Three-Dimensional Fully Kinetic Simulations of the Discharge Pulse in an AC-PDP cell

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ABSTRACT

The dynamics of the sustain discharge pulse between coplanar electrodes in an AC-PDP cell is investigated for the first time using fully kinetic (Monte-Carlo/PIC) 3-D simulations. These simulations are capable to reproduce all essential features of the discharge (such as a fine spatial structure of striations above the dielectric surface near the anode and an arch-shaped front of the discharge spreading along the cathode). Special numerical experiments are performed for better understanding of the physical phenomena in the anode area.

INTRODUCTION

Numerical simulations based on the hydrodynamic approximation proved to be a very useful tool for studying discharge in a Plasma Display Panel (PDP) cell, and currently are widely used [1-4]. They have provided very valuable information about detailed distribution of electric field in a cell, time-spatial evolution of the discharge, they allowed investigation of the dependence of different parameters of the discharge on the dielectric properties of the walls, electrode structure, gas mixture, etc., and they also gave clues for the development of analytical theories [5,6]. The advantage of numerical approach is that it allows one to "look" inside the discharge, find relations between discharge characteristics, which are hard or impossible to extract from experimental data. Moreover, one can even deliberately change the value of any physical parameter in the simulation in order to uncover some "hidden" relationships. All of this helped to form basic concepts and understand many features of the PDP discharge, and significantly improve its parameters.

One should remember, though, that hydrodynamic approximation requires too many assumptions about electron distribution function for the conditions of the PDP discharge. Indeed, while the electric field in the PDP varies very sharply in space and very fast in time, fluid models use transport coefficients and rates of excitation and ionization processes, obtained (in independent kinetic 1D - considerations!) for a uniform and stationary electric field. So, at most, one should consider fluid simulations, although extremely useful, but as giving a qualitative picture of the discharge, rather than quantitative. Note, that different modifications of "improved" fluid codes [3,4] create illusion rather than really improve their capability (and reliability). A number of attempts recently [7,8] to use fluid codes beyond their applicability indicates that the development of kinetic codes now deserves high priority.

The strength of the kinetic approach is that it uses only fundamental data (cross-sections, basic probabilities) characterizing different interactions between all kind of particles, and between particles and walls. The distribution of relevant particles is calculated self-consistently, as discharge develops, at every point in time and space, without any a-priori assumptions. The obvious difficulty of using kinetic codes is a significantly larger computer time compared to the fluid ones. That is why kinetic simulations of a PDP discharge were rare, and limited to a two- dimensional ones [8]. However, 2D kinetic codes ignore the geometrical structure of a PDP cell (such as barrier ribs, width of the address electrode, etc.) and cannot reproduce correctly spatial features of the discharge in the 3rd dimension (particularly the shape of discharge striations and the ionizing cathode wave observed in experiments). This problem is finally solved in our 3-D Monte-Carlo/PIC kinetic simulations described in the present paper.

We have chosen the Monte-Carlo/Particle-In-Cell (MC/PIC) method rather than the one based on the Boltzmann equation for the electron distribution function, since for the PDP conditions MC/PIC is much faster, and is the only method that correctly approaches statistical fluctuations – important, for example, for analysis of a jitter [9,10], or weak discharges with small number of charged particles.

The speed advantage of the MC/PIC method comes from the simple fact that Boltzmann equation operates with a 6-dimensional electron distribution function, and its discretization with any reasonable accuracy would require calculation of at least 10^9-10^{10} values at every moment, even if there are only a few electrons in the PDP cell. On the other hand, even during a strong sustain discharge pulse, the number of charged particles, transferred in a typical PDP cell is only of the order of 10^8. Without sacrificing the accuracy, one can use relatively small positive/negative macro-particles (representing up to a few tens of real ions/electrons), and limit the number of values recalculated at every moment to about 10^6. So, the speed advantage can be clearly of the order of 10^3-10^5.

DISCHARGE IN AC-PDP CELL

We consider one discharge pulse in a standard coplanar PDP cell, filled with neon-xenon (93% - 7%) mixture at a pressure of 500 Torr. The cell length, width, and height are 650μm, 220μm (including barrier ribs), and 160μm (including dielectric layers above sustain

and address electrodes), respectively. The sustain gap is 90μm, the sustain electrode width is 155μm, and the voltage applied to the sustain electrodes is ±220V.

When the distance between sustain electrodes is relatively small, the barrier discharge in AC-PDP cell develops through following stages illustrated in Fig.1.

Phase-1. At first, the positive charge is accumulated in the gap volume above the inner edge of the anode

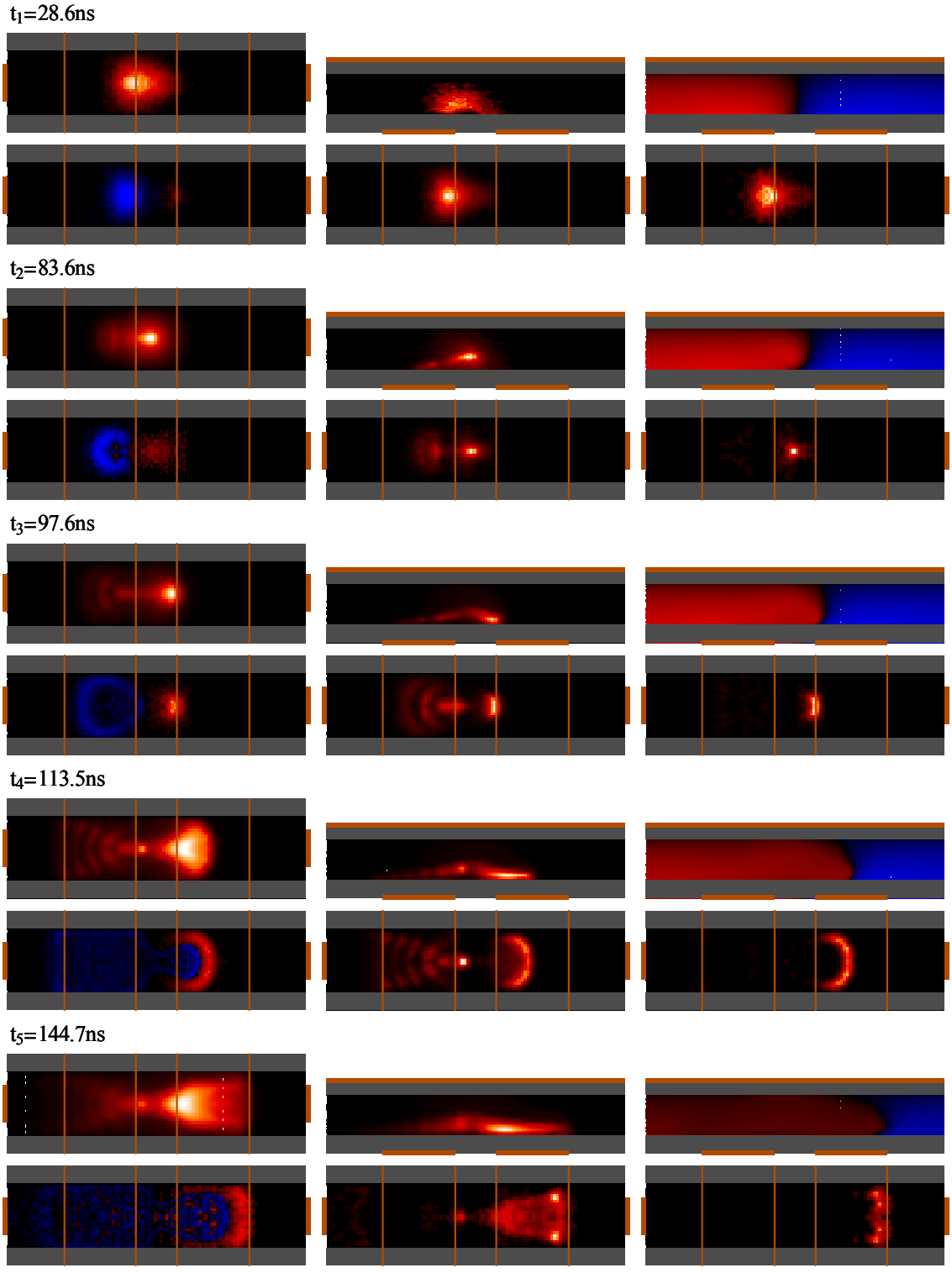

Fig.1. Spatial distribution of discharge characteristics at different moments of time. Each time-frame contains six windows showing (from left to right, from top to bottom): 1. ion density (top view), 2. ion density (side view), 3. electric potential (side view), 4. charge deposition rate on the dielectric surface above sustain electrodes, 5. Xe-excitation rate (top view), 6. Ne-excitation rate (top view). Red color corresponds to positive values, blue – to negative ones.

electrode and at the same time the negative charge is deposited on the dielectric surface. The distribution of the electric potential on this stage is almost the same as in empty gap (see Fig.1, the moment $t=t_1$).

Phase-2. Then, when the density of the positive charge reaches a certain critical level, ions starts to screen the electric field and detain the electrons in the gap volume. As a result, a plasma region forms above the inner edge of the anode and then gradually protrudes toward the cathode (see Fig.1, the moment $t=t_2$). There is a substantial positive charge on the tip of this plasma region (much like the charge on the tip of the conductor placed in an external electric field). At this stage, ongoing deposition of the negative charge on the anode dielectric surface is accompanied by formation of the first striations and deposition of the positive charge on the cathode dielectric surface is still inconsiderable.

Phase-3. When the plasma region approaches the dielectric surface above the inner edge of the cathode (see Fig.1, the moment $t=t_3$), the cathode fall (CF) is formed, and the current through the low resistant plasma channel sharply increases. Since the potential drop between the plasma region and the uncharged areas of the dielectric surface is substantially higher than the breakdown voltage, the CF expands along the cathode in a form of the ionizing wave (Fig.1, the moment $t=t_4$), and the positive charge is deposited on newer and newer areas of the dielectric surface (actually, the wave front overcharges this surface area so that the following deposition of the negative charge somewhat decreases the final value of the surface charge density). The speed of the ionizing wave is of the order of the characteristic drift velocity of the ions in CF region.

Phase-4. When the positive charge covers most of the dielectric surface above the cathode (see Fig.1, the moment $t=t_5$), the discharge extinguishes. In the afterglow, the number of ions and electrons in the PDP cell gradually decreases through the dissociative recombination of electrons on $Xe_2^{+\cdot}$ molecules. Charged particles are also pulled out toward the dielectric surfaces by the residual (and ambipolar) electric fields.

Note that the atoms of neon are excited mostly in the area of the cathode (where electric field is relatively strong), whereas the excitation of xenon atoms takes place in both anode and cathode areas (see Fig 1, Ne- and Xe-excitation rates). This difference is also observed in experimental data [11,12].

The deposition of the negative charge on the dielectric surface in the anode area initially also progresses in wave-like manner with quite pronounced wave front but with time, it becomes much more uniform (compare time moments t_4 and t_5 with time moments t_2 and t_4). To get a better understanding of the physical phenomena, which take place in the area of the anode, we perform several numerical experiments.

NUMERICAL EXPERIMENTS

In the first experiment, we replace the dielectric right above the anode by a metal material. In this case, the same ionizing wave propagates in the cathode area, but deposition of the negative charge occurs only within small area above the inner edge of the anode electrode (see Fig. 2). Now, there is no component of the electric field parallel to the metal material surface and electrons cannot be pulled to the new surface areas. Without the electrons, there are no ionizations (and ions) and no excitations, and therefore, there are no striations above the surface.

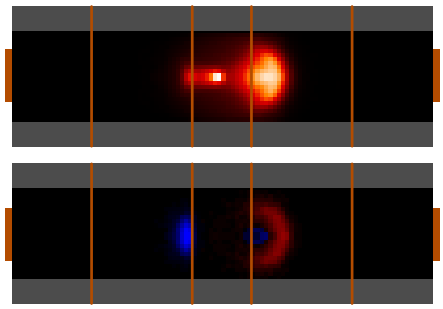

Fig. 2. Distribution of the ion density (top view) and charge deposition rate on the surface in the discharge when dielectric above the anode is replaced by a metal.

In the second numerical experiment we artificially make ions immobile when they are created in some part of the anode region. As one can see from Fig. 3, the formation of striations is not a result of any ion movements (contrary to [13]): plasma strips near dielectric surface are even more distinct when ion velocity is set to zero!

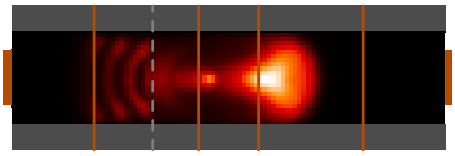

Fig. 3. Distribution of the ion density (top view) when ion velocity is artificially set to zero in the left part (from the dash line) of the PDP cell.

In the third experiment, we make a number of radical geometrical simplifications. In order to separate the physical phenomena near the anode from those near the cathode, we consider the formation of striations in the system composed only of the unbounded upper address electrode and the unbounded lower anode electrode covered by dielectric layer (with thickness d and dielectric constant ε). The anode is under positive potential V_0 so that there is only a vertical uniform electric field in the empty gap, $E_0 = V_0 / L_0$ (where L_0 is the vertical distance between address and anode electrodes). We also exclude the ion movements setting the velocity of all ions to zero. Imitating the electron source from the plasma channel in standard geometry, we inject electrons in small area above the anode dielectric. As one can see from Fig.4, the plasma strips and the front of the charging wave have the ring-like shape in the geometry where no preferred directions in

the horizontal plane.

At the beginning of the injection, the electrons drift in the vertical electric field and the negative charge is deposited on the dielectric surface right under the spot of the electron injection. With time, this negative charge reverses the sign of the vertical component of the electric field (at first, under the injection spot) and creates the horizontal component parallel to the dielectric surface, which pulls electrons to new area of bigger radius. Note, that ions created by the ionization processes in the gap above the dielectric surface play an important role in delivering electrons to the uncharged area of the surface.

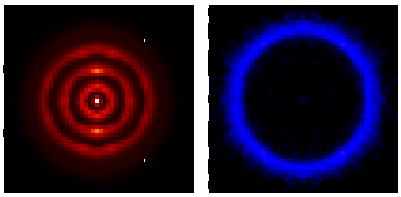

Fig.4. Distribution of the ion density (top view) and charge deposition rate on the dielectric surface above the anode in the system composed of two electrodes.

Our simulations show that the result displayed in Fig. 4 almost does not depend on the shape of the injection current $I(t)$ (if this current is not too strong). It means that radius of the front of charging wave (and number of striations) depends on the amount of the charge Q already deposited on the surface rather than on time t. In a sense, the time is excluded from our problem!

When the distance between upper and lower electrodes is great and thickness of the dielectric layer is small, in our super simplified geometry there are only two external parameters which influence the charge deposition process: the initial electric field E_0 and the effective thickness d/ε. Note, that the smaller the latter parameter, the slower the deposition process (i.e., to get the same striation picture one must inject approximately two times more electrons when one takes two times smaller parameter d/ε).

Although we tried several different energy distributions of the injected electrons (and had got the similar results), now it is not clear how this distribution influences on the formation of the striations. For example, is there any distribution of the injected electrons at which there are no striations at all? There is also no full understanding of the role of the electrons trapped by the positive charge of the ion rings.

CONCLUSIONS

As barrier discharge in AC-PDP cell develops between coplanar electrodes, it deposits the positive charge on the dielectric surface above the cathode and the negative charge on the surface above the anode. These processes progress in wave-like manner with quite pronounced wave fronts. Let us compare the properties of the cathode and anode waves:

-- Propagation of the cathode wave is, in essence, an extension of the cathode fall wherein ionization processes play a very important role. In the anode wave, the main process is deposition of the negative charge on the dielectric surface.

-- The velocity of the **cathode ionizing wave** is of the order of ion velocity in the cathode fall. The velocity of the **anode charging wave** does not depend on the velocity of the slow ions. It is determined by the rate of the delivering of the negative charge (through the plasma channel) in the area of the anode.

-- When the effective dielectric thickness d/ε decreases, the cathode ionizing wave moves faster, and the anode charging wave moves slower (so that it does not propagates at all above the bare electrode).

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