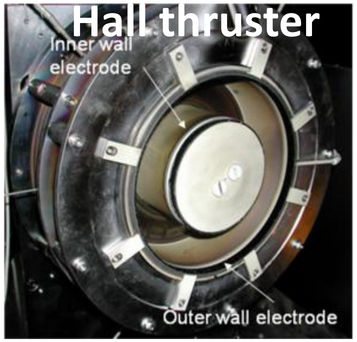
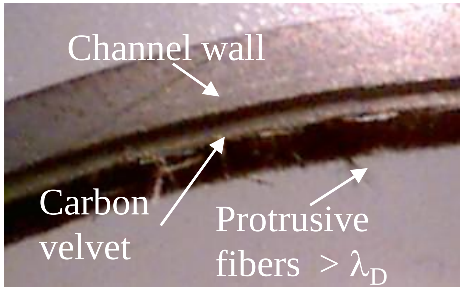
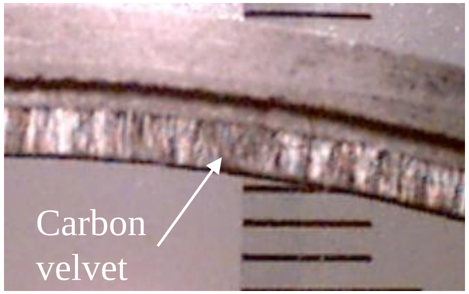
Application of carbon velvet to channel walls improves considerably thruster performance by reducing the electron cross-field current and by increasing nearly twice the maximum electric field in the channel compared with the conventional BN ceramic walls.

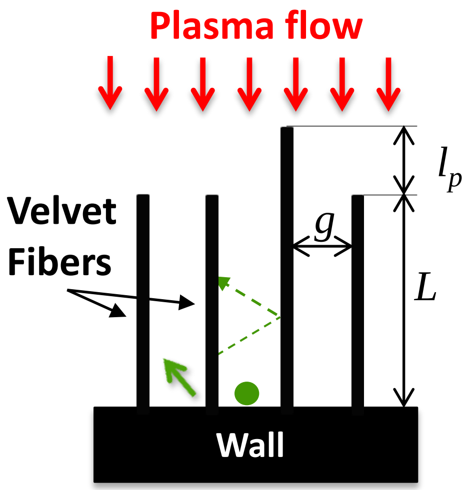


Velvet before plasma

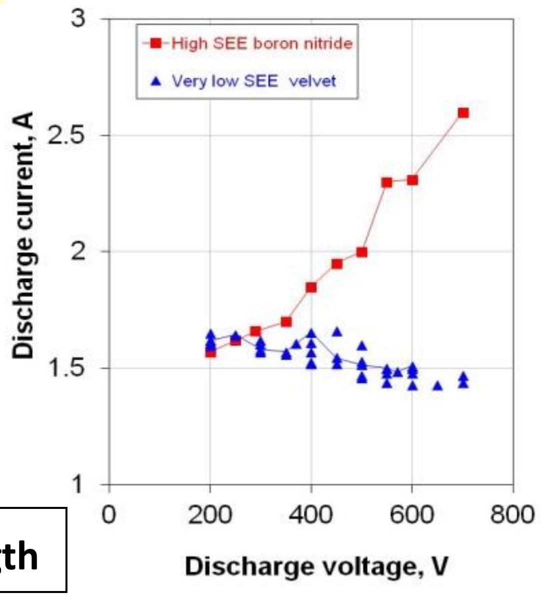


Plasma burned out all protrusive fibers





To avoid field emission g, l_p < Debye length

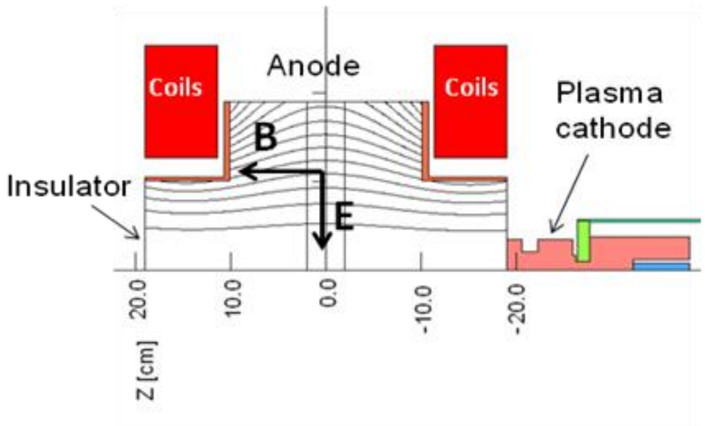


- **Velvet suppresses SEE and reduces current at high voltages (good)**
- **Sharp tips can enhance field emission leading to arcing (bad)**
- **Need to engineer velvet morphology so that inter fiber gaps and protrusions are located well inside the sheath to avoid damage by arcing**

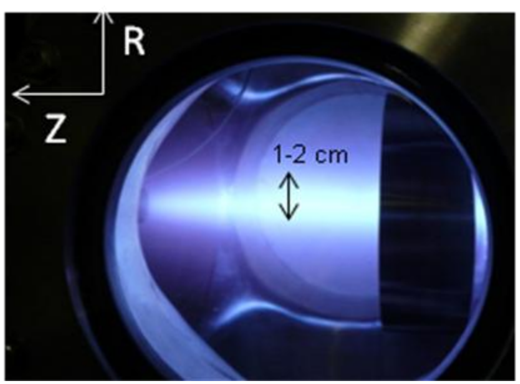
Need to take into account spatial and temporal variations of sheath width due to plasma non-uniformity or instabilities

Low Temperature Plasma Experiment (LTPX) was assembled to study kinetic effects of SEE on plasma properties

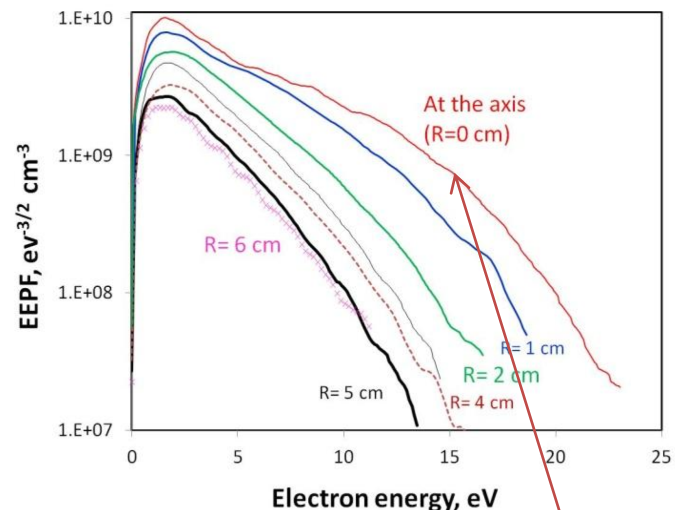
LTPX uses E×B plasma discharge with easy access for probe and optical diagnostics



Plasma operation with xenon gas

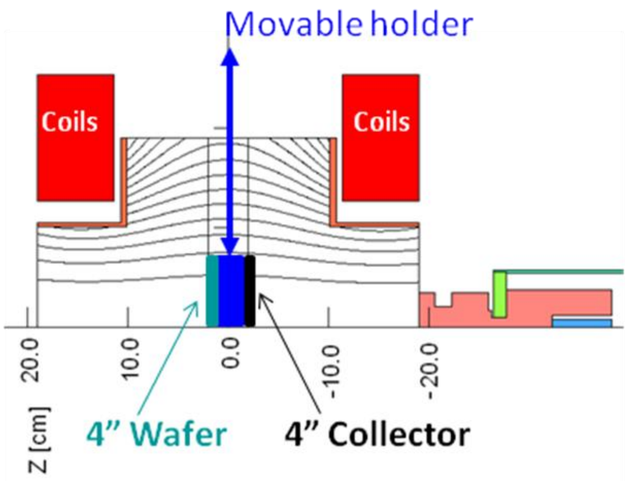


Measured Electron Energy Distribution Functions in LTPX

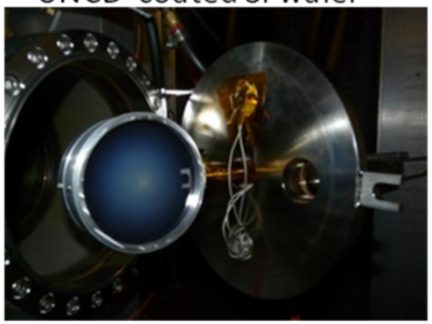


- Hot electrons near the axis, $R \leq 2$ cm, are due to electrons coming from cathode.
- Electron energy near axis is 20-30 eV; that is sufficient to induce SEE from ceramic materials.
- Electron energy can be additionally increased by application of higher bias voltage.

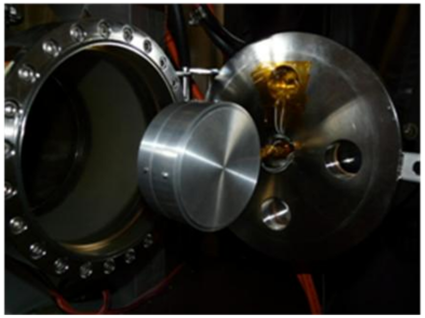
Experiments with micro- and nano-engineered materials immersed in LTPX plasma



UNCD coated Si wafer



Probe-collector



Micro-engineered materials are expected to minimize SEE, but may be a source of electron field emission due to surface irregularities.

Electron field emission may weaken electrical and thermal insulating properties of the sheath similar to SEE effects.

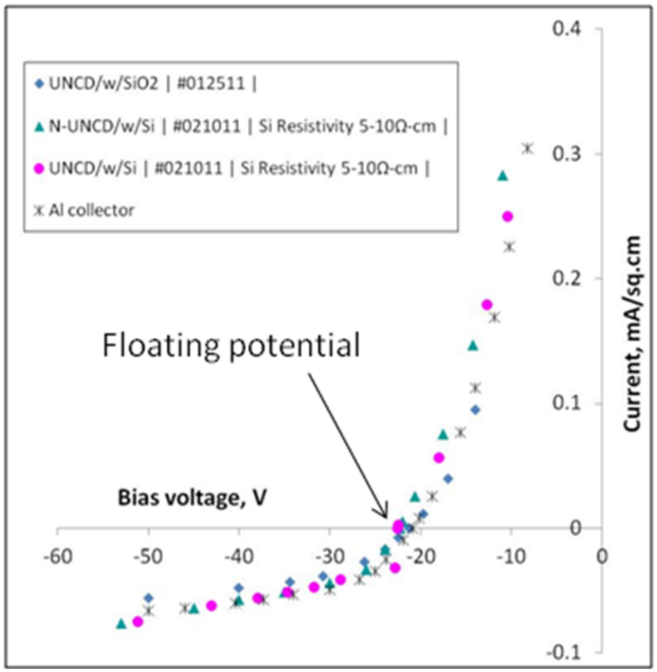
To evaluate possible effects of field and photoelectron emission, we immersed a 4" silicon wafer coated with ultrananocrystalline diamond (UNCD) in the plasma of LTPX setup.

Ultrananocrystalline diamond has several nm's grains with non-uniformities of up to 100's nm and is often used as field emitter.

Y. Raitses and A. V. Sumant, XXI International Material Research Congress*, 2012*

Characterization of electron emission from micro- and nano-engineered materials immersed in non-equilibrium plasma of LTPX

Collector current vs. collector bias voltage for UNCD and aluminum collectors



Main result: no difference was observed between probe collector current measured with diamond and aluminum; this suggests that the field emission from diamond is insignificant.

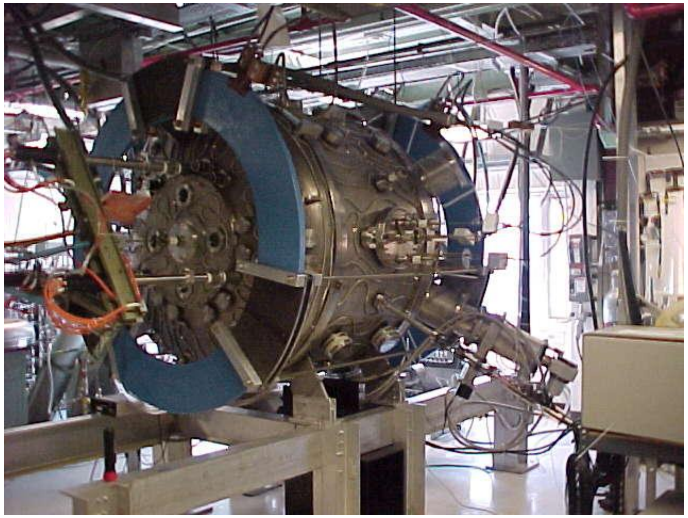
According to the Fowler-Nordheim law, the field strength of $E_{max} \approx \beta E > 10^3$ kV/mm is required to produce an appreciable field-emission current. Here, β is the field enhancement coefficient.

In these experiments, the maximum electric field in the plasma-wafer sheath: $E_{max} \sim V_b/\lambda_D \sim$ 1 kV/mm. Here, V_b is the bias voltage; $\lambda_D \propto (Te/Ne)^{0.5} \approx 3 \cdot 10^{-2}$ mm, is the Debye length. λ_D is large compare to the grain size. Therefore, the field enhancement is negligible due to thick sheath $\beta \sim 1$.

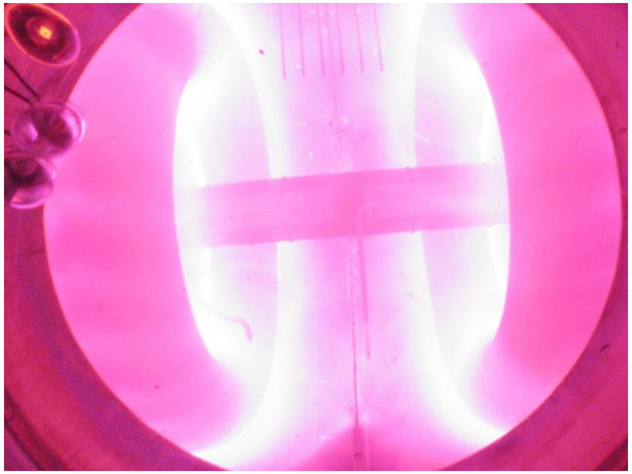
Electron field emission from micro-engineered materials facing the plasma should not be an issue as long as size of characteristic features of these materials is much smaller than the sheath size.

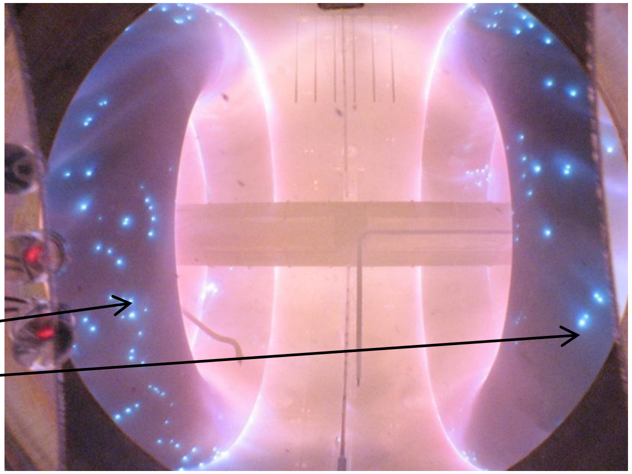
Surface coating can produce highly-localized plasma objects : *Unipolar Arcs*

PPPL Magnetic Reconnection Experiment



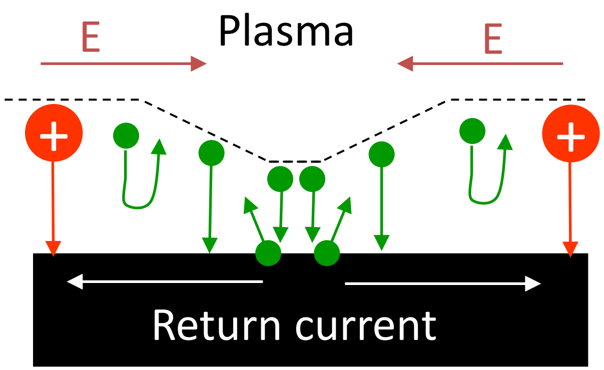
No arcs are observed on clean metal surface.





Dielectric coating on metal wall promotes formation of unipolar arcs seen as blue spots of light.

Necessary conditions for unipolar arcing



Schematics of current profiles in unipolar arc.

- A. E. Robson and P. C. Thonemann, Proc. Phys. Soc. 1958
- A. V. Nedospasov and V. G. Petrov, J. Nucl. Materials, 93, 1980

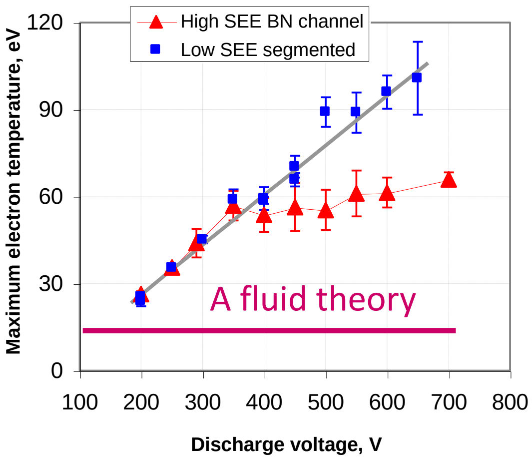
- Necessary conditions for unipolar arcing:
  - The sheath potential drop, V_{sh} exceeds the breakdown/arc voltage.
  - Plasma can support sufficiently large arc current to form the spot, for example, by evaporating of wall materials or producing thermionic or field emission.
- Unipolar arcs also occur when walls are made from micro-engineered material with complex surface architecture. They were observed in PPPL Hall thrusters experiments with carbon velvet walls.

✓ Arcing can induce permanent damage to walls

✓ Micro-engineered materials needs to be designed so that characteristic feature size is less than sheath. Plasma conditioning may remove features protruding above the sheath.

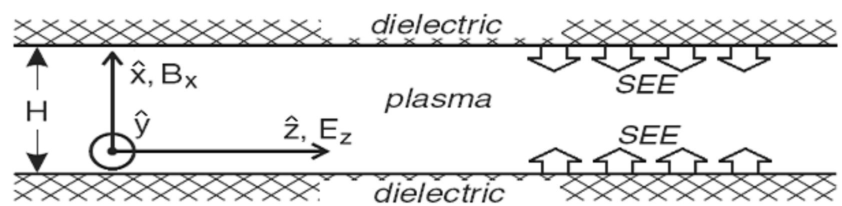
✓ Coatings needs to be removed.

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

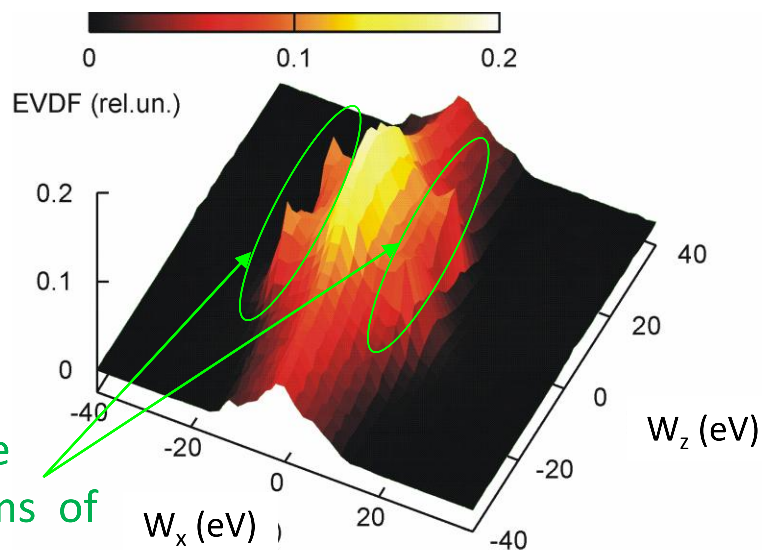


Large quantitative disagreement between experiments and fluid theories for predictions of the electron temperature in Hall thrusters

Y. Raitses et al., Phys. Plasmas 2006
I. Kaganovich et al., Phys. Plasmas 2007

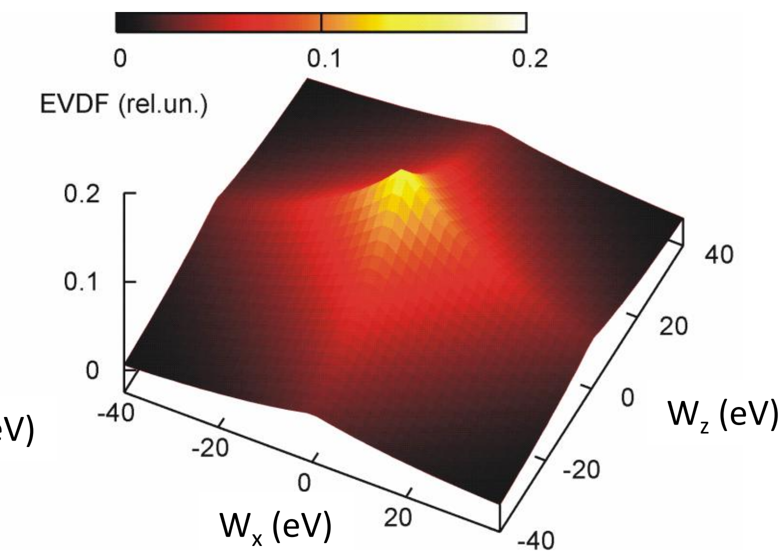


Hall thruster plasma, 2D-EVDF

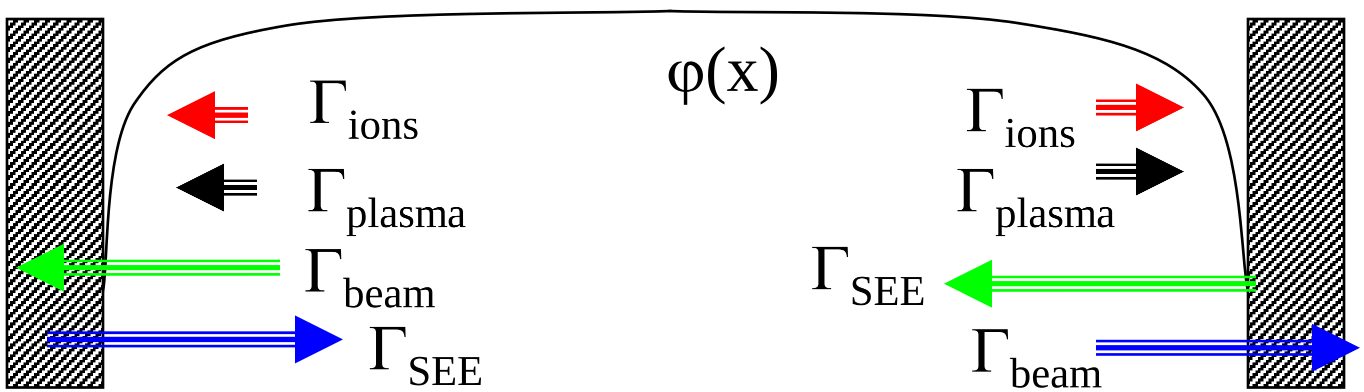


Loss cone and beams of SEE electrons

Isotropic Maxwellian plasma, 2D-EVDF



Electron fluxes have several components, including plasma bulk electrons, and counter-streaming beams of SEE electrons from walls

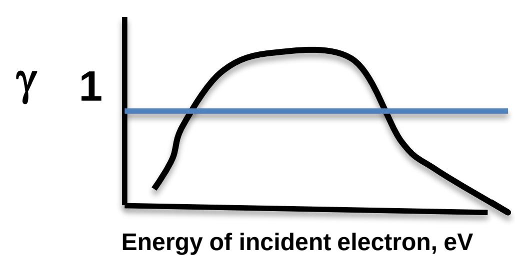


Net secondary electron emission γ_{net} accounts for kinetic effects by separating SEE yield of plasma (γ_p) and beam electrons (γ_b)

Total emission coefficient: $$\gamma_{net} \approx \frac{\gamma_p}{1+(\gamma_p - \gamma_b)}$$

Note: $\gamma_{net} > 1$ **if** $\gamma_b > 1$

SEE Yield as function of incident electron energy



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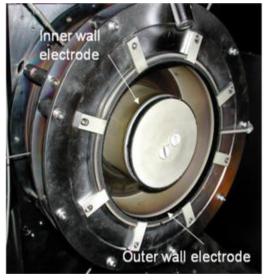
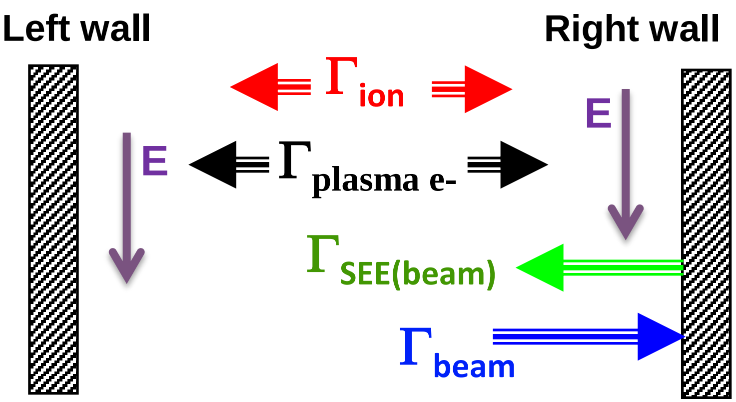
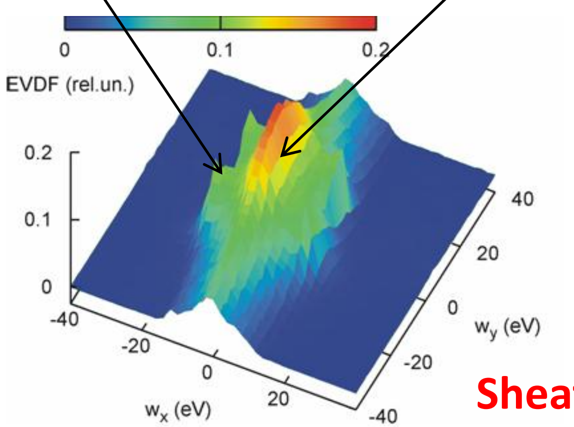
Particle-in-cell (PIC) simulations of plasma in Hall thrusters

12 cm diameter
2 kW Hall thruster

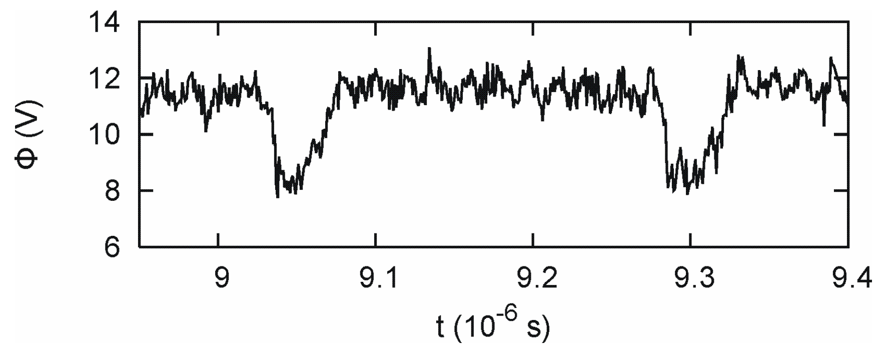




Sheath oscillations occur due to coupling of the sheath potential and non-Maxwellian electron energy distribution function with intense electron beams emitted from the walls.



Plasma potential as a function of time



Sheath instability causing fluctuations of plasma potential may enhance electron cross field transport, which leads to reduction of the electric field in plasma channel and accelerated ion energy.

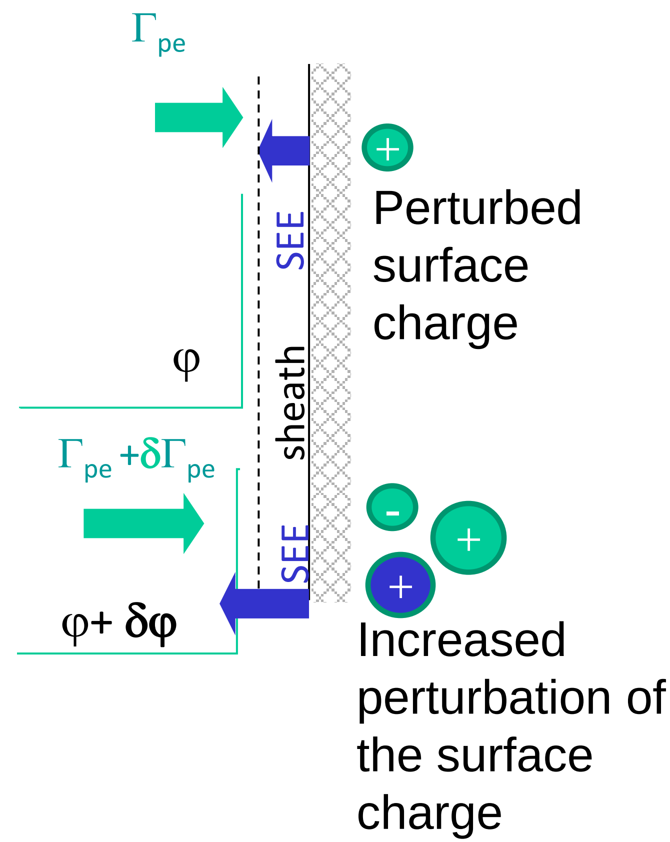
D. Sydorenko et al, Phys Rev Lett. ***103****, 145004 (2009)*

Criterion for onset of sheath oscillations in the presence of strong SEE

Obtained analytical criterion for sheath instability, $dJ/d\varphi>0 \Rightarrow \gamma_{w=\varphi} > 1$.

If sheath potential decreases due to positive charge fluctuations on the wall ($\delta\varphi$), the incident electron flux increases. If secondary electron emission coefficient of additionally released electrons $\gamma_{w=\varphi} > 1$, the emitted electron fluxes increases more than incident flux and wall charges more positively instead of restoring to the original wall charge.

Schematic of instability



M. Campanell et al., Phys. Rev. Lett. ***108****, 235001 (2012)*

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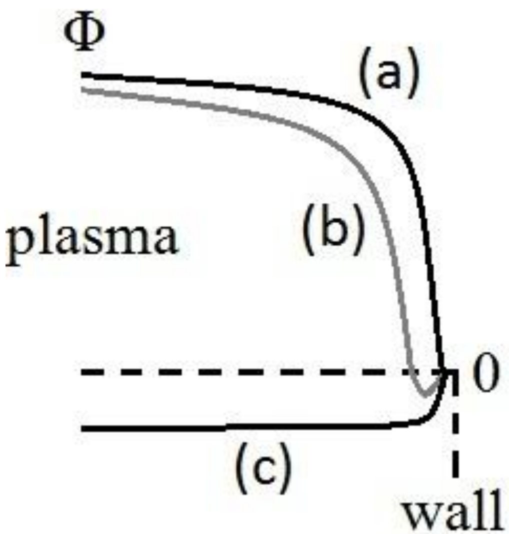
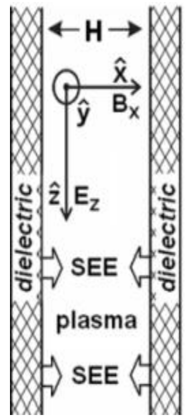
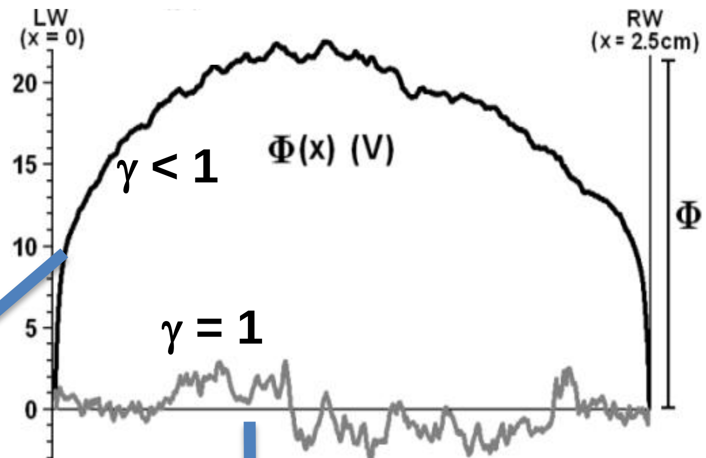
New regime of plasma-wall interaction with a very strong SEE, $\gamma > 1$

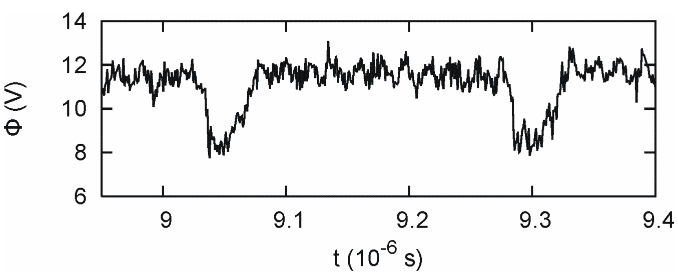
The main result - Disappearance of sheaths due to SEE







~4 MHz



- SEE electrons acquire enough energy from the electric field parallel to the wall causing $\gamma = 1$
- Sheath collapse leads to extreme wall heating by plasma and plasma losses

M. Campanell et al., Phys. Rev. Lett. ***108****, 255001 (2012)*

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Michael Campanell, Princeton University

Dr. Alex Khrabrov, PPPL

Dr. Dmytro Sydorenko, University of Alberta, Canada

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)

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