

3D Fully Kinetic Simulation of Near-Field Plume Region

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Abstract: The near-field plume region of Hall-effect thruster is investigated using a three-dimensional Particle-in-Cell/Monte Carlo collision (PIC-MCC) model. A detailed electron-surface interaction model has been implemented on the thruster exit plane. Results show the important role of magnetic field in the first 4 cm and of the azimuthal fluctuation together with asymmetry driven by the cathode and with the plasma-surface interaction on the exit plane.

Nomenclature

ρ	=	charge density
t	=	time
φ	=	electric potential
$\mathbf{E}$	=	electric field
$\mathbf{B}$	=	magnetic field
x	=	spatial coordinate
y	=	spatial coordinate
$\mathbf{v}$	=	particle velocity
z	=	spatial coordinate
m	=	electron mass
q	=	elementary charge
Δt	=	time step
Ω	=	cyclotron frequency vector
ω	=	plasma frequency

I. □ Introduction

Several physical phenomena controlling the functioning of Hall-effect thruster occur in the near-field region of the plume: ion acceleration, anomalous electron transport, ionization, charge exchange, ion beam neutralization, asymmetry induced by the cathode location. Therefore, understanding the plasma physics involved in this region can be crucial for the improvement and optimization of Hall-effect thrusters.

Few models¹⁻⁵ have been developed to study the near-field plume region. However, due to the complexity of this transition region, and in particular to the following elements:

- magnetic field still large enough to magnetized electrons;
- collisions not sufficient to guarantee the equilibrium;
- the system can not be reduced to two dimension because of the cathode location;
- strong plasma/fields gradients present;
- the quasi-neutral hypothesis fails very close to the exit plane where magnetic field lines terminates and a strong electron-surface interaction happens;

the assumptions done in existing models are strong and not realistic. In Smith *et al.*^{1,2} the electric field is not calculated but a fixed map is used. Keidar *et al.*³ considers a one-dimensional model of the plume region and show how the magnetic field strength affects the plasma potential in the beam. However in this model the beam

divergence is prescribed. Boyd *et al.*⁴ and Taccogna *et al.*⁵ develop a fluid and a hybrid kinetic models, respectively: kinetic effects and azimuthal direction are not taken into account.

For these reasons, we have developed a 3D fully kinetic Particle-In-Cell/Monte Carlo Collision (PIC-MCC) in a Cartesian frame (x,y,z) using a geometrical scaling^{6,7} scheme.

II. □ 3D Particle-In-Cell with Monte Carlo collisions model

The Particle-in-Cell with Monte Carlo Collisions simulation (PIC-MCC) is a well-known and widely used numerical methodology representing plasma system from a kinetic level⁶. The electric field is self-consistently obtained from Poisson's equation (electrostatic version) interpolating the charge carried by macro-particles directly

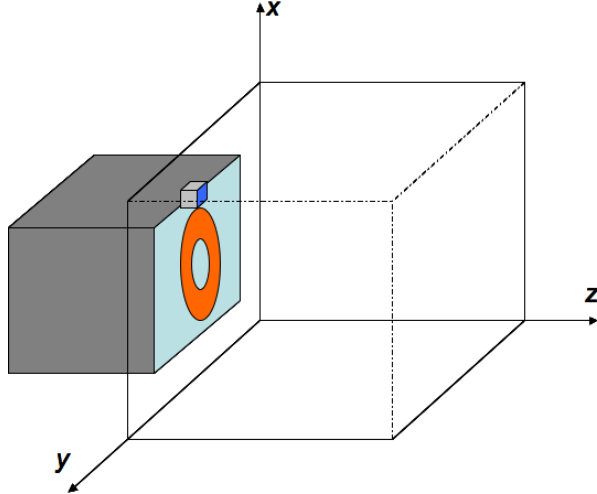


Fig. 1. Schematically description of the simulated configuration. The orange ring represents the exhaust region of the thruster; ions are emitted from this area. The light blue surface is boron-nitride surface. Electrons are emitted from the cathode represented by the blue surface. The coordinate system used is also represented.

on a grid. In the present model the magnetic field is treated as an input data and considered fixed but not homogeneous, while collisions (electron-neutral elastic, excitation and ionization and ion-neutral momentum and charge transfer) are included via Test Particle Monte Carlo null collision method⁸.

Figure 1 shows the schematic description of the configuration simulated. Ions (only Xe^+ included) are injected from the annular exhaust of the Hall discharge (see Fig. 1 in orange at $z=0$), with a velocity that corresponds to the electric potential drop between the anode and the exit plan. The radial distance from the channel axis and divergence angle are chosen according to experimental fitted data⁵. Electrons are injected from the external cathode, (blue in Fig. 1) with a velocity directed 45° toward the channel axis with half-Maxwellian distribution at a given temperature $T_{e,0}$ (see Table 1). Particles reaching the outflow boundaries of the simulation domain are deleted from the list while when they reach the dielectric surface of the exit plan (light blue region in Fig. 1) are neutralized: charges accumulated on the surface have been taken into account for the calculation of boundary condition on the electric potential (see eq. (2)). Secondary electron emission is calculated according to the energy of the incident electron⁹.

The neutral propellant unionized and exhausted from the channel is considered as a fixed background of Xe atoms with uniform density and temperature (see Table 1). All the input data used are the same of ref. [10].

Simulation parameters	Value
Domain dimension $L_x \times L_y \times L_z$ (cm)	16 x 16 x 5.5
Number of cells $N_x \times N_y \times N_z$	230 x 230 x 80
Time step Δt (s)	3.5×10^{-12}
Macroparticle weight w	250
Scaling factor f	10
Cathode current I_d (A)	4.5
Electron temperature at the cathode injection $T_{e,0}$ (eV)	2
Potential drop between the anode and the exhaust plan ΔV (V)	200
Atom density n_0 (m^{-3})	10^{18}

Table 1. Simulation parameters and input data used.

The electron current emitted from the cathode I_d is fixed (see Table 1), while the ion current emitted from the channel I_{beam} is calculated as a function of the electron current entering the channel I_{e-ch} according to a value of the current efficiency of $\eta_c=0.7$:

$$I_{beam} = 2.75 I_{e-ch}. \quad (1)$$

Fixed potential are kept on the channel exit $\phi_{exit}=100$ V (orange area in Fig. 1) and on the cathode surface $\phi_{cathode}=0$ V. On the $z=0$ plane, the boundary condition used on the thruster surface (light blue area) is:

$$\left. \frac{\partial \phi(x,y)}{\partial z} \right|_{z=0} = - \frac{\sigma_w(x,y)}{\epsilon_0} \quad (2)$$

where σ_w is the surface density charge accumulated, while around this surface a zero electric field condition ($E_z=0$) has been used.

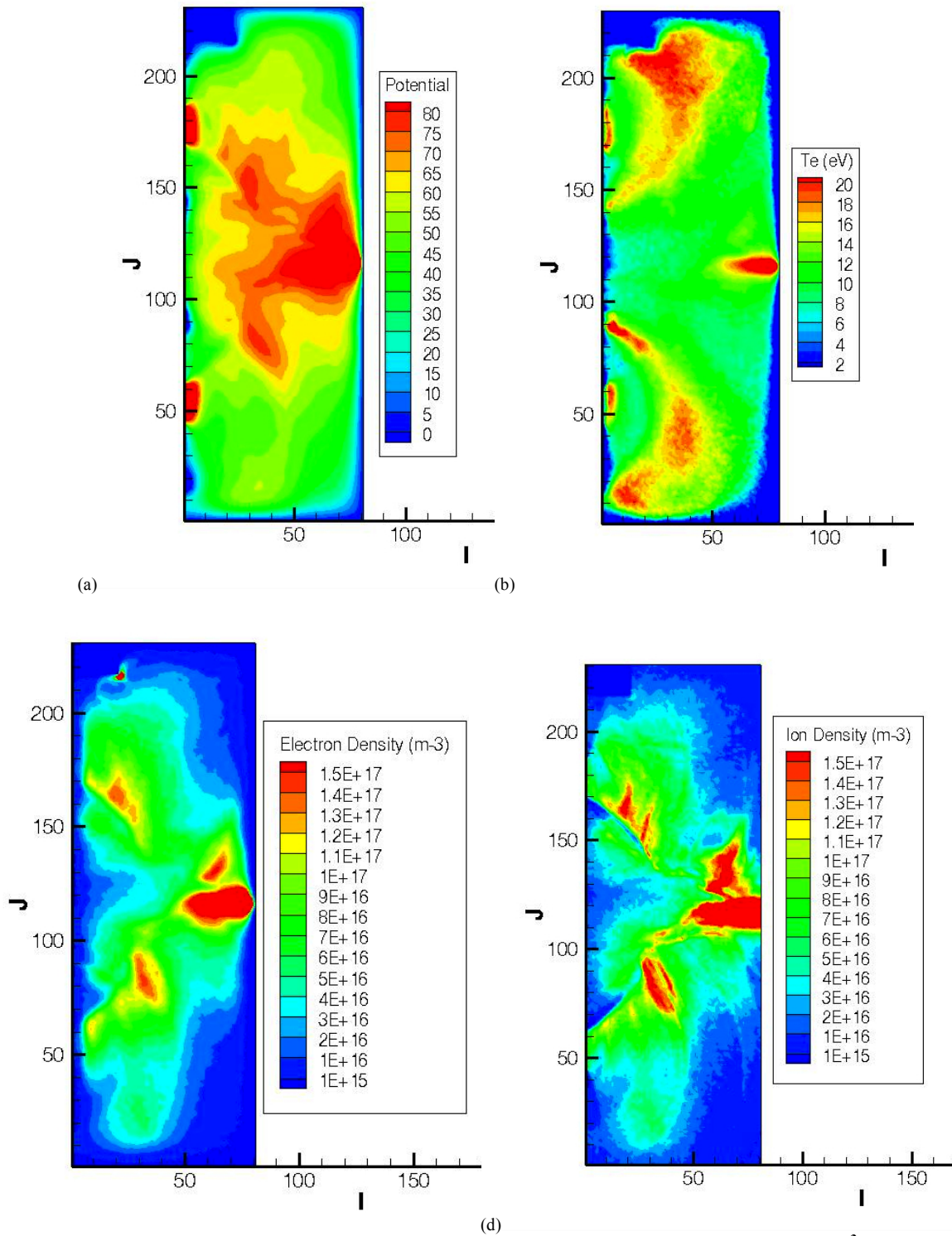
III. Results

After $1\mu s$, about 7% of the electron current emitted by the cathode reaches the exit plane $I_{e-ch}=0.3$ A. It gives origin (following eq. (1)) to an ion beam current emitted from the channel of $I_{beam}=0.83$ A. The remainder of electron current emitted from the cathode ($I_d-I_{e-ch}=4.2$ A) is used to neutralize the ion beam (0.83 A) and lost on the exit plane and cathode surfaces (3.37 A). Part of emitted ion beam is in turn lost as CX backflow on the exit plane surface ($I_{back}=0.15$ A). The secondary electron emission coefficient averaged on the exit plane surface is $\gamma=0.85$. Figures 2 show (a) electric potential, (b) electron temperature, and (c) electron and (d) ion density maps in (x, z) plane at $y=L_y/2$, that is the plane containing the cathode. Plasma potential drops from the channel exhaust (located between the x-mesh index $J=44$ and $J=62$ and between $J=168$ and $J=186$) and visible as red spots. It shows a potential minimum 5 mm from the exit plane (see Fig. 6 where the axial profiles are reported) representing the continuation of the acceleration region. Farther, potential increases of about 15 V and it remains almost flat for 15 mm before to start the monotonic decreasing in the far region. The potential peak corresponds to the confinement region for electrons. In fact, as already observed by fluid and hybrid magnetized models³⁻⁵ ambipolar plasma flowing across magnetic field (ion are not magnetized) region may require an electric field to appear which will trap the ions. Thus, one can expect the potential to increase across the magnetic field. This picture is also remarked by the electron temperature trails that faithfully follow the magnetic field lines. The electron temperature map shows how electrons corkscrew along the magnetic field lines inside the magnetic bottle. Electrons are reflected from the dense field region and only the hottest will be trapped there. The cold one are responsible for the secondary electron emission on the exit plane surface

Electron and ion density show the violation of neutrality close to the exit plane and to the cathode. The space charged region in the vicinity of the channel exhaust (first 3mm) can be partially due to the boundary condition on the orange area (see Fig. 1). In fact, we assume that only positive ions are injected from this boundary, while probably some electrons from the channel follow them. Moreover, the assumption on the injected ion current given by eq. (1) is questionable. Indeed, the ratio between the ion beam current and the electron current entering the channel is averaged over a given period in the experimental measurements. While, in our simulation we consider that this ratio is constant. Finally, the fixed potential value imposed on the exit plane of the channel represents a strong assumption.

A non-negligible asymmetry is present in this plane showing the important role of out-of-axis location of the cathode. It has to be pointed out that results can be influenced by the strong boundary conditions imposed on the outflow planes, where a fixed potential to the cathode value ($\phi_{outflow}=0$ V) is kept. This creates artificial sheath attached to outflow planes inducing a further electron electrostatic confinement. This solution has been adopted for numerical stability reason and it will be improved in future works.

As a confirmation of the asymmetry, in Figs. 3 the corresponding x-profiles at a distance of $z=5.5$ mm have been reported.



(c) (d)
Figure 2. (a) Electric potential ϕ (V), (b) electron temperature T_e (eV) and (c) electron n_e (m^{-3}) and (d) ion $n_{\text{Xe}+}$ (m^{-3}) (d) density maps in (x, z) plane at $y=L_y/2$, that is the plane containing the cathode.

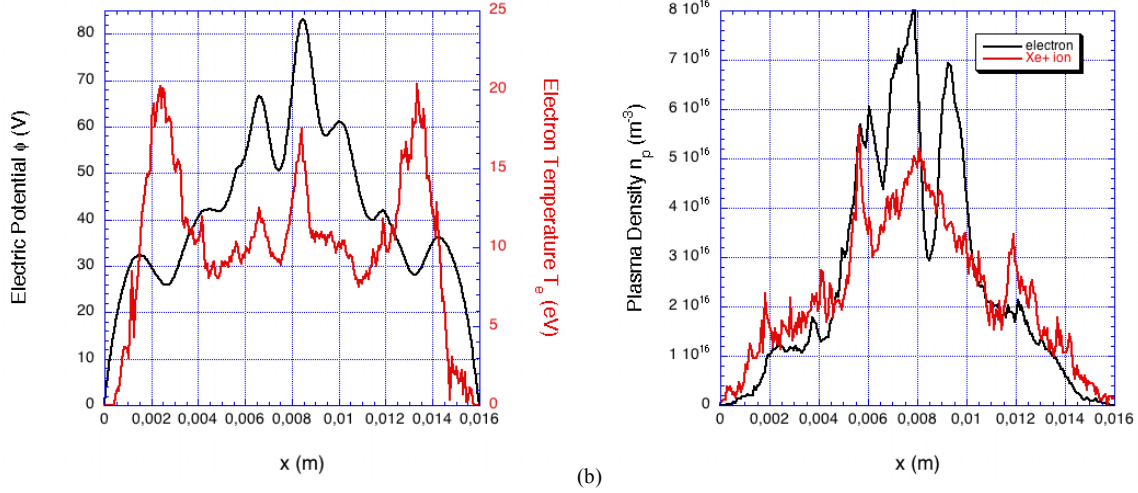


Figure 3. Profile along the x coordinate extracted from maps reported in Figs. 2 for a distance $z=5.5$ mm from the exit plane: a) Electric potential ϕ (V) and electron temperature T_e (eV); b) electron n_e (m^{-3}) and ion n_{Xe^+} (m^{-3}) density.

Figures 4 show the same quantities reported in Figs. 2 in the (x, y) frame for a distance from the exit plane of $z=5.5$ mm: (a) electric potential, (b) electron temperature, and (c) electron and (d) ion density. The most evident feature is the azimuthal modulation, which is present in different rings. The main ring, projection of the coaxial channel presents 14 peaks, corresponding to a wave number of $k_c=558 m^{-1}$. The fluctuation, clear sign of the electron drift instability, is perturbed and damped by the cathode which creates the asymmetry already observed in the (x, z) frame of Figs. 2. In order to see the modulation more clearly in Figs. 5 the azimuthal profiles extracted from Figs. 4 have been reported. They refers to a radial distance of $r=(r_{in}+r_{out})/2$ from the thruster axis, that is the middle of the channel width.

Finally, the present near-field region model together with the model of the channel¹⁰ suffers from the important limitation of decoupling at the exit plane, that is a strong particle and field boundaries are imposed at the exit plane. In order to verify the quality of both models we have reported in Fig. 6 the axial profiles of (a) electric potential and electron temperature and of (b) plasma density at $r=(r_{in}+r_{out})/2$ and $\theta=\pi/4$ starting downstream from the anode (see ref. [10]) to 7 cm from the anode (4.5 cm from the exit plane). As it can be seen the two models show a reasonable continuity crossing the exit plane in all the quantities reported. Nevertheless the next step will lead to a full 3D model of the channel and near-field region of the plume.

IV. □ Conclusion

Using a 3D PIC-MCC model we have studied the near-field plume region of a Hall thruster. We have shown the main plasma parameters in two 2D maps (x, y) and (x, z) . Our results show the effect of the magnetization of electrons on the plasma expansion and the importance of electron-wall interaction on the thruster exit plane. Furthermore, results evidence the presence of azimuthal fluctuations mainly in the region located between the exhaust plan and the cathode. The next step will concern further investigations of these fluctuations and their role on the electron transport across the magnetic field.

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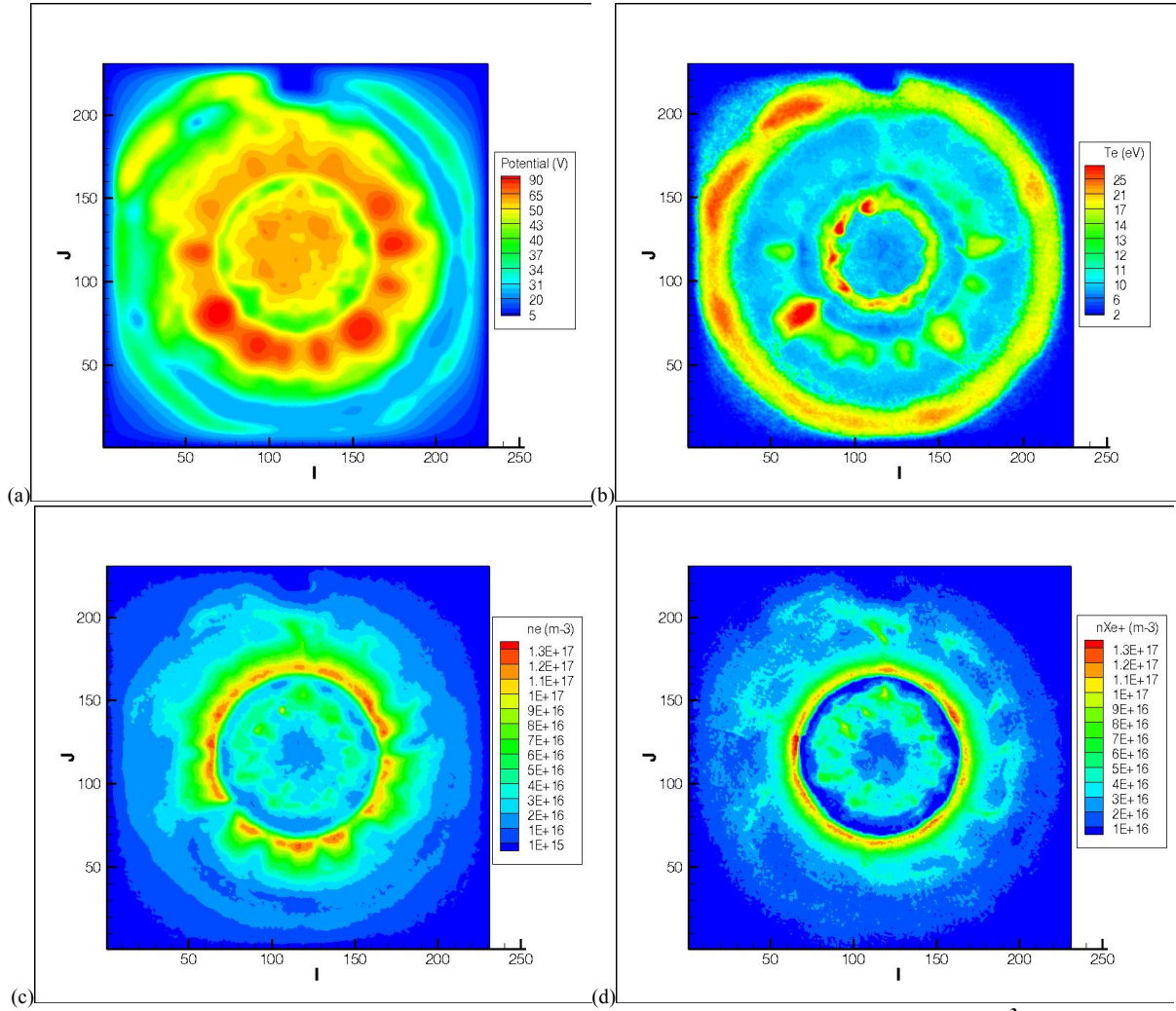


Figure 5. (a) Electric potential ϕ (V), (b) electron temperature T_e (eV) and (c) electron n_e (m^{-3}) and (d) ion n_{Xe^+} (m^{-3}) density maps in (x, y) at a distance $z=5.5$ mm from the exit plane.

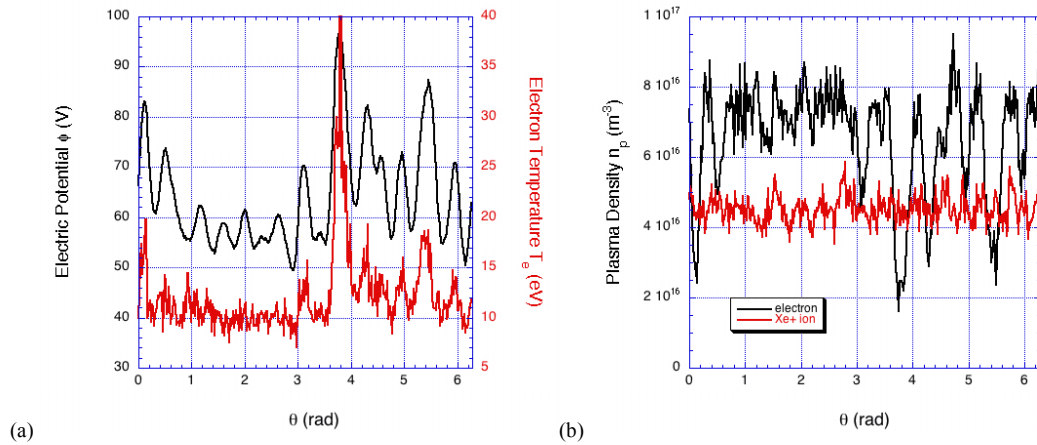


Figure 5. Profile along the θ coordinate extracted from maps reported in Figs. 4 for a distance $r=(r_{\text{in}}+r_{\text{out}})/2$ from thruster axis: a) Electric potential ϕ (V) and electron temperature T_e (eV); b) electron n_e (m^{-3}) and ion n_{Xe^+} (m^{-3}) density.

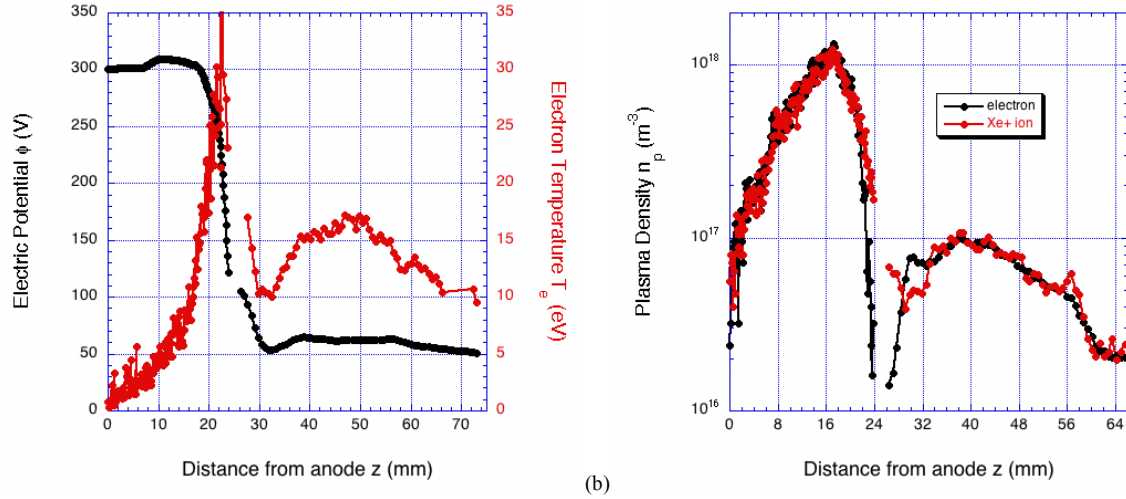


Figure 6. Axial profiles coming from the channel and near-field region models calculated for a distance $r=(r_{in}+r_{out})/2$ from thruster axis and for $\theta=\pi/4$: a) Electric potential ϕ (V) and electron temperature T_e (eV); b) electron n_e (m⁻³) and ion n_{Xe+} (m⁻³) density.

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