Complex phenomena in magnetized plasmas in the presence of electron emission from the wall

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Topics covered

- Importance of plasma-surface interaction (PSI)
- Plasma-wall sheath
- Electron emission from the wall:
  - Cooling of plasma electrons
  - Near-wall double layer
- Kinetic effects of secondary electron emission (SEE) in collisionless magnetized plasmas.
- Near-wall conductivity across magnetic field.
- SEE-induced plasma instabilities.
Man-made plasmas are almost always surrounded by walls

Once plasma is formed, it diffuses towards the walls (electrodes, containing tube or vacuum vessel, targets, etc).

PSI occurs affecting both the plasma and the wall:

- The plasma is trying to “break” the walls by submitting it to intense particle and heat fluxes.
- The wall is trying to take revenge acting as a sink for charged particles, and “cooling” the plasma through energy losses, emission of colder electrons, “recycling” and pollution of impurities.
Recombination, trapping, displacements, implantation, erosion, desorption etc.

The incident energetic ions can set off collision cascades in the wall leading to its erosion.

Ion-induced sputtering may be involved in destruction of interstellar dust grains

It is believed that interstellar dust particles (silica, carbon etc) are destroyed by sputtering erosion, as they move at high velocities (~10’s km/sec) through regions of space containing ions (H, He, heavier) created by stellar shock waves.

Interstellar dust clouds
(active region of star formation in the Large Magellanic Cloud)
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 $\sim R_{Le} = m v_e / e B$


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

Hall thruster (New)  Hall thruster after 6000 Hrs

Courtesy:
L. King
F. Taccagona

Michigan Tech.
Heat fluxes from plasma can cause ablation of the walls

- 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

- Vaporization of graphite anode in a carbon arc discharge for nanotube growth

\[ \approx 60 \frac{MW}{m^2} \]

\[ \approx 40 \frac{MW}{m^2} \]
In plasma processing technologies, plasma-surface interaction is everywhere.

Example: deposition and coating of films by sputtering magnetron discharge.

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

From: www.angstromsciences.com
Langmuir probe: electron temperature, plasma density, electric potential, EEDF

Single probe

Ion region

LAP, Brazil (no relation to V-I)

Multi-cusps

Emissive probe

R. L. Stenzel, UCLA, Winter '97
http://www.physics.ucla.edu/plasma-exp/
Macroscopic wall effects on plasma:
Particle balance determines the electron temperature

Volume Ionization = Flux Through the Boundaries (e.g. wall)

\[ \nu_i \frac{\hbar}{N} V = \hbar c_s A \]

\[ T_e \text{ increases with } \frac{1}{Nd} \]

\[ n, N \text{ plasma, neutral density} \]
\[ V, A \text{ volume, surface area} \]
\[ \nu_i = 5 \cdot 10^{-14} \exp\left(-\frac{E_i}{T_e}\right) \cdot N \text{ s}^{-1} \]

\[ c_s = \sqrt{\frac{T_e}{M_{ion}}} \text{ Ion acoustic velocity } (T_e \gg T_i) \]
Macroscopic wall effects on plasma:

Energy Balance Determines the Plasma Density

\[ P_{in} = IU \approx P_{abs} = e(n c_s A) \varepsilon_T \]

Density is linearly proportional to power

\[ \varepsilon_T = \varepsilon_c(T_e) + 2T_e + \varepsilon_{ion}(T_e) \]

- Energy lost per e-i pair created
- Mean energy lost per electron lost to the wall
- Mean energy lost per ion lost to the wall
Macroscopic wall effects on plasma: Confinement by magnetic field

The magnetic field reduces the effective surface area and therefore decreases the electron temperature.

The decrease of the electron temperature results in an increase of the plasma density.

From: http://iter.rma.ac.be

Fruchtman et al., PST 2005
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:

\[
\Gamma_{pe} = \Gamma_{ion}
\]

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

\[
\Gamma_{ion} = n_s \sqrt{T_e/M}
\]
From the balance between the electron flux at the wall and the ion flux at the sheath edge:

\[
\phi_w = \phi_{ps} - \phi_f = \frac{kT_e}{e} \ln\left(\frac{M}{2\pi m_e}\right)^{1/2}
\]

For Xenon (131.3): \( \phi_w = 5.27 \, T_e \)

Only electrons with energies \( \varepsilon > 5.27T_e \) can leave the plasma to balance the ion flux to the wall.
A small fraction of fast, nonlocal electrons can dramatically change the thickness of and electric field in the near-wall sheath.

Even when $n_f << n_b$, the sheath potential can increase dramatically resulting in a comparable increase in the sheath thickness.

\[
\phi_w = \phi_{w, J_{ef} = 0} + \frac{kT}{e} \ln \left( \frac{J_i}{J_i - J_{ef}} \right)
\]

FIG. 2. Near-wall potential drop in Xe afterglow plasma. Pressure is 0.2 torr. Measurements (stars), calculation with formula (5) (diamonds) and calculations taking into account fast electrons, and the resulting anomalous potential jump (boxes).

*V. Demidov et al., PRL, 95 (2005).
A hot floating wall can be positive with respect to plasma (transient double layer)

Axial variation of the plasma potential

Floating hot wall at z=0

Emission coefficient \( \delta = \frac{J_{\text{max}}^{\text{emit}}}{J_{e\_\text{plasma}}} \)

At \( \delta \sim 1 \), a virtual cathode (E~0) is formed. It attenuates electron currents from both wall and plasma sides.


Note I. Langmuir predicted a double layer near cathode in 1929
Zero current balance at the floating emitting wall

Wall

\[ \Gamma_{EE} = \delta(T_w) \Gamma_e \]

or

\[ \Gamma_{SEE} = \gamma(T_e) \Gamma_e \]

- Thermionic emission from hot wall
- Field emission from sharp surfaces
- Electron and ion-induced SEE

\[ \gamma = \gamma(T_e) \]

\[ \Gamma_i + \Gamma_{pe} - \Gamma_{see} = 0 \]

\[ \Gamma_{pe} = \frac{1}{1 - \gamma(T_e)} \Gamma_{ion} \]

if \( \gamma \to 1 \)

\( \Gamma_{pe} \to \infty \)
Secondary electron emission (SEE)

\[ \gamma = \frac{\text{Secondaries}}{\text{Pr imaries}} \]

\[ \gamma = \gamma(T_e) \]

Example of energy spectrum (for steel)

*Furman and Pivi, LBNL 52807, 2003*
SEE from dielectrics reaches 1 at lower energies (< 50 eV) of primary electrons than for metals.

Note: for boron nitride, if primary electrons are Maxwellian, $\gamma(T_e) \approx 1$ at $T_e = 18.3$ eV

*Dunaevsky et al., Phys. Plasmas, 2003*
Electron emission from the wall can significantly reduce the sheath potential

\[ \phi_w \approx \frac{kT_e}{e} \ln\left(1 - \gamma \left(\sqrt{\frac{M_{\text{ion}}}{2\pi m_e}}\right)\right) \]

When \( \gamma = 0 \), \( \phi_w = 5.27 \, T_e \) (for Xenon)

When \( \gamma(T_e^{cr}) = \gamma_{cr} \approx 1 \rightarrow \phi_w^{scs} \approx T_e \)

SEE turns to space-charge limited regime [Hobbs and Wesson, 1967]

For Boron Nitride ceramic, Xenon ion:

\[ T_e^{cr} \approx 18.3 \, \text{eV} \quad \gamma_{cr} \approx 0.983 \]
Fluid theory predicts that emitting wall acts as extremely effective energy sink for electrons

\[
\frac{P_{\text{wall}}}{A} = u_b N_e \varepsilon_w = u_b N_e \left[ \frac{2T_e}{1 - \gamma(T_e)} + e|\phi_w| + 0.5T_e \right]
\]

Energy lost per electron lost to the wall
Energy lost per ion lost to the wall

When no SEE ($\gamma = 0$), Xenon plasma
\[\varepsilon_w \approx 7.77 \cdot T_e\]

For space-charge saturated (SCS) sheath, when $\gamma(T_e) = \gamma_{cr} \approx 0.983$
\[\varepsilon_w \approx 120 \cdot T_e\]
In the presence of strong SEE:
- Ions accelerated in the reduced sheath potential drop produce less sputtering.
- Enhanced electron flux leads to heating of the walls and cooling of plasma electrons.
Plasma applications with strong SEE

- Divertors and limiters of fusion devices
- Plasma thrusters (esp. Hall thruster)
- Emissive probes
- Plasma processing (esp. PIII)
- Dusty plasmas
- Plasmas with nanotubes
Hall Thruster (HT)

- 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 ~ $10^{-3}$ - 1 N
- $I_{sp}$ ~ 1000-3000 sec
- Efficiency ~ 6-70%

- $\rho_e << L << \rho_i$

- HT is not space-charge limited.
- Higher current densities than in ion thrusters.
Parameters of Hall thruster plasma

<table>
<thead>
<tr>
<th>Neutral density</th>
<th>~ $10^{12}$-$10^{13}$ cm$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma density</td>
<td>~ $10^{11}$-$10^{12}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Highly ionized flow: $\Gamma_{\text{ion}}/\Gamma_n$</td>
<td>~ 80%</td>
</tr>
<tr>
<td>Electron temperature</td>
<td>~ 20-60 eV</td>
</tr>
<tr>
<td>Ion temperature</td>
<td>~ 1 eV</td>
</tr>
<tr>
<td>Ion kinetic energy</td>
<td>~ $10^2$-$10^3$ eV</td>
</tr>
</tbody>
</table>

| $\lambda_{ea}/h$ | ~ 20 – 200 |
| $\lambda_{ei}/h$ | ~ $4 \times 10^3$ |
| $\lambda_{ia}/h$ | ~ 10-100 |

Energy relaxation length in the inelastic range

| $\lambda^*/h$ | ~ 30 - 300 |

Collisionless, non-equilibrium plasma with magnetized electrons and high energy, non-magnetized ions
Non-local effect of channel wall materials on the V-I characteristics

Narrow low-SEE segments at the channel exit drastically change V-I characteristics

- Boron nitride - high SEE.
- Carbon velvet - low SEE.

Note: carbon segment is short and so Simon’s short-circuit has a small effect

Y. Raitses et al., Phys. Plasmas 2006
SEE effect on plasma electrons: comparing experiment with predictions

According to fluid theories, the maximum electron temperature should not be above 18.3 eV (for BN and Xenon)

Fluid theory $T_{e\text{max}} \approx 18.3$ eV

Large quantitative disagreement with fluid theory!
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)

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

Mean free path $>>$ system size

$\Phi$

$x$

$\ln f$

$\varepsilon_x > e\Phi$

$e\Phi$

$\varepsilon_x$
Evolution of evaporation flux for Hall thruster plasma (HT).

- Loss cones and beams 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
Electron scattering due to elastic collisions with atoms and ions governs the electron wall fluxes.

The EVDF in the loss cone is:

- Refilled due to the elastic scattering (from outside of the loss cone)
- Emptied by the free flight to the walls with the rate determined by the transit time ($\sim H/v_x$).

Electron flux to the wall is limited by elastic e-a and e-i collisions, which are rare in HT plasma.

$$\Gamma_e = \frac{H}{8\lambda_e} n_e \sqrt{\frac{8T_{ez}}{\pi m}} \exp\left(-\frac{\Phi}{T_{ez}}\right)$$

Electron fluxes have several components, including counter-streaming beams of SEE electrons from opposite walls.

1- primary
2- secondary

SEE coefficients:

\[ \gamma_p \equiv \frac{\Gamma_{2p}}{\Gamma_{lp}} \quad \text{SEE due to plasma electrons} \]
\[ \gamma_b \equiv \frac{\Gamma_{2b}}{\Gamma_{lb}} \quad \text{SEE due to beam electrons} \]
\[ \alpha \equiv \frac{\Gamma_{lb}}{\Gamma_2} \quad \text{penetration coefficient of the SEE beams} \]
1. If beam electrons are trapped in plasma, $\alpha = 0$,

$$\Gamma_{1p} = \Gamma_{i} / (1 - \gamma_{p})$$

(Fluid case)

2. New case - if no trapping ($\alpha = 1$)

$$\Gamma_{i} = \Gamma_{1p}$$

The SEE contribution to the current balance is canceled

Total emission coefficient:

$$\gamma_{\text{eff}} = \frac{\gamma_{p}}{1 + \alpha(\gamma_{p} - \gamma_{b})}$$

Note $\gamma_{p}$ can be $> \gamma_{cr}$ if $\gamma_{\text{eff}} < \gamma_{cr}$
In HT, the two-stream instability is weak because the EVDF is a decreasing function of $v_x$.

- Beam penetration is high, $\alpha \approx 0.9$

Sydorenko et al, Phys. Plasmas 2007
Cyclotron rotation and ExB drift modify the energy of emitted electrons

- Kinetic energy of emitted electron oscillates during the flight.
- SEE produced by emitted electrons may be significant: $\gamma_b \neq 0$
- The near wall conductivity (NWC) may appear

Morozov, Saveljev, 2001
SEE beams contribute to the enhancement of the electron cross-field current

The displacement \( \rho_c = \nu_\perp / \omega_c \), \( \nu_\perp = u_d = \frac{E_z}{B_x} \) during the flight time \( H/u_{bx} \)
gives average velocity \( \langle u_z \rangle \sim u_d u_{bx} / H \omega_c \) and current \( J_{bz} \approx \frac{m}{H} \frac{\gamma_p}{1-\gamma_b} n_e \sqrt{\frac{T_{ex}}{M} \frac{E_z}{B_x^2}} \).

SEE beams may explain the experiment

![Diagram showing electron trajectories in a magnetic field](image)
Lowering the effective SEE coefficient with the oblique magnetic field

SEE electrons accelerated by a sheath E-field and gyrate due to the Lorentz force in a B-field. The latter causes the electrons to return to the surface.

\[ R_{\text{Le}} > \lambda_{\text{sh}} \Rightarrow \text{the higher the energies of SEE electrons or the lower } T_e \text{ (thinner sheath), the more the secondary electrons return to the surface.} \]

Applications: divertors, PIII systems

Nishimura et al., Vacuum, 1996

Effect of the oblique angle on the SEE under the condition of SCS

The low pressure laboratory and technological plasmas are always bounded with walls. The electron flux to the wall is determined by the electron velocity distribution function (EVDF) and by the sheath potential, which are consistent with the wall properties.

Fluid theories predict that the electron emission from the wall reduces the potential drop in the sheath between the plasma and the wall and, thereby, weakens electrical and thermal insulating properties of the sheath.

In more complex situations, such as exist in collisionless and magnetized plasmas, electron kinetic effects can substantially alter the plasma-wall interaction and change transport properties of the magnetized plasma.

These situations can be relevant to various cross-field discharge devices such as Hall thrusters, advanced tokamak divertors with low recycling, plasma immersed ion implantation systems etc.
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Michael Keidar (GWU)
- D. Whyte, ”The Challenges of Plasma-Surface Interactions in Magnetic Fusion” MIT ANS Seminar, April 9, 2007.
Related references on plasma-wall interactions in Hall thruster plasma

More information on http://htx.pppl.gov