Absence of a steady-state space charge limited regime

for a sheath in a weakly collisional plasma bounded by walls with high secondary electron emission

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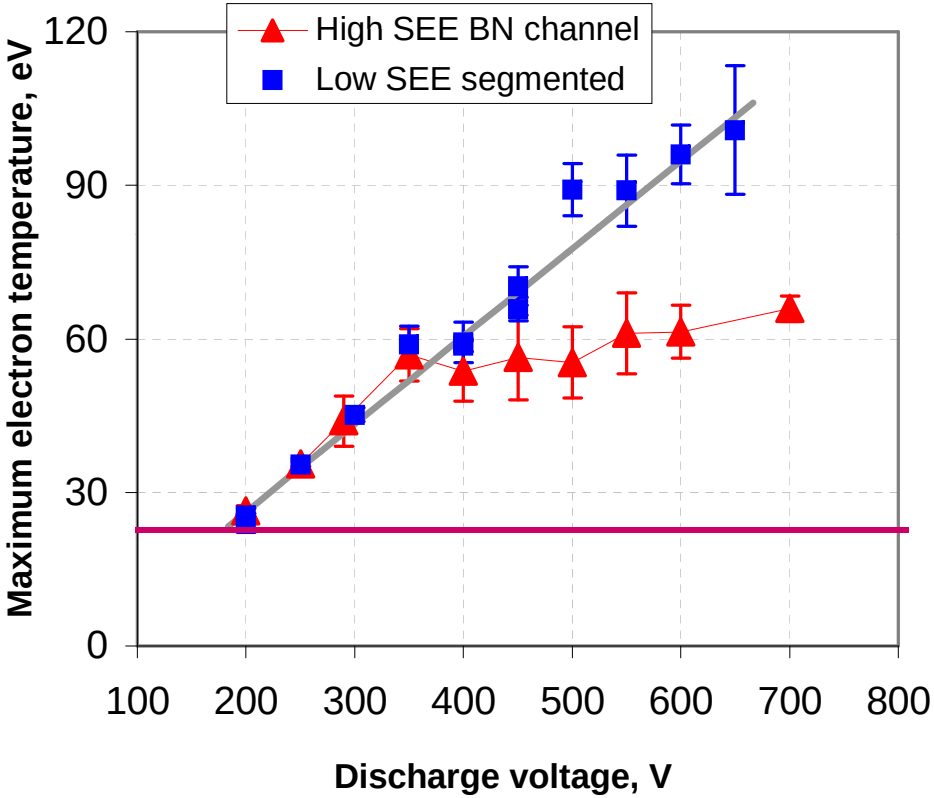
Fluid theory prediction cannot explain experimental data.

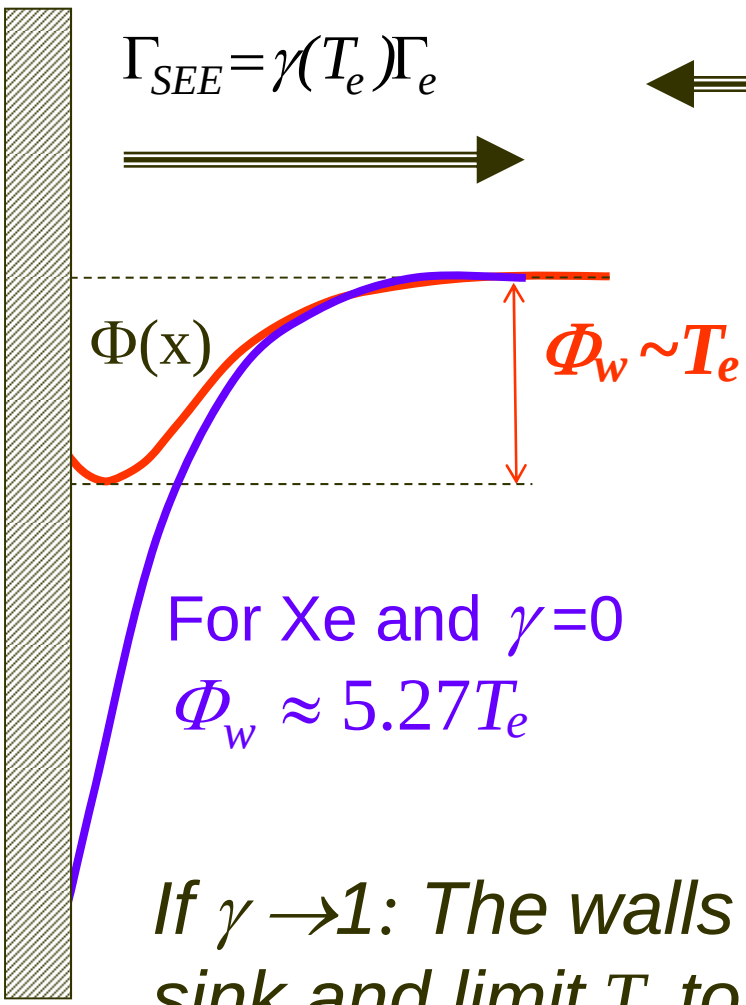


Large quantitative disagreement with fluid theories for predictions of the electron temperature.

A prediction based on *space charge limited regime*.

From: Y. Raitses, et al., Phys. Plasmas **12**, 073507 (2005).

Fluid theory: Wall losses strongly increase due to secondary electron emission.



$$\Gamma_{SEE} = \gamma(T_e)\Gamma_e$$

$$\Gamma_e = n\sqrt{\frac{T_e}{2\pi m}}e^{-\Phi_w/T_e}$$

$$\Gamma_{ion} = n\sqrt{\frac{T_e}{M}}$$

$$\Gamma_e = \frac{1}{1-\gamma}\Gamma_{ion}$$

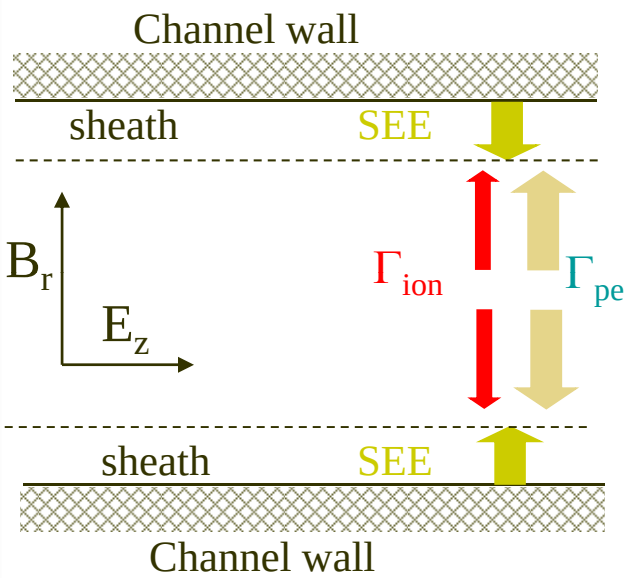
$$\Phi_w \approx -T_e \ln\left(\sqrt{\frac{M}{2\pi m}}(1-\gamma)\right)$$

For Xe and γ=0

$\Phi_w \approx 5.27 T_e$

If $\gamma \rightarrow 1$: The walls act as an effective energy sink and limit T_e to 18eV, where $\gamma(T_e)=1$.

Kinetic studies show two major factors misrepresented by fluid theories



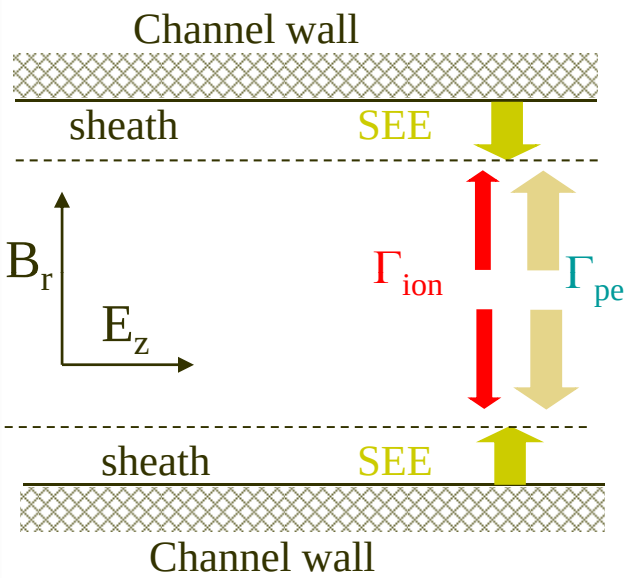
1. Secondary electrons emitted from opposite wall reach the wall without mixing with plasma electrons either due to collisions or collective effects

=> SEE fluxes from opposite walls totally compensate each other.

E. Ahedo and F.I. Parra, Phys. Plasmas **12,** 073503, (2005).

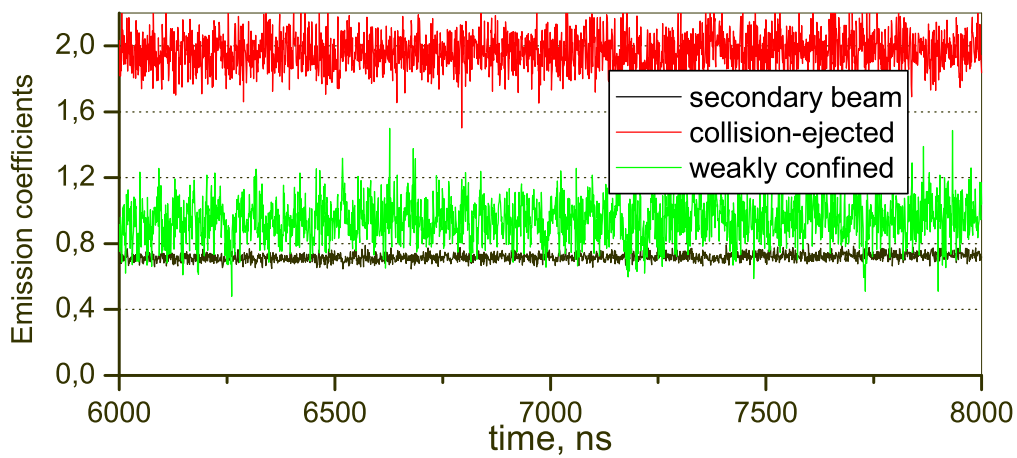
2. Flux to the wall of plasma electrons with energy large compared to the wall potential is a factor of ten smaller than predicted by fluid theory due to strong depletion of EVDF.

Because the cold SEE fluxes from opposite walls compensate each other, the plasma SEE coefficient >1.



Results of PIC simulations for H = 2.5 cm, ν_t = 5.6 10^6 s^{-1}, E_z = 140 V/m, and B = 100 Gauss.

A. Khrabrov, et al, IEPC paper 91 (2009).



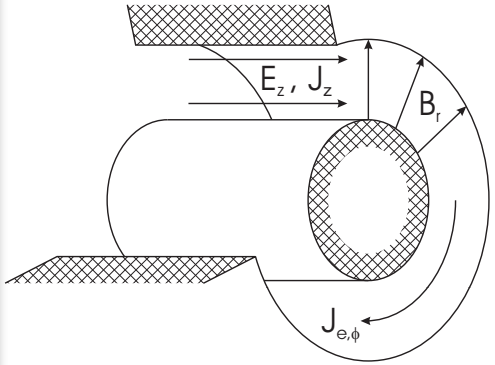
SEE coefficients:

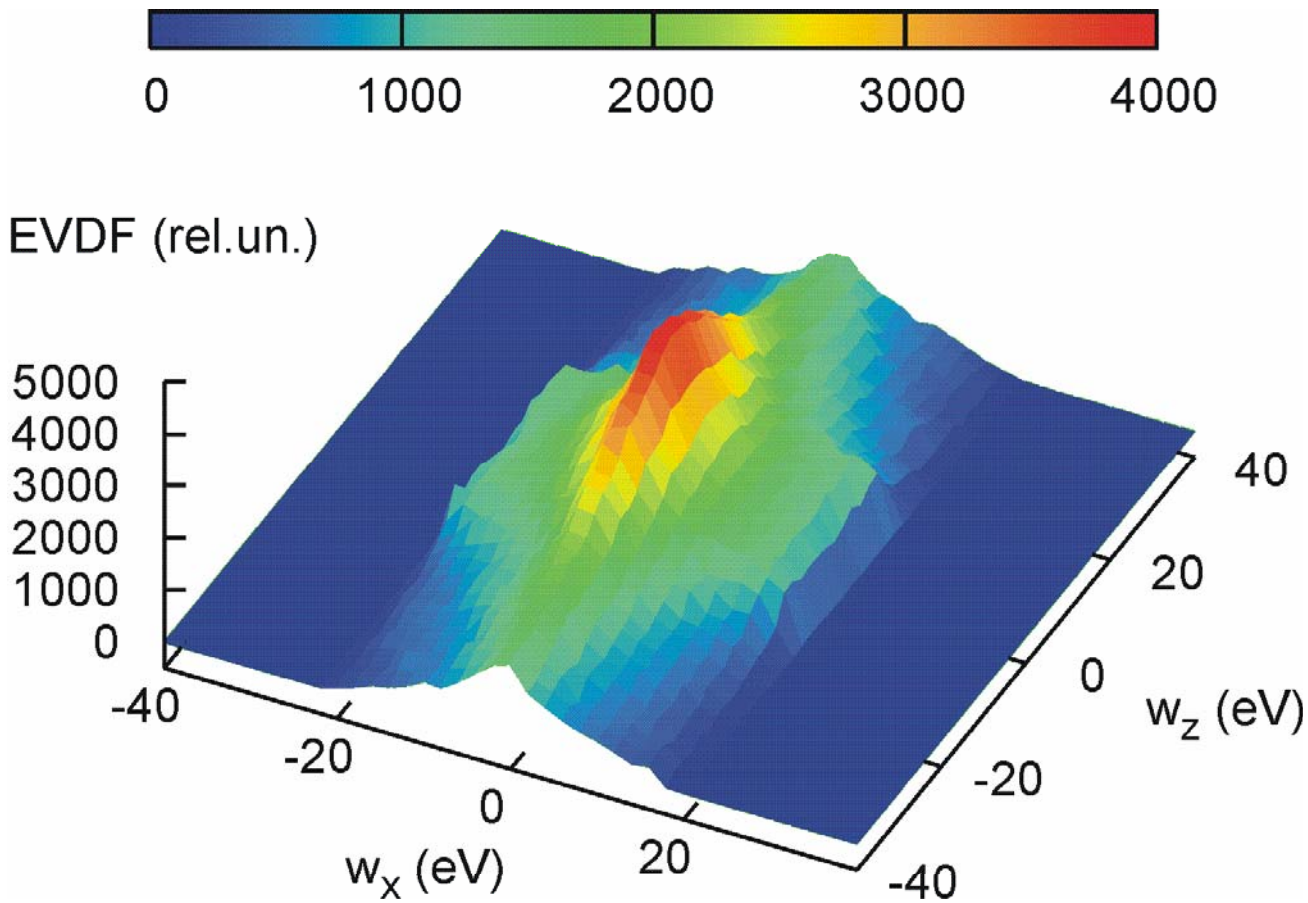
$\gamma_p \equiv \Gamma_{2p} / \Gamma_{1p}$ - SEE due to plasma electrons >1.

$\gamma_b \equiv \Gamma_{2b} / \Gamma_{1b}$ - SEE due to beam electrons <1.

No space charge limited regime!

3D view of the EVDF





E_z=200 V/cm

B_x=100G

T_x = 12.1 eV

T_z = 36.7 eV

From: D. Sydorenko et al, Phys. Plasmas, **13**, 014501 **(**2006).

Depletion of fast electrons due to wall losses in a Hall thruster channel

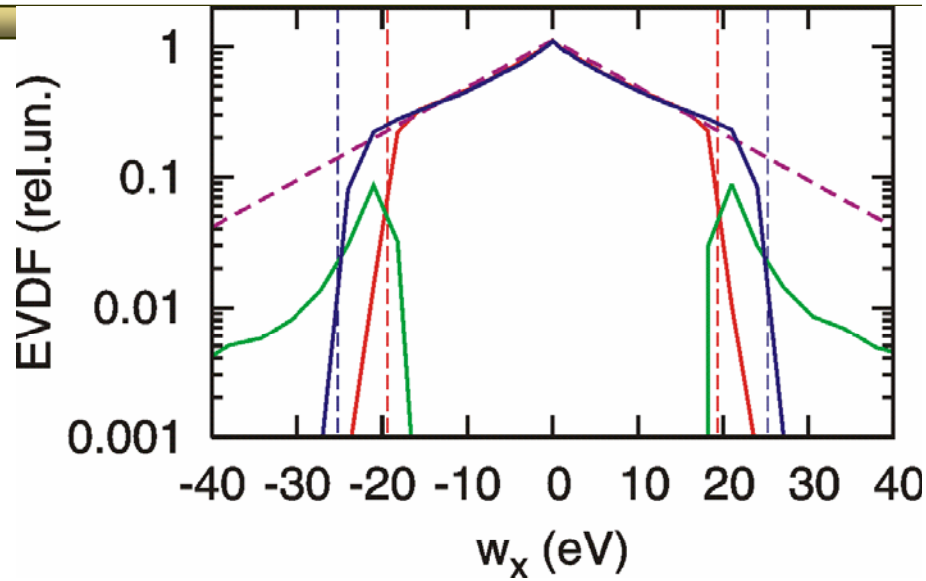
E_z=200 V/cm, B_x=100G

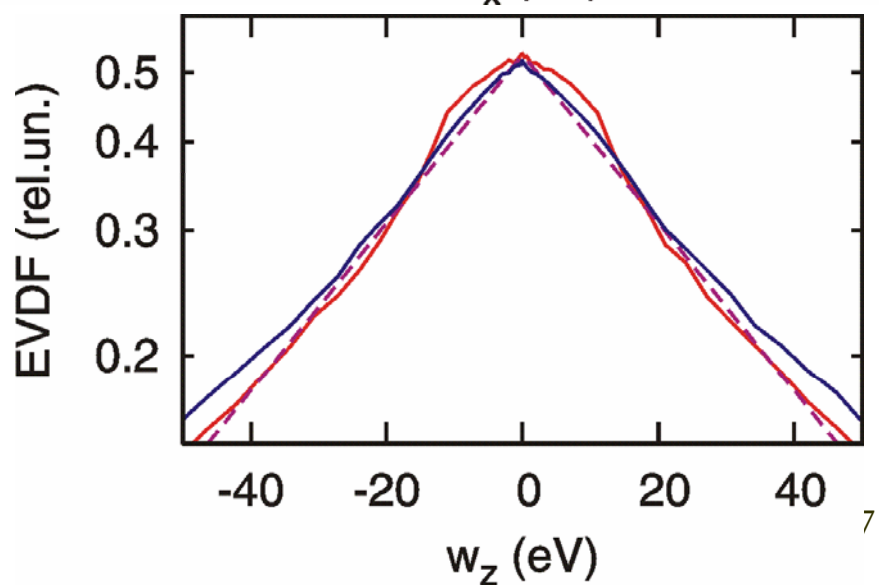
T_{ex}=12eV, Φ_w =19.4eV ! Not 5T_e

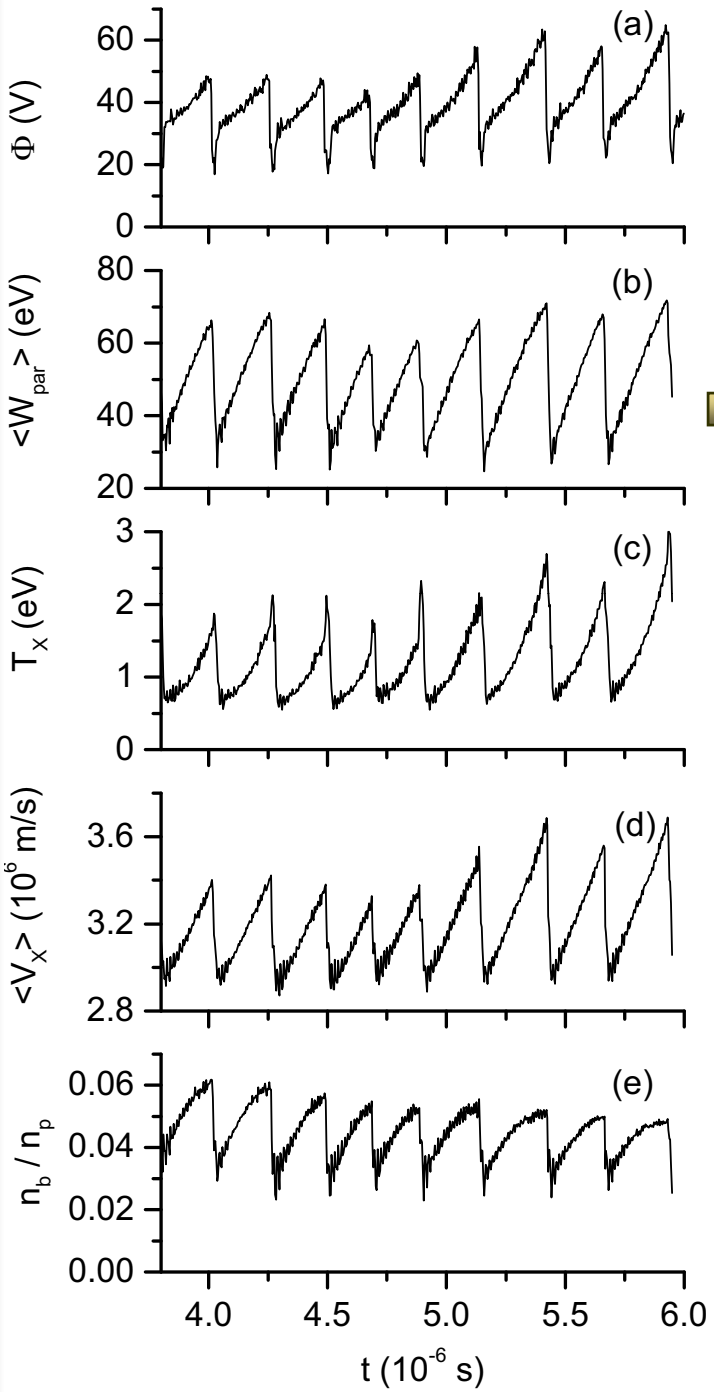
Bulk electrons with SEE
Bulk electrons with no SEE
Maxwellian EVDF, **T_{ex}=12eV T_z = 36.7 eV**

λ_{ec} >> H, ⇒
EVDF is depleted in the B- field direction, $w_x > e\Phi_w$!

EVDF is not depleted in the E-field direction, $w > e\Phi_w$!







Plasma is not always in steady state: exhibits relaxation oscillations

a) Potential in the middle
b) Average energy of motion parallel to the walls
c) Temperature, normal to the walls

d) Average beam velocity, normal to the walls

e) Relative beam density

D. Sydorenko, Ph.D. Thesis, (2006), PRL (2009).
F. Taccogna, JPC 2007.

T_e = 40 eV, M_i = 131 amu: general dependencies vs time

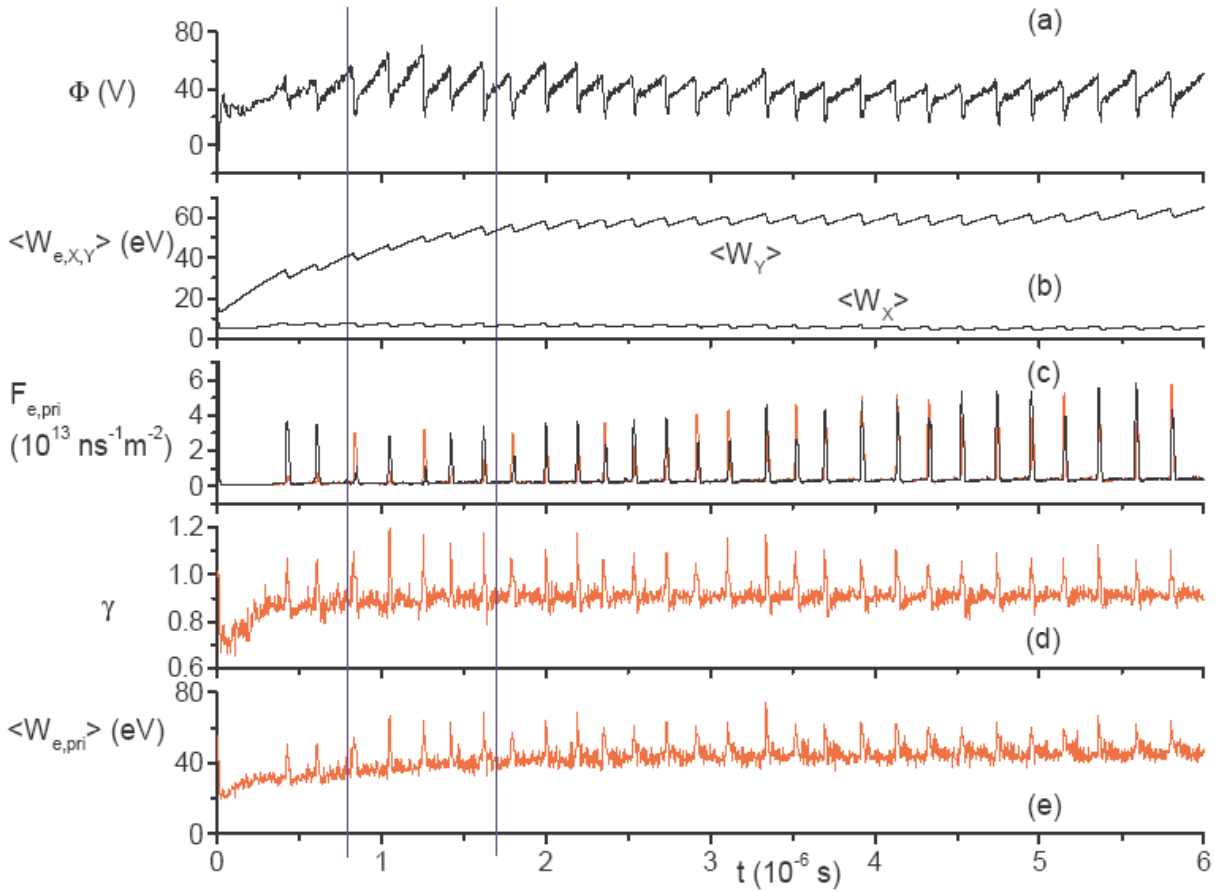
Potential

Average electron energy

Flow of primary electrons

Emission coefficient

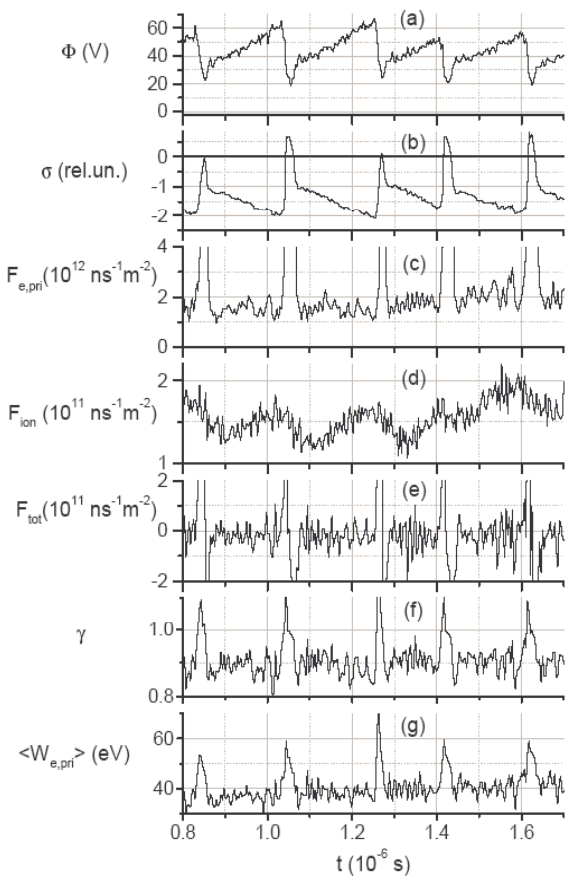
Average energy of primary electrons



On (c), (d), (e): red lines – right wall, black lines – left wall.

T_e = 40 eV, M_i = 131 amu: general dependencies with the fine time scale

Left wall



Potential

Surface charge

Primary electron flow

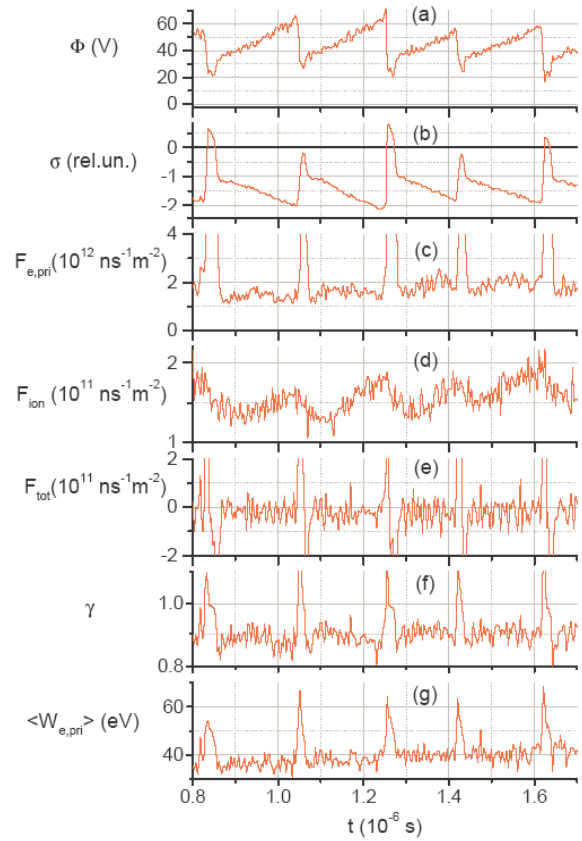
Ion flow

Total charge flow

Emission coefficient

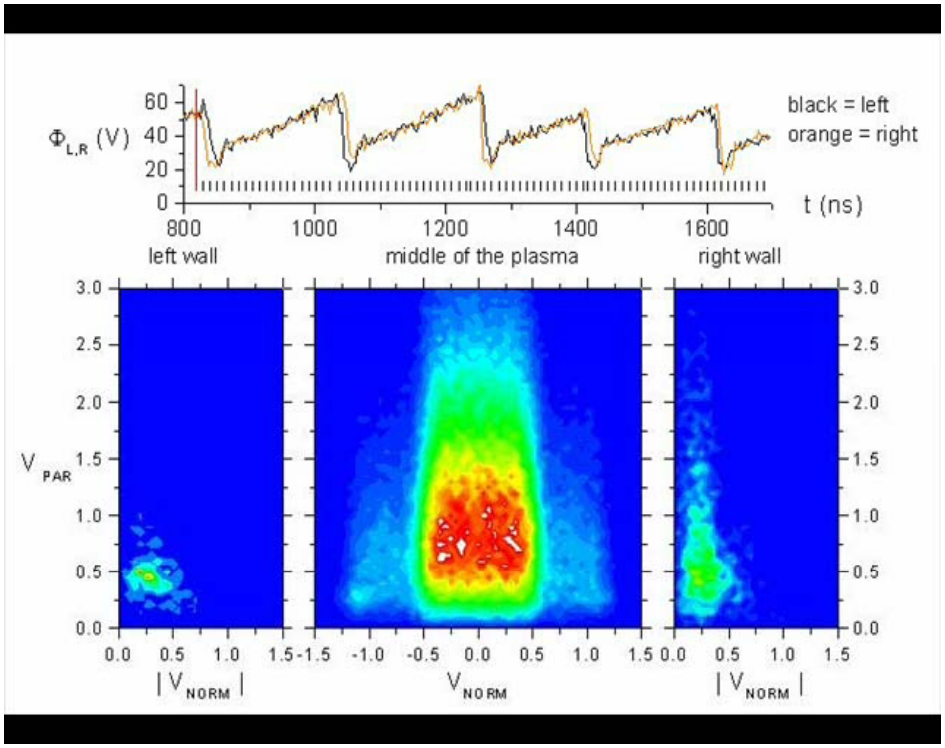
Average energy of primary electrons

Right wall



$T_e = 40$ eV, $M_i = 131$ amu: evolution of the phase planes

Potential



Electrons hitting the left wall

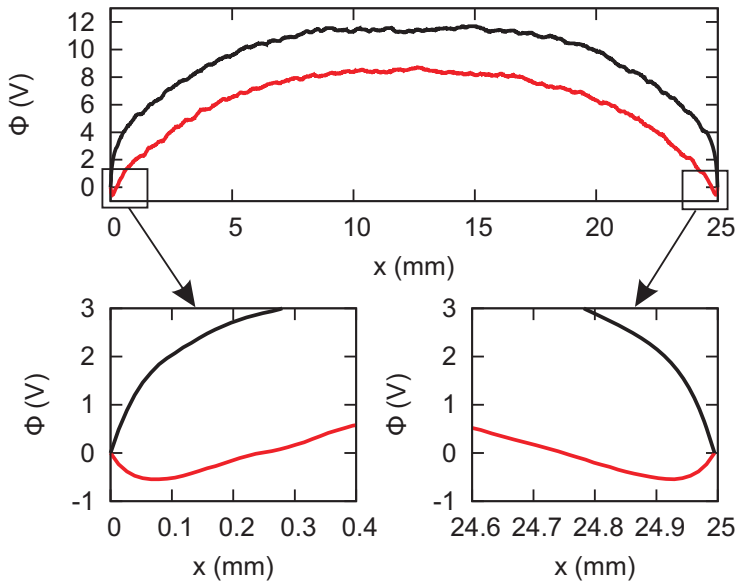
Electrons hitting the right wall

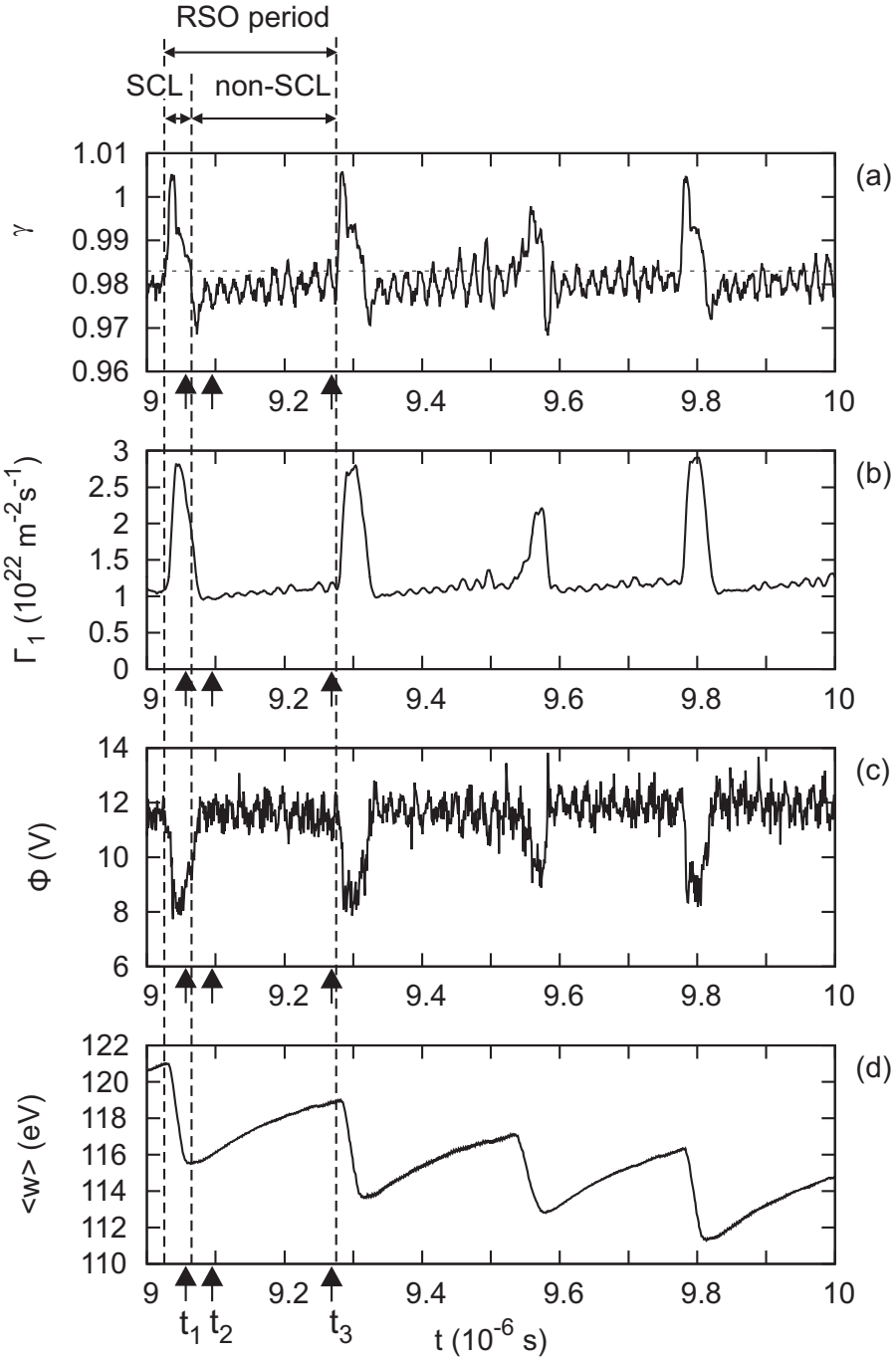
Electrons in the plasma bulk

Details of Relaxation Oscillations

Temporal evolution of plasma parameters
(a) emission coefficient at wall
(b) primary electron flux at wall
(c) plasma potential in the center
(d) averaged electron energy

Dashed vertical lines mark the beginning and the end of the RSO period and the transition from to non-space-charge limited state shown below.





Space charge limited regime does not establish due to strong modifications of EVDF

Temporal evolution of EVDFs

(a,d) in the SCL stage

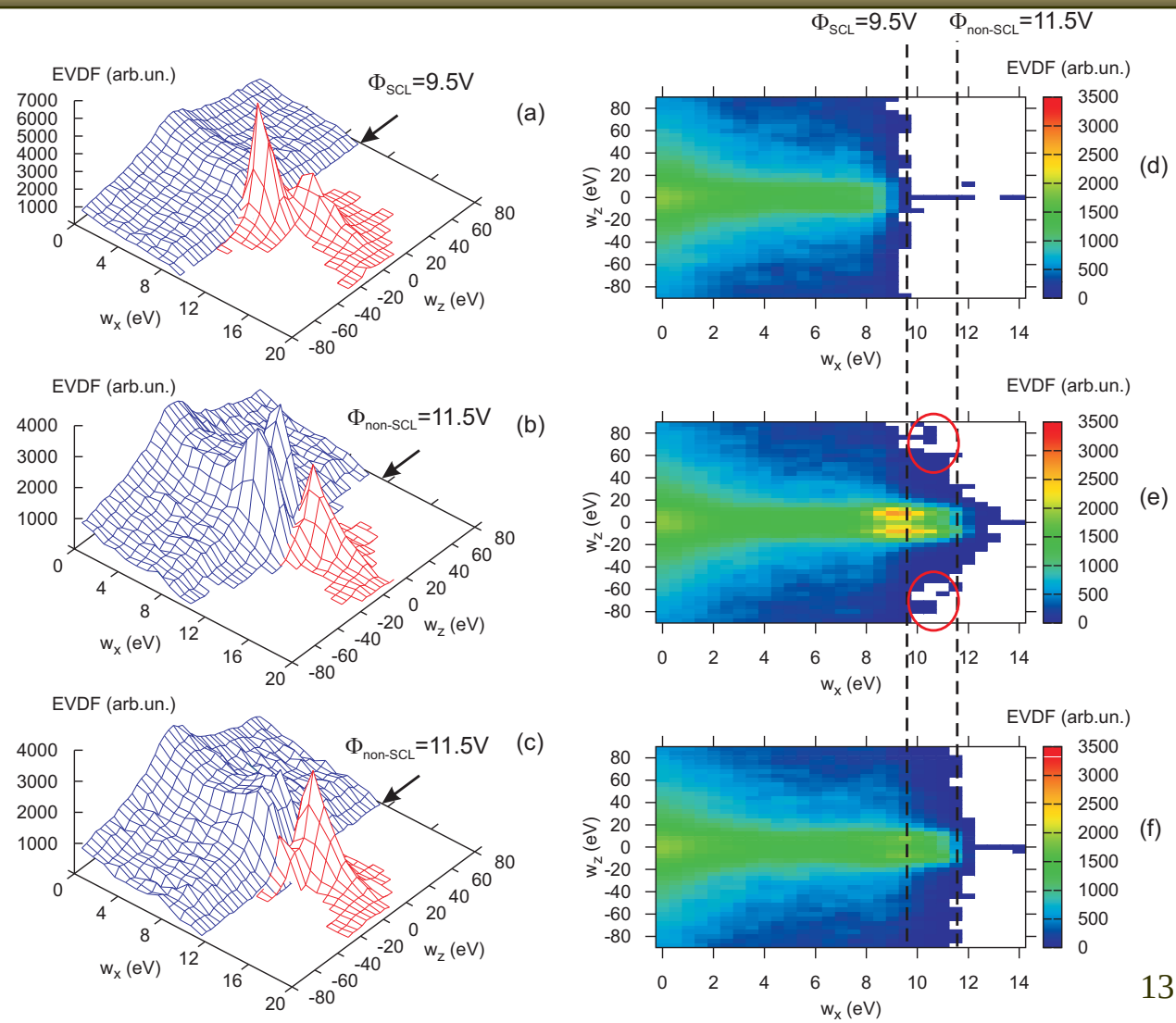
(b,e) in the beginning of the non-SCL stage

(c,f) in the end of the non-SCL stage.

The blue and the red surfaces in (a,b,c) correspond to the electrons of the plasma bulk and the secondary electron beam.

Panels (d,e,f) are the color maps of the plasma bulk EVDFs corresponding to the blue surfaces in (a,b,c), respectively. White areas in (d,e,f) contain no particles. Red ovals in (e) mark areas which are gradually replenished during the non-SCL stage.

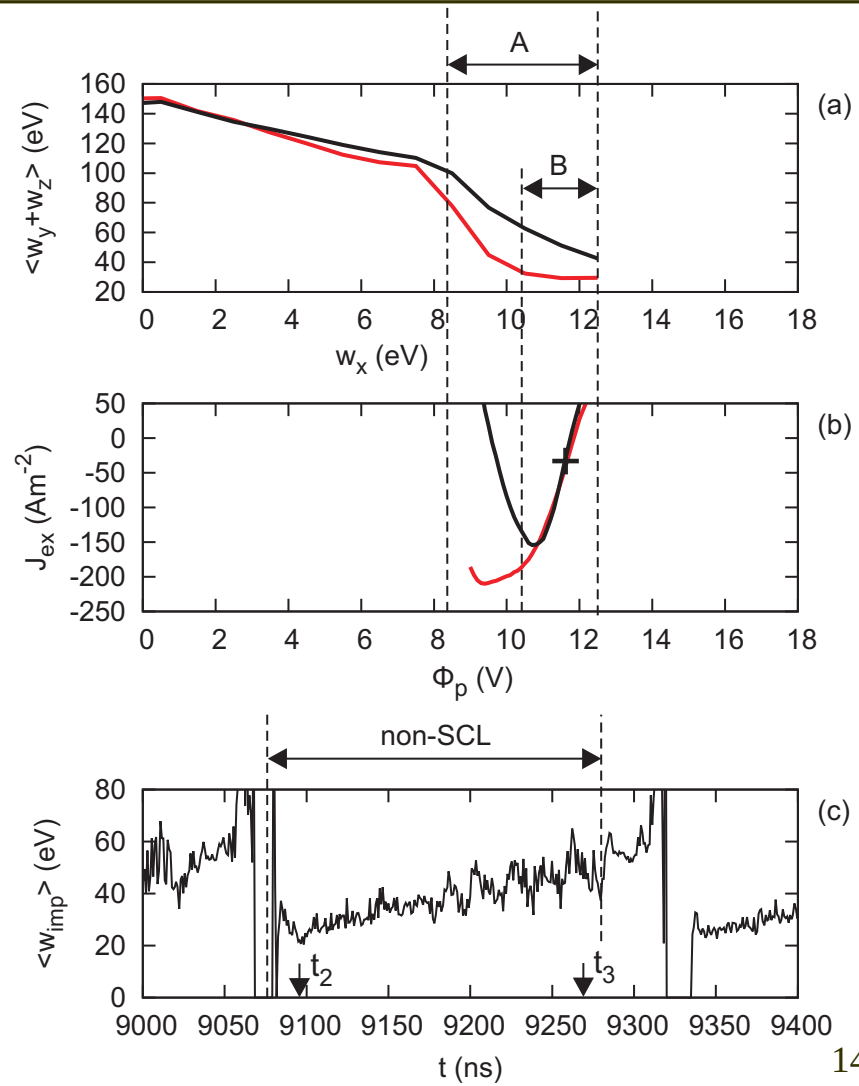
D. Sydorenko, et al PRL (2009).



Relaxation Oscillations are triggered by sheath instability due to high SEE.

(a) Average energy of motion of plasma bulk electrons in the direction parallel to the walls versus the energy of electron motion normal to the walls.
(b) Total electron current at the wall $x = H$ versus the plasma potential relative to the wall.
(c) average energy of weakly confined electrons vs time.

Red curves are obtained in the beginning of the SCL stage, black curves are obtained in the end of the SCL stage. Crosses mark the actual values of emission coefficient. Region A corresponds to electrons escaping to walls during the SCL stage (the weakly confined electrons). Region B corresponds to the range of perturbations of the plasma potential in the system.



Conclusions

Because cold SEE fluxes from opposite walls compensate each other, the plasma sheath never reaches a steady space charge limited (SCL) state

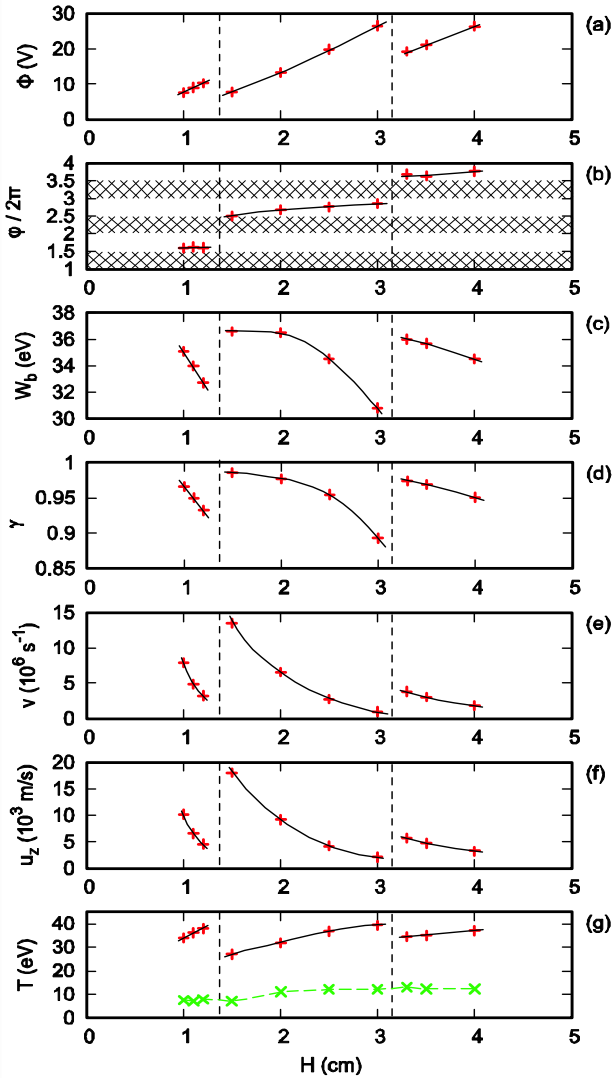
- even though the plasma SEE coefficient >1.

The plasma-sheath system can perform relaxation oscillations related with the negative differential resistance of the sheath.

- The oscillation cycle starts with the plasma potential drop. Energetic electrons leave the plasma and due to their high SEE yield, the sheath enters the SCL regime. When an intense flux of cold electrons from the opposite wall arrives, the SCL sheath regime quenches. Trapped cold SEE electrons are heated until the current-voltage characteristics of the sheath acquires a negative conductivity branch and the sheath becomes unstable again.

The oscillatory relaxation process crucially depends on the intense anisotropic heating of electrons.

Jumps in HT plasma parameters as a function of the width of the gap, H.



Plasma potential Φ_D in the midplane x=H/2

Final beam cyclotron rotation phase $\phi=\omega_c\tau$. Cross-hatched phase areas are forbidden.

Final secondary electron beam energy

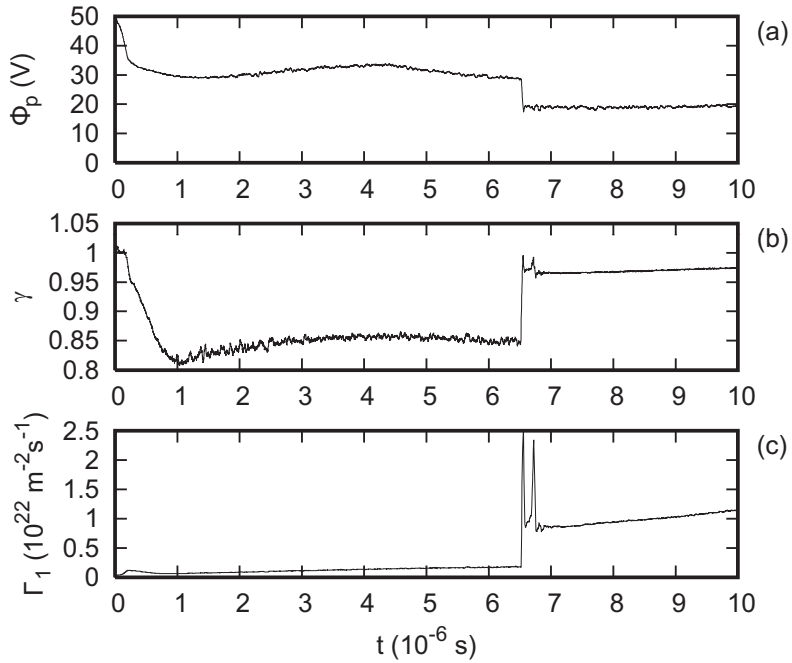
Total emission coefficient

Frequency of electron-wall scattering $\nu=2\Gamma_1/\langle n\rangle H$

Axial electron flow velocity averaged over the plasma gap

Electron temperature (T_z=red, T_x=green)

Effects of sheath instability on plasma properties in a Hall thruster



Plasma potential

Total emission coefficient

Primary electron flux Γ_1

When SEE is strong, the contribution of secondary electrons emitted at one wall to the primary electron flux to the opposite wall may be dominant. In this case, the sheath conductivity may become negative and the plasma potential, correspondingly, unstable due to a strong dependence of the beam energy on the plasma potential implemented via the time of electron flight between the walls.

From: D. Sydorenko, et al, Physics of Plasmas **15**, 053506 (2008).