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# Ion transport through Radio-Frequency sheaths studied by Particle-In-Cell simulations

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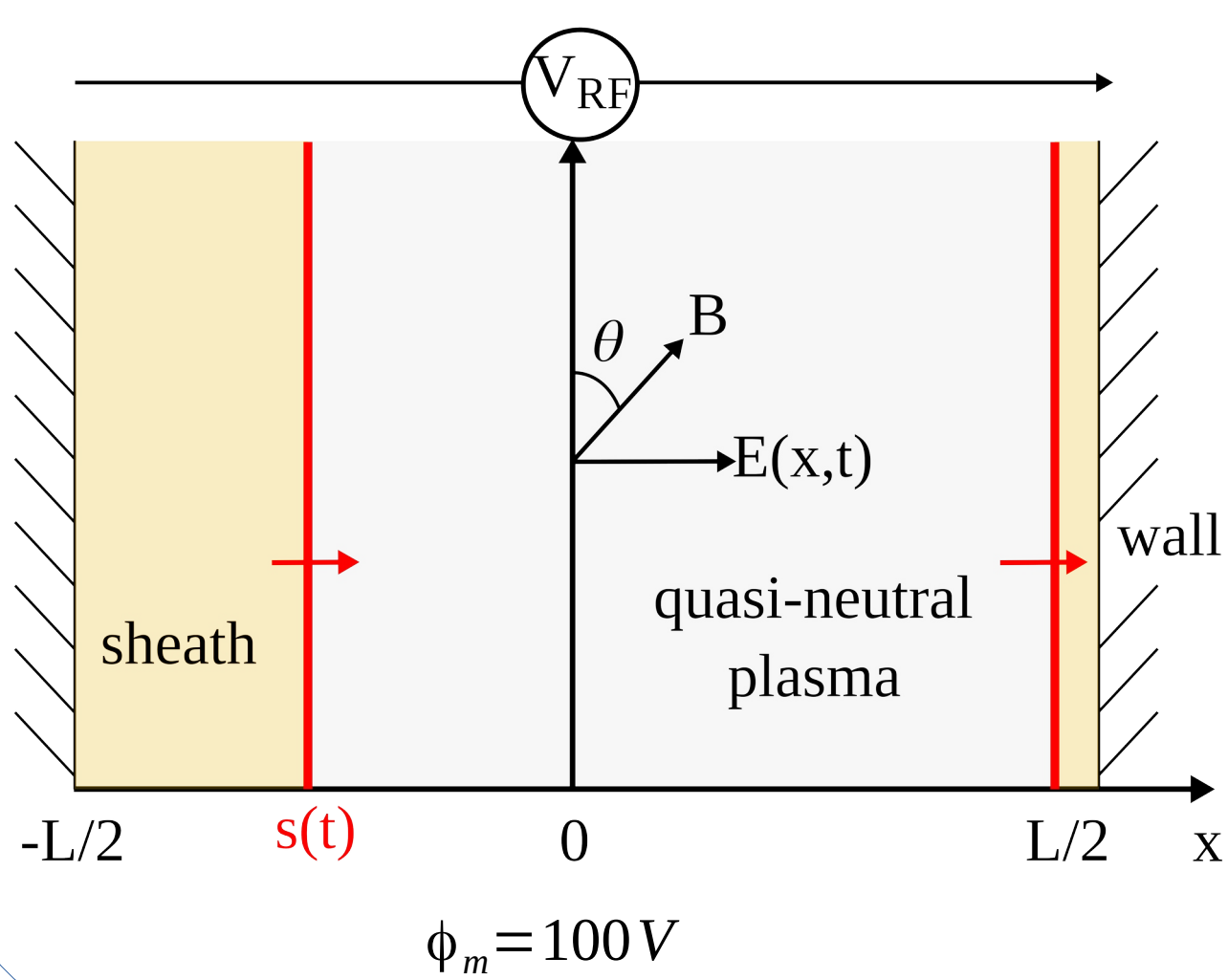
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## Context of the Simulations

- 1d/3V PIC simulations ( $L=600\lambda_d$ ).
- Plasma submitted to a RF voltage drop such that:

$$V_{RF} = \phi_m \times \sin \omega t$$



- Several ion-to-electron mass ratios, ie. 500 (reduced mass), 1836 (hydrogen) and 3672 (deuterium)

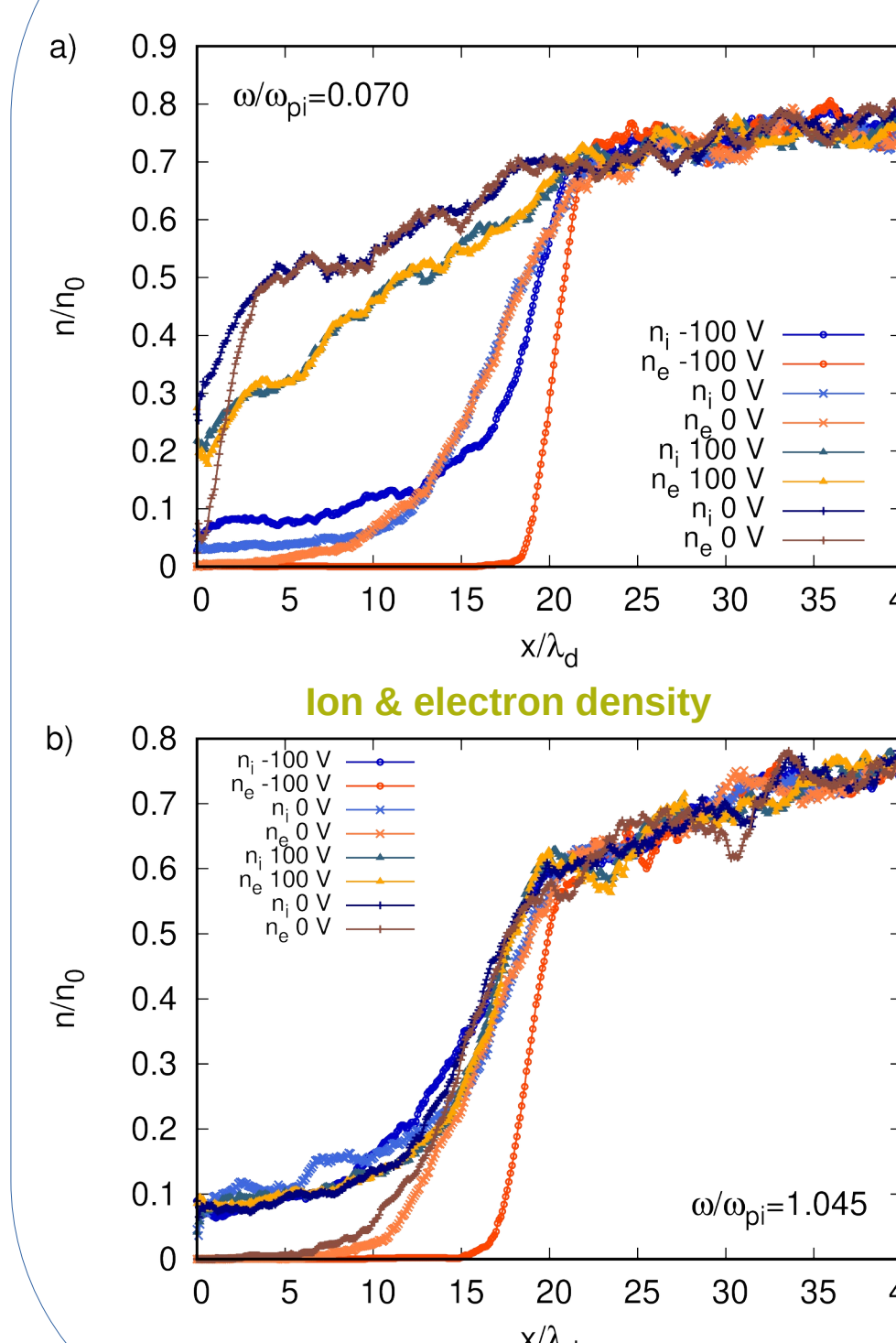
-  $T_i = T_e = 2\text{eV}$  and the density ranges between  $10^{16}$  to  $10^{19} \text{ m}^{-3}$  depending on the mass ratio in order to have similar  $\omega/\omega_{pi}$  for  $\omega$  in the tens of MHz mark.

- No collisions were taken into account and the magnetic field is considered perpendicular to the surface at first.

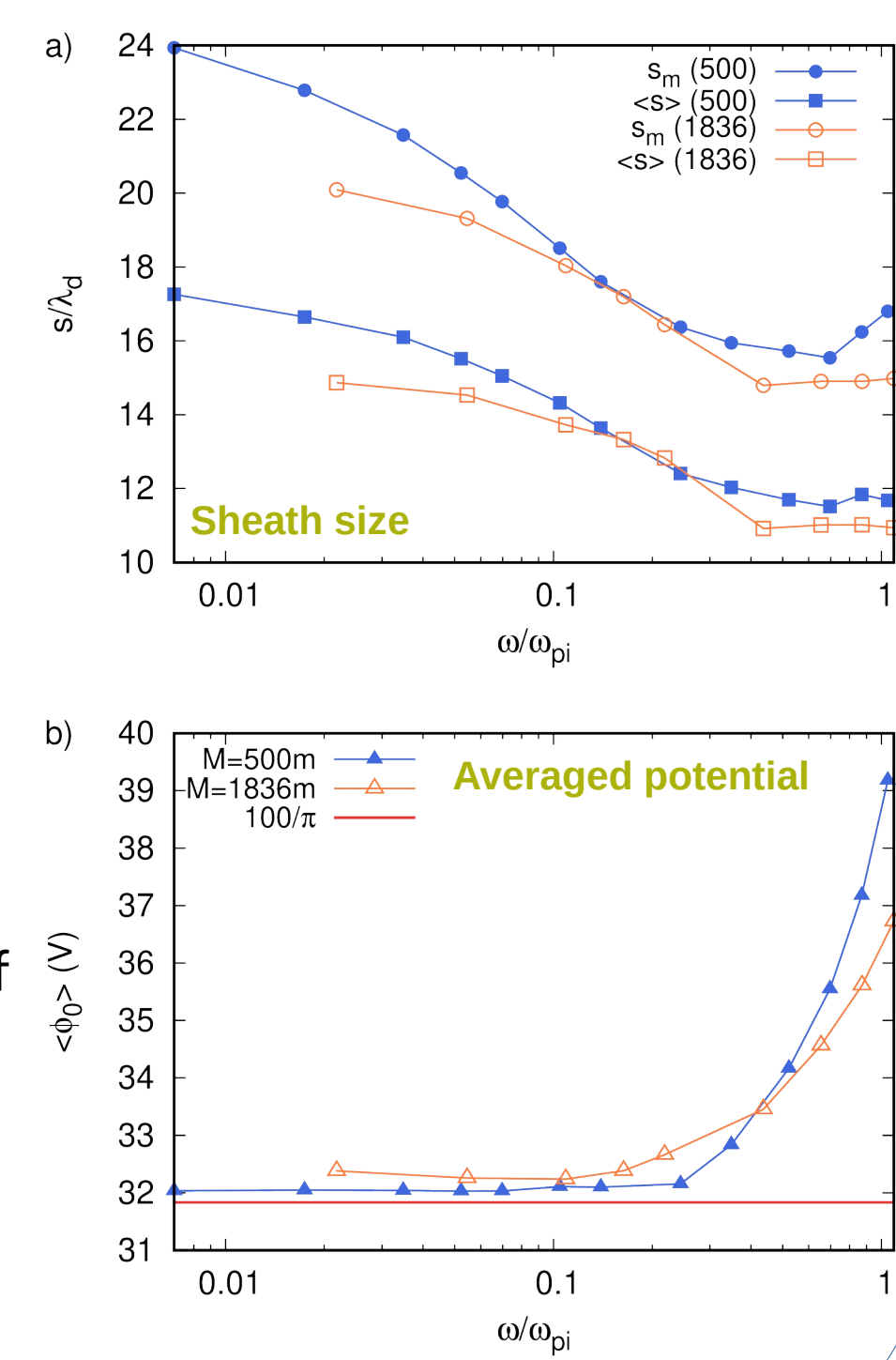
- During RF cycles, both sheaths (left and right) oscillate in anti-phase.

- We can access to the instantaneous density or space potential profiles as well as the averaged characteristics (velocity, potential, electric field...). Ions impacting the wall are analyzed in term of angle of impact ( $\alpha$ ) on the surface and incident energy vs  $\omega/\omega_{pi}$  ratios.

## Sheath size, space potential and plasma density



- Sheath building is strongly impacted by the RF voltage : for large RF frequency ions no longer follow the potential time variations and react to an averaged potential drop in the sheath



- Average sheath size and plasma potential strongly depend on the RF frequency as a consequence of the ion dynamics.

## Sheath rectification vs $\omega/\omega_{pi}$

$$\omega/\omega_{pi} < 1 \quad \phi_0 = \frac{\omega}{2\pi} \int_0^{2\pi} \phi_m \sin \omega t dt = \frac{\phi_m}{\pi} \quad [1]$$

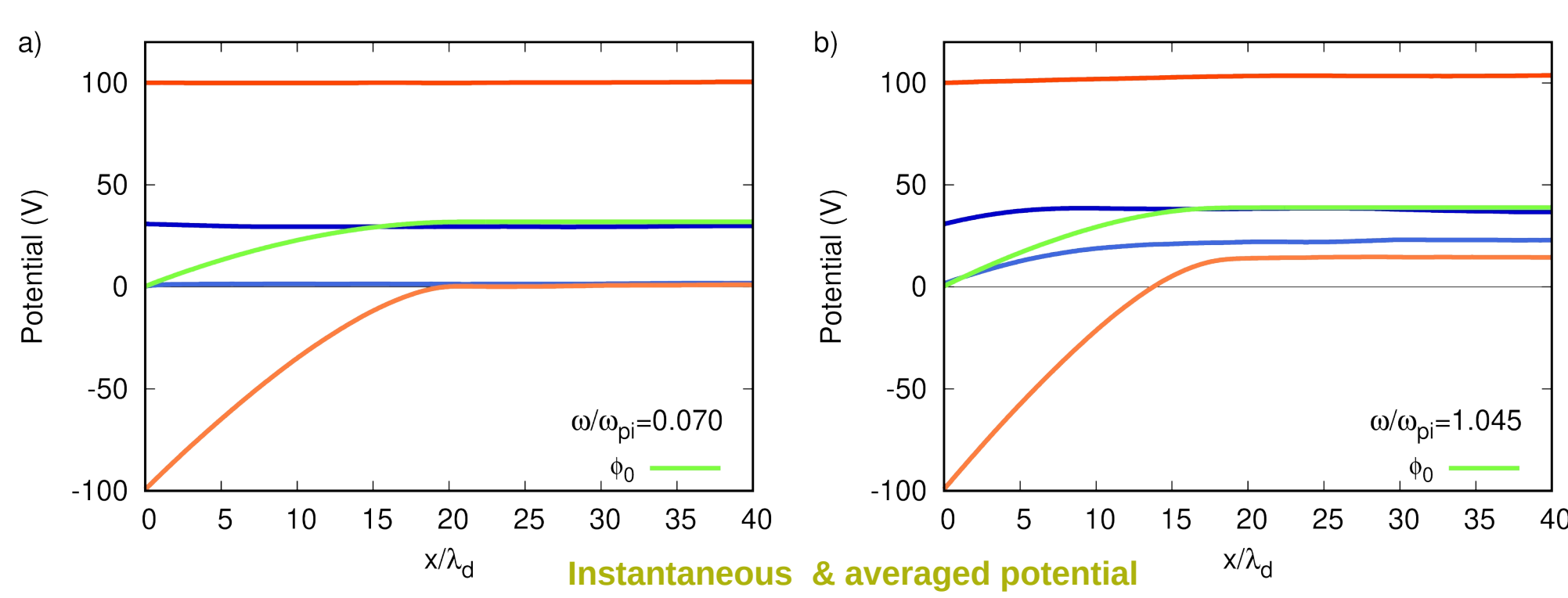
$\omega/\omega_{pi} > 1$  Let us assume that the potential drop in the sheath is of the form:

$$\Delta \phi_s(t) = \frac{\phi_m}{2} \sin \omega t + \phi_0$$

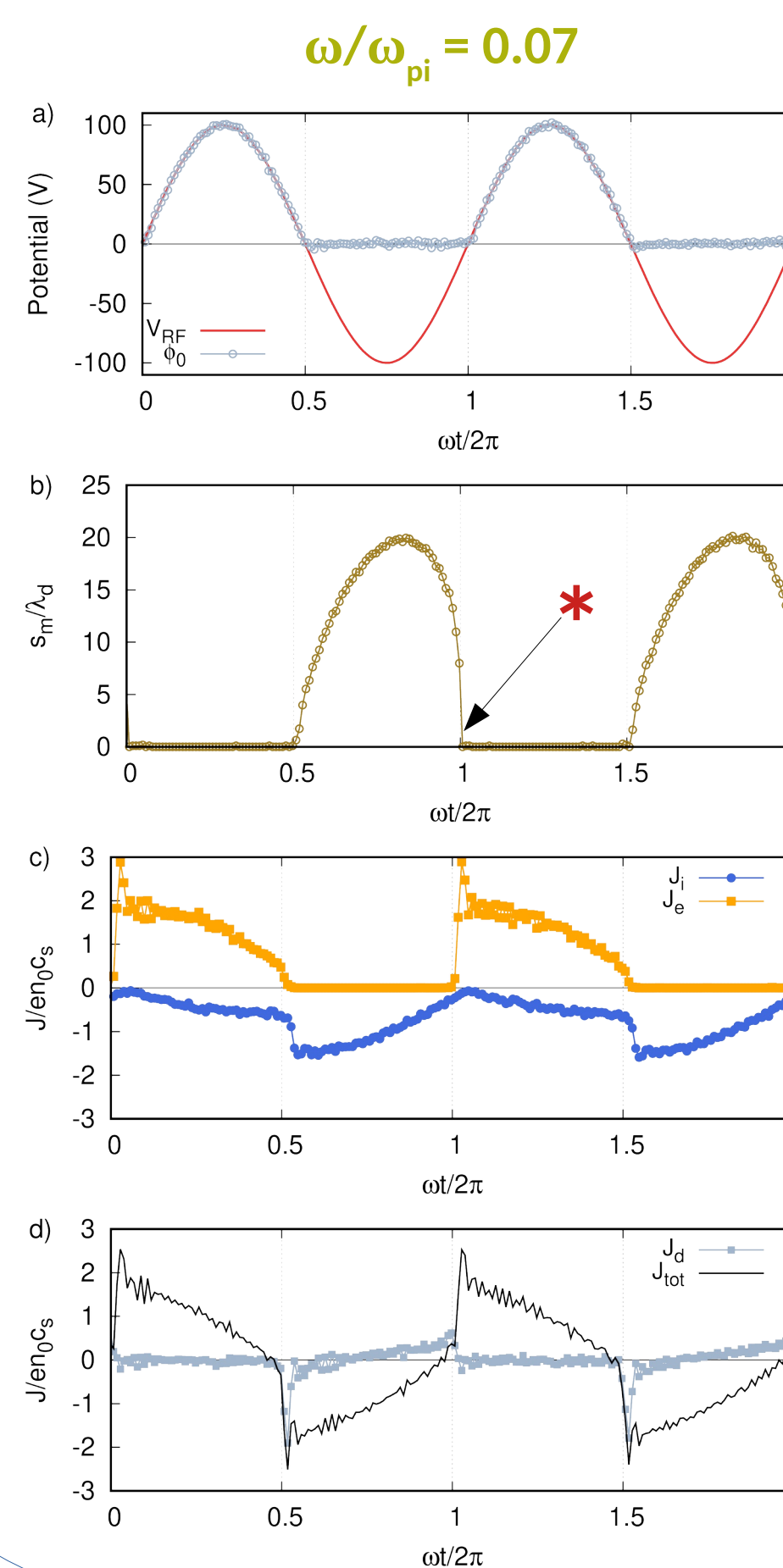
The ambipolarity at the surface (the ion Bohm flux balances the electron current) writes:

$$\frac{\omega}{8\pi} \int_0^{2\pi} n_s c_e \exp\left(-\frac{e\Delta\phi_s(t)}{k_b T_e}\right) dt - n_s c_s = 0$$

$$\text{Then } \phi_0 = \frac{k_b T_e}{e} \ln I_0\left(\frac{e\phi_m}{2k_b T_e}\right) + \phi_{float} \approx \frac{\phi_m}{2} \text{ for } e\phi_m \gg k_b T_e \quad [2]$$



## Time variations



- Capacitive effects arise when RF frequency reaches the ion plasma one inducing:

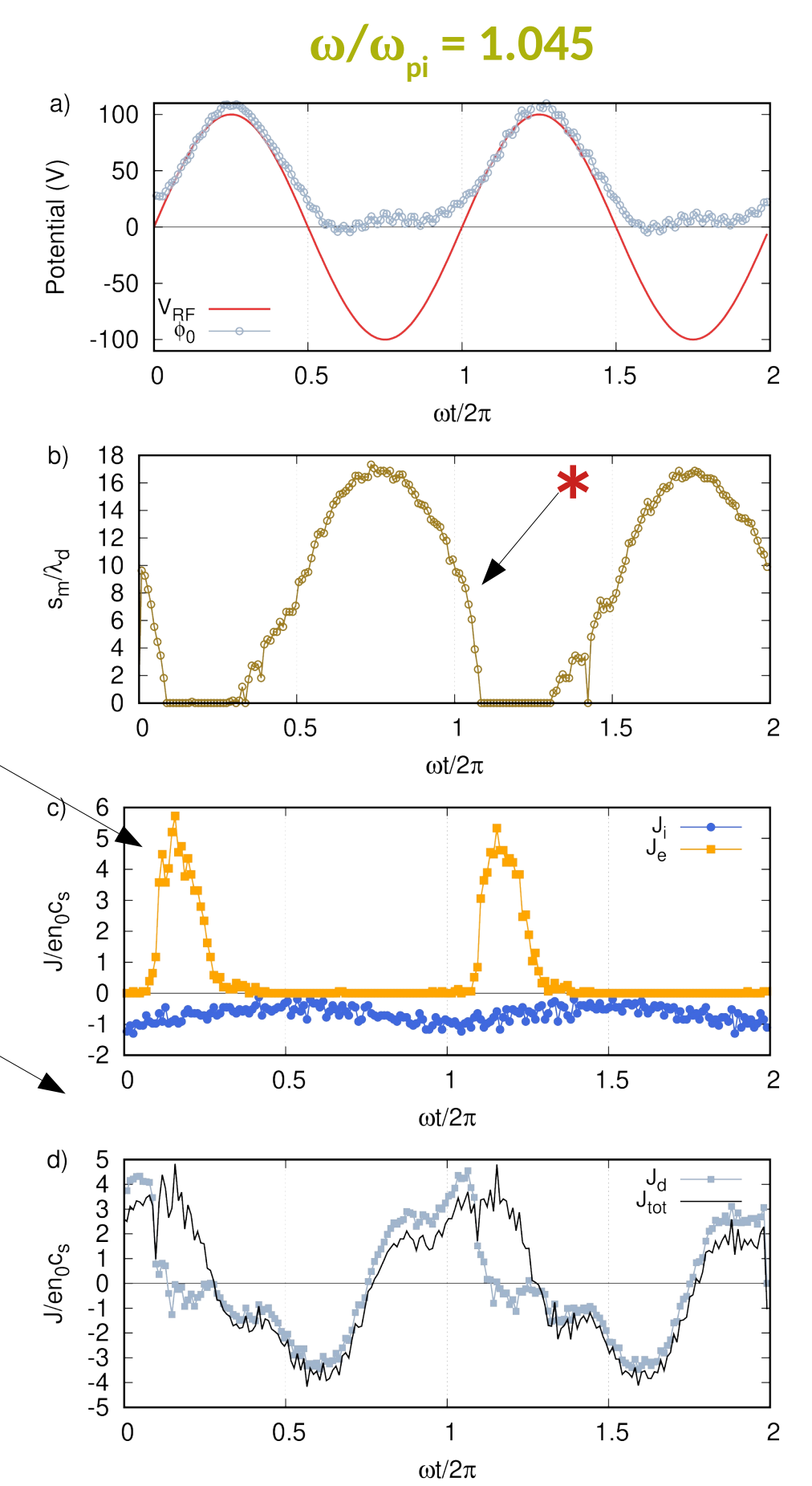
→ The collapse of the sheath is delayed with respect to the potential time variation \*

→ The transfer of electrons at the surface to compensate the ion current arises during a small part of the half RF cycle

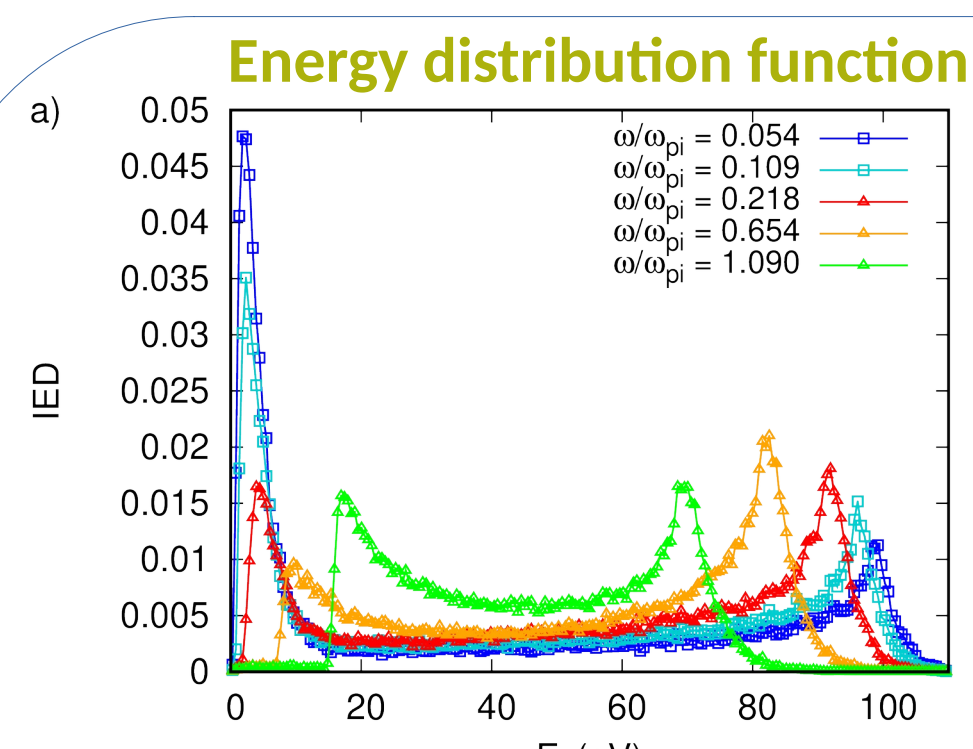
→ Displacement current can not be neglected anymore

$$J_d = \epsilon_0 \frac{\partial E}{\partial t} \approx \omega \epsilon_0 \frac{\phi_m}{s}$$

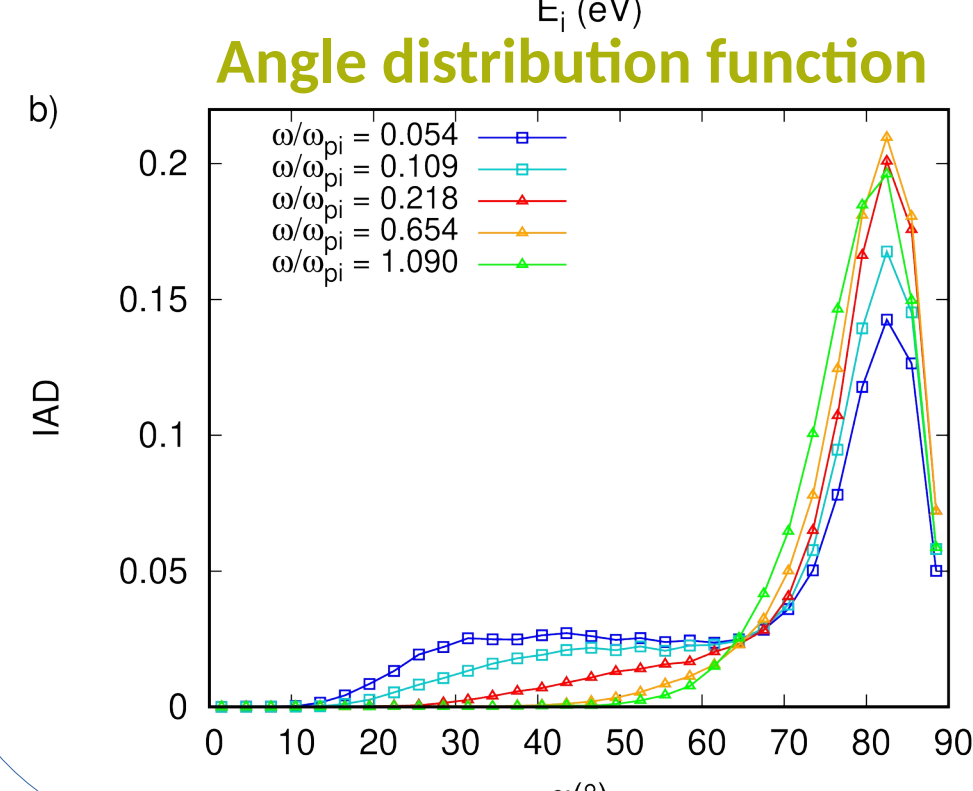
$$\frac{J_d}{J_i} \approx \frac{\omega}{\omega_{pi}} \left(\frac{e\phi_m}{k_b T_e}\right)^{1/4} \quad [3]$$



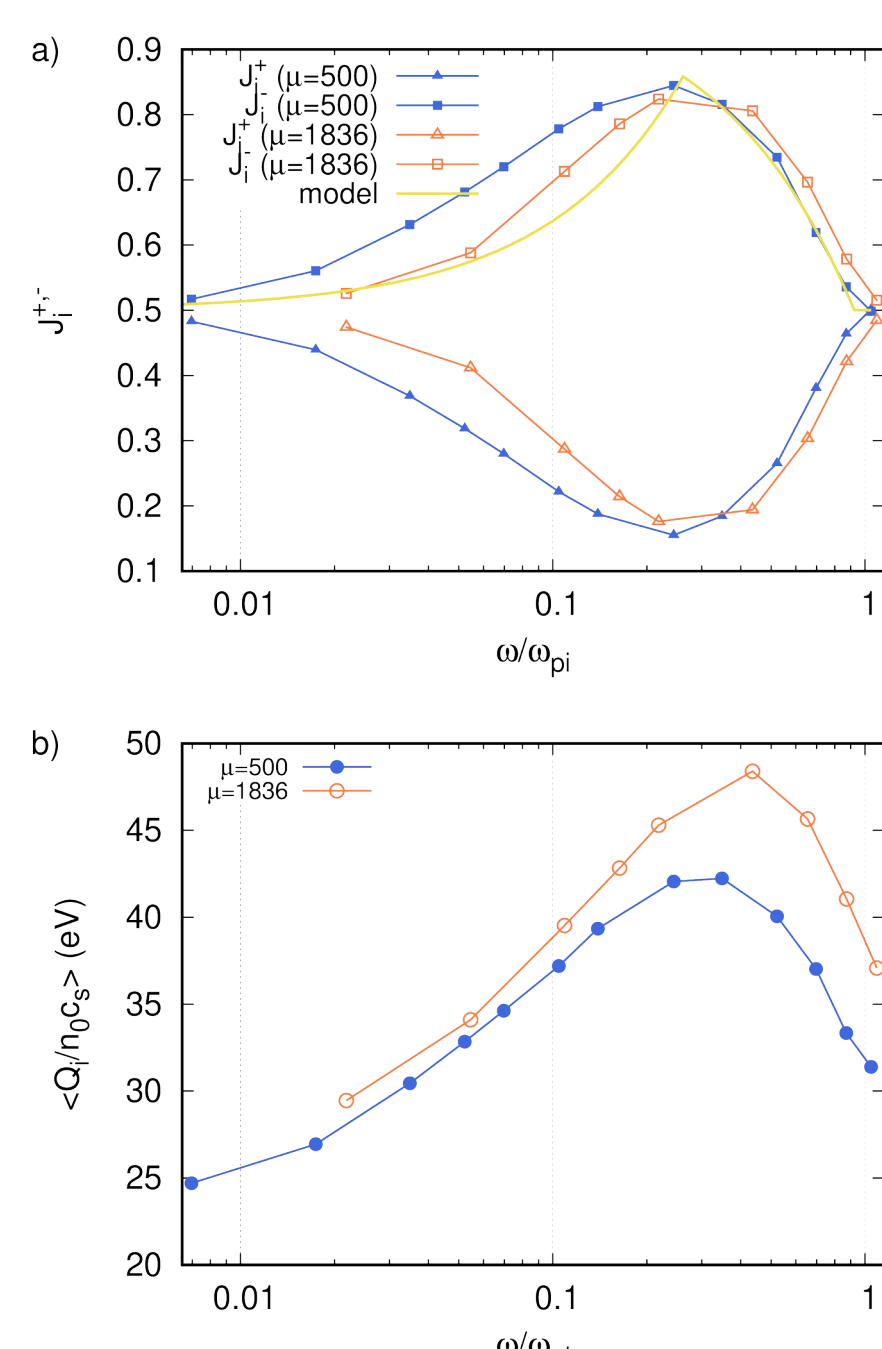
## Heat and particle flux to the surface vs $\omega/\omega_{pi}$



- When the RF frequency increases, ions do not undergo instantaneous potential variation and subsequent acceleration in the field [4] → the gap between the energy peaks decreases (since eventually only one peak subsists).

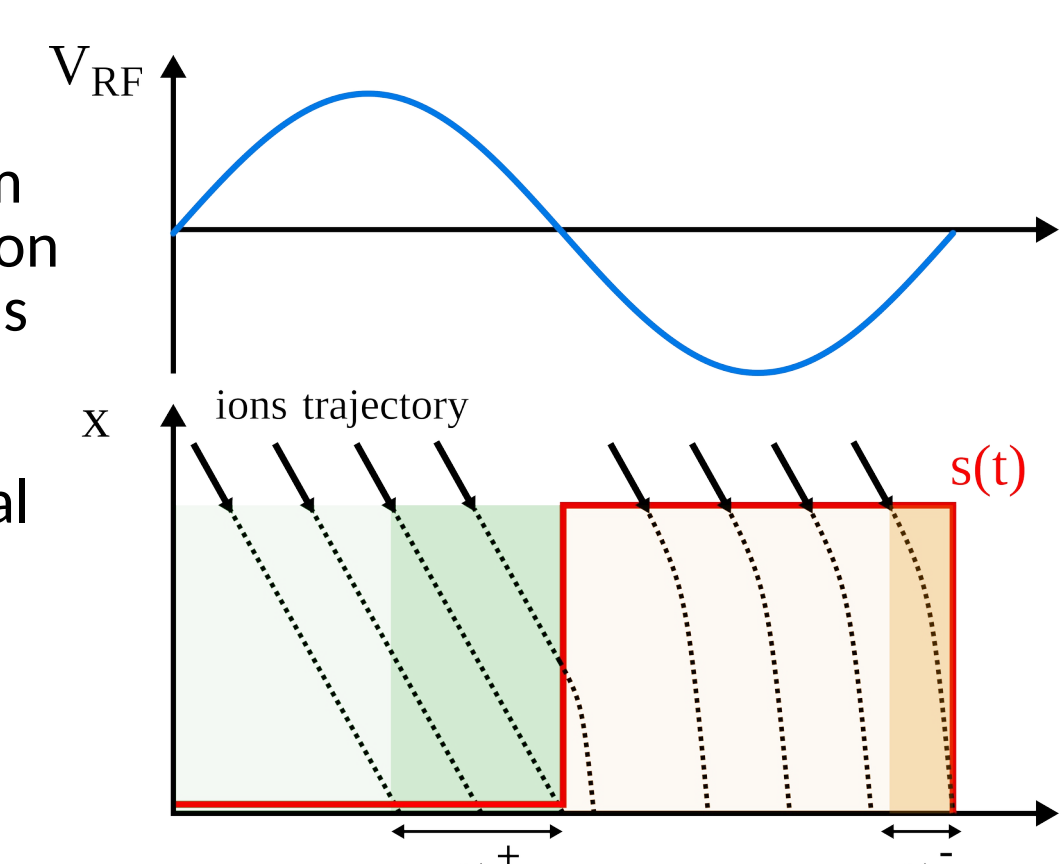


- the distribution of the angle of impact of ions onto the surface is displaced towards the perpendicular direction since a larger proportion of them are strongly accelerated in this direction when the RF frequency increases.



-  $J_i^+$  (resp.  $J_i^-$ ) represents the proportion of the total ion flux reaching the wall when the wall potential is positive (resp. negative). This proportion depends on the time of flight of ions in the sheath area vs. the RF period as depicted in the figure below (see for instance ref [5]).

- It induces a maximum of the heat deposited on the wall because at this point, a maximum of ions has undergone a large negative potential drop in the sheath.



## References:

- [1] W. Schwarzenbach et al. J. Vac. Sci. Technol. 14, 132 (1996)
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