Propagating double layers in electronegative plasmas

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Double layers have been observed to propagate from the source region to the diffusion chamber of a helicon-type reactor filled up with a low-pressure mixture of Ar/SF6 [N. Plihon et al., *J. Appl. Phys.*, **98**(023306), 2005]. In the present paper the most significant and new experimental results are reported. A full self-consistent hybrid model where the electron energy distribution function, the electron temperature and the various source terms are calculated is developed to investigate these propagating double layers. The spontaneous formation of propagating double layers is only observed in the simulation for system where the localized inductive heating is combined with small diameter chambers. The conditions of formation and the properties of the propagating double layers observed in the simulation are in good agreement with that of the experiment.

I. EXPERIMENTAL RESULTS

Recent experiments by Plihon et al. [1, 2, 3] have demonstrated that double layers can form in the expanding region of an inductively coupled electronegative plasma in Ar/SF_6 and Ar/O_2 mixtures. The system is composed of a source chamber, a 30-cm-long 15-cm-diameter pyrex tube and surrounded by a double-saddle helicon antenna; the source is attached to a 26-cm-long 32-cm-diameter aluminum diffusion chamber. A schematic of the setup is shown in Figure 1. The helicon antenna is powered by an rf power supply operating at 13.56 MHz and capable of delivering 2 kW of forward power in capacitive or inductive modes.

Plihon et al. [1, 3] showed that a static double layer is formed in the vicinity of the expanding region of the system ($z \sim 30$ cm) for moderate electronegativities, i.e. for a rather narrow range of SF_6 concentrations (between 8% and 13%) and for O_2 concentrations above 72% and for a neutral gas pressure of 1 mTorr. For low electronegativities, no double layer is observed.

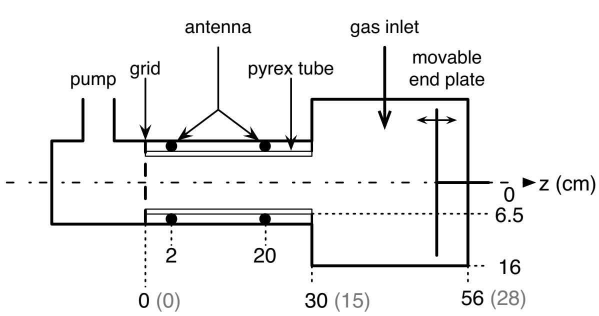

FIG. 1: Schematic of the experimental setup. The dimensions under bracket in gray are that of the corresponding simulation.

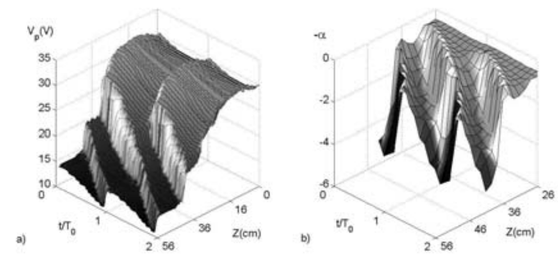

FIG. 2: Spatiotemporal evolution of (a) the plasma potential and (b) the electronegativity in the experimental setup. Time is normalized to the instability period (∼850 ms) for a 25% SF_6 concentration plasma at 600 W and 1 mTorr.

At high electronegativities, i.e. in Ar/SF_6 mixtures with SF_6 concentrations above 13%, propagating double layers are observed. A full parametric investigation of the periodic formation of propagating double layers is presented in ref. [2]. As shown in the plasma potential measurements in Figure 2(a), the propagating double layers were born in the vicinity of the interface between the two chambers ($z \sim 26$ cm) and propagate downwards, in the diffusion chamber. Note that this regime is periodic-like, with a 5% variation on the period width. The speed and frequency of these propagating DLs are such that irrespective of the parameters, the number of DLs simultaneously present in the system is constant. The speed of propagation is of the order of 150 m/s (which is much slower than the ion sound speed under present condi-

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tions) and the frequency in the kHz range.

Figure 2(b) shows the time- and space-resolved electronegativity in the diffusion chamber of the experimental setup for the same parameters as in Figure 2(a). As for the static case [1, 3], the propagating double layer separates a low electronegativity plasma upstream from a high electronegativity plasma downstream. The correlation between the spatio temporal plasma potential evolution and the electronegativity is shown in Figure 2.

II. MODEL

The simulation of electronegative double layers and more particularly the simulation of propagating double layers is rather challenging; the challenge arises from various things such as the rather high plasma densities, the disparity between the negative ion and electron densities, the long time-scale oscillations, the necessity of self-consistency etc. Under such conditions, the use of a full particle-in-cell (PIC) simulation would be too computationally expensive, while the use of a "classical" hybrid PIC-Boltzmann model would not be appropriate as it is not completely self-consistent; hence, we have developed the "improved" hybrid PIC-Boltzmann simulation *h2x* where the electron temperature and the source term profile are calculated by coupling a Monte Carlo model for particle electrons to the classical hybrid model.

A very simplified mixture of argon and SF_6 is to be simulated. Only one type of negative ion with the same mass as the argon positive ion and with an opposite charge $-e$ is considered. Due to the presence of the third species, namely the negative ions, a number of events, such as attachment and recombination (SF_6 is recombination-dominated, hence detachment is not considered), have to be treated in addition to ionization. In addition to undergoing collisions with argon neutral atoms, electrons can also undergo collisions with neutral SF_6. Positive and negative ions recombine with a rate $K_{\rm rec} = 10^{-13}$ $\rm m^3s^{-1}$ unless stated otherwise.

A. Characterization of the propagating double layers

Direction of propagation: Figure 3 shows various characteristics of typical propagating double layers for an SF_6 concentration of 40%. Figure 3(a) is a 3D mapping of the plasma potential as a function of time and space. Although the present double layers propagate in the opposite direction, they appear to be a phenomenon very similar to that observed by Plihon et al. [2], as discussed later.

Velocity of propagation: Figure 3(b) is a contour-plot over 5 ms of the plasma potential profile. As can be observed, the double layers always form at the same critical position and propagate towards the source at ~ 100 m/s.

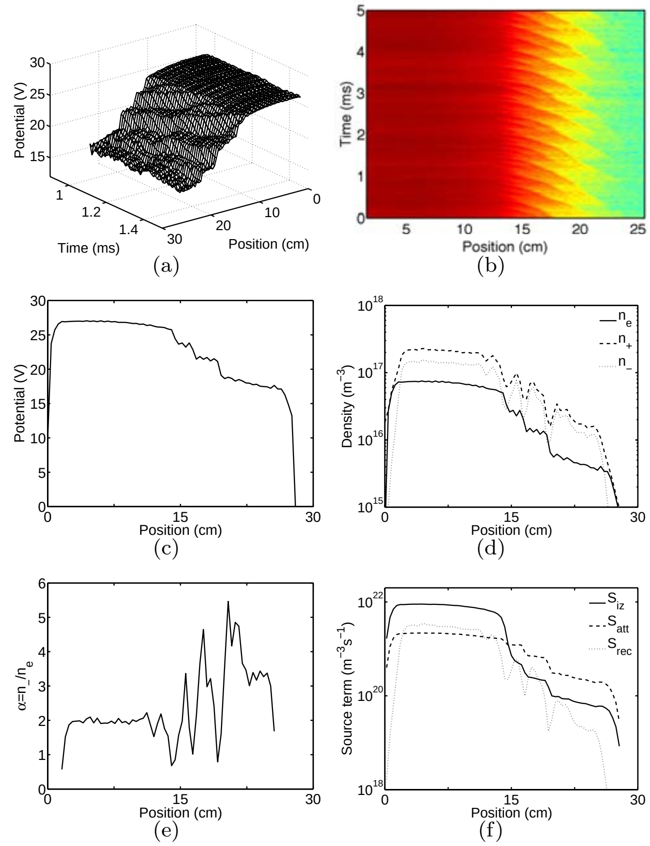

FIG. 3: (Color online) Propagating double layers in an Ar/SF_6 mixture, with an SF_6 relative concentration of 40% at 1 mTorr. (a) 3D mapping of the plasma potential profile as a function of space and time; (b) contour-plot of the plasma potential profile as a function of space and time, increased brightness indicates decreased potential; (c) snapshot of the plasma potential profile showing successive double layers, propagating from the diffusion chamber (right) to the source (left); (d) snapshots of the electron (solid line), positive (dashed line) and negative (dotted-dashed line) ion density profiles; (e) snapshot of the electronegativity $\alpha = n_-/n_e$ profile; (f) snapshots of ionization (solid line), attachment (dashed line) and recombination (dotted-dashed line) source term profiles.

Note that the simulation was run up to 100 ms without any major variation.

Electronegativity: Figures 3(c) and 3(d) are snapshots of the plasma potential and the electron, positive and negative ion densities. At the position of each double layer, a region of positive and negative ion rarefaction can be observed. Figure 3(e) shows a snapshot of the electronegativity $\alpha = n_-/n_e$ at the same instant and the electronegativity is minimal at the positions of the double layers, but maximal immediately downstream. The regions of high electronegativity are trapped between two successive double layers, and are pushed towards the source by the moving double layers, which is very much aligned with the experiment, as shown in Figure **??**.

TABLE I: Experimental and simulated propagating double layers.

Parameters	Experiment	Simulation
$\%_{SF_6}$	13-25%	15%
K_{rec}	not a parameter	critical
P	$\sim$ 5 mTorr	$\sim$ 5 mTorr
Expansion	not critical	not critical
Small diameter	?	critical
Chamber length	critical	critical
Properties	**Experiment**	**Simulation**
Frequency	$\sim$ kHz	$\sim$ 2 kHz
Velocity	150 m/s	100 m/s
Direction	$\rightarrow$	$\leftarrow$
α	$\sim$ 4	4-6
Potential drop	7 V	5 V
T_{up}/T_{down}	5/3.5 eV	5/3.5 eV
Bohm criterion	?	satisfied

Source term profiles: Figure 3(f) shows the ionization (solid line), attachment (dashed line) and recombination (dotted-dashed) source term profiles. The source is ionization-dominated, while the diffusion chamber is attachment-dominated. The recombination takes place mostly in the source, but also in the high-electronegativity regions, where the ion densities are maximum.

III. CONCLUSION

The propagating double layers were experimentally characterized and the window of parameters, such as the neutral gas pressure, the relative concentration of SF_6, the input power etc. for which they form was fully determined in ref. [2]. The propagating double layers spontaneously forming in the self-consistent simulation were shown to be a very similar phenomenon to that observed experimentally. The main features of the propagating double layers observed experimentally and in the simulation are summarized in Table I. Despite the fact that these propagating double layers do not propagate in the same direction, they share many properties, such as their velocity of propagation, frequency, electronegativity, temperature drop etc. Also, they appear under very similar conditions, such as neutral gas pressure, relative SF_6 concentration etc. More experimental and simulation results as well as a formation mechanism are given in ref. [5].

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