Periodical Plasma Structures Controlled by External Magnetic Field

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Abstract. Periodical structures in propulsion type magnetized plasma are detected both in kinetic simulations and laboratory experiment. Stationary two-dimensional double layers with a several potential steps appear both parallel and across (more pronounced) the magnetic field. The double layers are weak with a potential jump much smaller than the electron temperature. The electrical current is found to be stratified and aligned with magnetic field vector. The channels of current flow coincide with the ridges of the plasma density.

INTRODUCTION

A series of stationary, magnetized, two-dimensional weak double layers with a several potential steps has been observed in a laboratory experiment for the first time by Intrator, Menard, Hershkowitz [1]. The double layer potential drops were found to be followed across any given potential profile. Borovsky, Joyce [2] in PIC simulations that weak magnetization results in the double layer electric-field alignment of particles accelerated by these potential structures and that strong magnetization results in their magnetic-field alignment. A morphological invariance in two-dimensional double layers with respect to the degree of magnetization observed in Ref. [2] implied that the potential structures scale with Debye lengths rather than with gyroradii.

A weak double layer is a nonlinear electrostatic structure in plasmas, consisting of two sheets of positive and negative charges, with a characteristic electric potential jump, providing local electric field. Recently, most of the studies have addressed strong or ion acoustic double layer in magnetized plasmas (see for example [3-7] while the mechanism of weak two dimensional double layer formation is still not fully understood.

In this paper, in kinetic simulations we study the formation of steady-state multi-steps double layers structure in magnetized low temperature plasma. Two dimensional double layers (DLs) appear across and along the oblique magnetic field and rearrange the plasma density and electrical current in the area of quasineutral plasma. The evidence of existence of periodical structure in low temperature plasma in oblique magnetic field is also found in our experiment.

SIMULATION AND EXPERIMENTAL DETAILS

We consider the magnetized plasma at low gas pressure, P=10^{-4} Torr, which is embedded in a cylindrical chamber. The oblique external magnetic field is constant over the volume. A magnitude of magnetic field B is ranged from 50 to 200 G. The angle between the magnetic field vector and a normal to the side wall, α_B, (see Fig.1) changes from 0 to 65°. The radius of plasma chamber is 4 cm and height of 10 cm. The cathode with radius r=3 cm is placed at 0.2 cm < z < 0.3 cm. In simulations, the cathode is grounded and the wall potential is 90 V.

To describe the evolution of the magnetized plasma in external applied voltage we solve Boltzmann equations (two dimensional in space and three dimensional in velocity space) for distribution functions for electrons $f_e(\vec{r},\vec{v})$ and ions $f_i(\vec{r},\vec{v})$

$$\frac{\partial f_e}{\partial t} + \vec{v}_e \frac{\partial f_e}{\partial \vec{r}} - \frac{e(\vec{E} + \vec{v}_e \vec{B})}{m} \frac{\partial f_e}{\partial \vec{v}_e} = J_e, \quad n_e = \int f_e d\vec{v}_e, \tag{1}$$

$$\frac{\partial f_i}{\partial t} + \vec{v}_i \frac{\partial f_i}{\partial \vec{r}} + \frac{e(\vec{E} + \vec{v}_i \vec{B})}{M} \frac{\partial f_i}{\partial \vec{v}_i} = J_i, \quad n_i = \int f_i d\vec{v}_i, \tag{2}$$

where v_e, v_i, n_e, n_i, m, M are the electron and ion velocities, densities and masses, respectively. J_e, J_i are the collisional integrals for electrons and ions. The external magnetic field B is constant. No magnetic field due to currents in the plasma is taken into account. The Poisson equation describes the electrical potential and electrical field distributions

$$\triangle\phi = 4\pi e\,(n_e - n_i)\,, \quad \vec{E} = -\frac{\partial \phi}{\partial \vec{r}}\,. \tag{3}$$

The system of equations (1)-(3) is solved with the 2D3V Particle in cell Monte Carlo collision method (PIC MCC) with PlasmaNOv code (see for example [8]). The scattering of electrons and ions with background Ar gas is taken into account.

The external ionization provides the plasma density n_e of about 10^8 cm^{-3} in quasineutral part. An electron-ion pair was generated with Maxwellian distributions with the electron temperature T_e, and the ion temperature T_i = 0.05 eV. The electron temperature T_e varies from 2.5 eV to 10 eV for different cases. It should be noted that the mean electron energy in plasma ϵ_e is smaller than $3/2T_e$. The potential drop over the sheath near the wall $\delta\phi_w$ is 3 V ÷ 10 V, for our plasma parameters and the electrons with energy larger than $\delta\phi_w$ escape from the plasma. Therefore in the steady-state, the ϵ_e ranges from 1.6 eV to 3.4 eV.

For these plasma parameters the electron Larmor radius r_L is comparable to the Debye length λ_D, $r_L \leq \lambda_D$=0.1 cm ÷ 0.2 cm. $\omega_p \leq \Omega_e = 5 \times 10^8 s^{-1} \div 5 \times 10^9 s^{-1}$, where ω_p is the plasma frequency and Ω_e is the electron gyrofrequency. In simulations the electron time step is (2-5)×10^{-12} s. The grid is uniform in z-direction and nonuniform over radius condensing with increasing r. The total number of pseudo particles being chosen so that there is an average of approximately 100 positive and negative particles per Debye sphere.

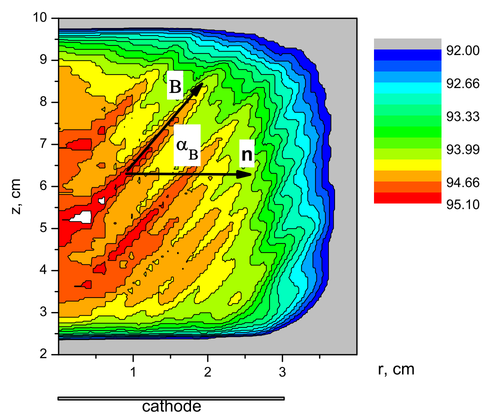

FIGURE 1. Potential distribution for B=100 G, $\alpha_B = 65°$ and T_e=5 eV. B is the magnetic field vector, n is directed over radius of the chamber, α_B is the angle between B-vector and n. Cathode is between z=0.2 cm and 0.3 cm.

In the experiment, testing was carried out using the vacuum chamber at pressures of 10^{-4} Torr. A diagram of the experimental setup is shown in Fig.2. A plate placed in-between two electro-magnetic solenoids can have the current development measured using positively biased probes at various distances. A titanium cathode of thruster was used as the Maxwellian plasma source for this experiment, having an electron temperature of T_e = 1-2 eV. A Tektronix TDS 2004B oscilloscope was used to collect the electron data from the four probes. Two electrodes were placed, to create an electric field orthogonal to the magnetic field lines. The magnetic strength used in the experiment was 100 G.

Four cylindrical copper probes were placed horizontally at the center of the at plate at heights of 4 mm, 6 mm, 8 mm and 10 mm from the surface. Measurements were taken in increments of 5 degrees from 0 to 90 degrees of plate's angle (with rotation) relative to magnetic field vector. More experimental details can be found in Ref.[9]. In our experimental study, we observed the current oscillations depending on angle α_B. In Fig.3, the measured current as a function of α_B is shown for different distance from the wall. The nature of this j_e oscillations was unknown.

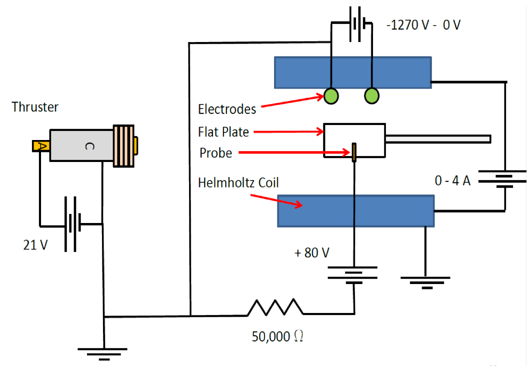

FIGURE 2. Setup for oblique magnetic field experiments.

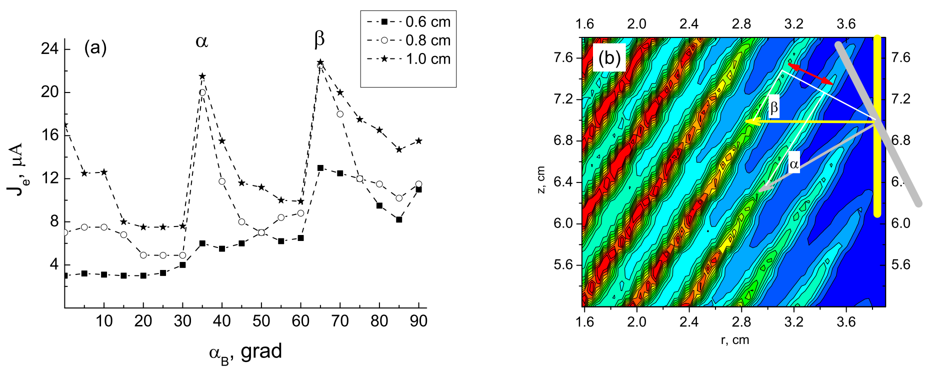

FIGURE 3. (a) Measured electron current as function of α_B for 0.6 cm, 0.8 cm and 1 cm from the wall and (b) electron density distribution for B=100 G and T_e=2 eV. Angles α =35° and β=65° show the angles between magnetic field vector and normal to the wall. Yellow and white arrows show the direction of measurements from the wall (thick yellow and white lines).

From the comparison of experimental and theoretical data in Fig.3(a) and (b), it is clear that when plate is rotating, a tip of the probe cross the maxima and minima of the electron density. Note that the peak of electron density coincide with current channels. The inter-peak distance calculated from experimental data shown in Fig.3(a) is 0.35 cm. As seen in Fig.3(b), the computed inter-peak distance is 0.37 cm, that is in good agreement with experimental data.

The ridges (maxima) of electron and ion density distributions and current flow exactly follow the B-vector direction in the area of quasineutral plasma. Only within the sheaths where the strength of electrical field is much larger, the ion current is directed normally to the surface. The radial component of electron j_{er} and ion j_{ir} currents over z-axis taken at r=3 cm is shown in Fig.4 for B=100 G, α_B=65° and T_e=5 eV. The ion current is about 20 time less than the electron one, but both j_{er} and j_{ir} clearly indicates their periodical structure. Each electron current peak is splitted with a scale of $2r_L$, where r_L is Larmor radius.

The periodical structure in potential distribution (see Fig.1) appears in quasineutral plasma, where the electrical field strength is small. The electron and ion density distributions also exhibit peaked profiles, but the ridges of n_e and n_i density peaks are shifted relative each other. In Fig.5, the electron density, charge distributions and potential profiles are shown for B=200 G, α_B= 65° and T_e=10 eV. The occurrence of sheets of positive and negative charges results in DL formation. The potential profiles are shown in Fig.5 (c) for three cross sections, taken in normal direction to the charge stripes, starting from z=6 cm, 6.5 cm and 7 cm. The DLs across B-vector have potential drops of about 0.3 V.

In conclusion, in PIC simulations and in the experiment we found the stratification of plasma density in oblique external magnetic fields. The broadening of the peaks of plasma density is set by the electron Larmor radius. The stratification appears only in quasineutral plasma where the electrical field is small. The reason of stratification is distortion of local quasinetrality due to the presence of magnetic field. When electron-ion pair appears after an ionization event an electron starts Larmor gyramotion. The electron is shifted from the ion in normal to B direction and a local charge

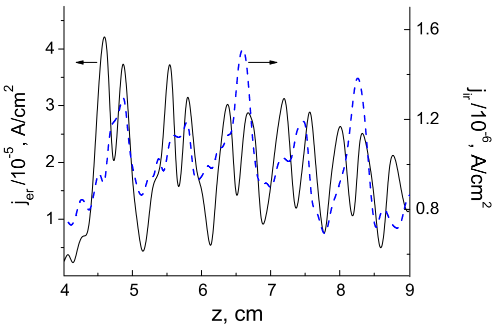

FIGURE 4. Radial components of electron and ion current distribution over z-axis at r=3 cm for B=100 G, α_B= 65° and T_e=5 eV.

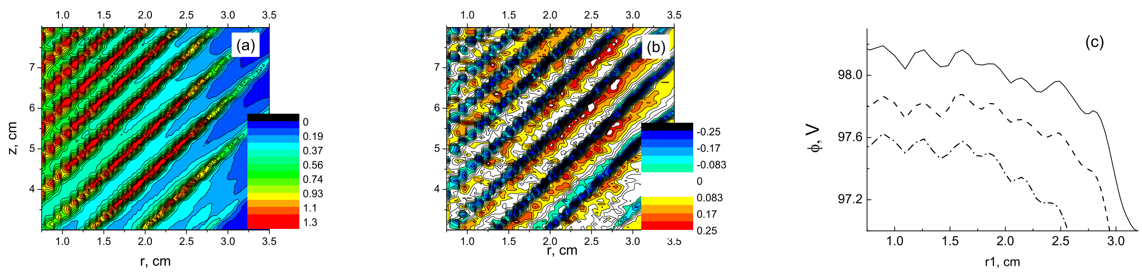

FIGURE 5. Electron $n_e/10^8$, cm^{-3} (a) and charge $(n_e - n_i)/10^8$, cm^{-3} (b) density distributions, potential profile along r_1 orthogonal to B-vector (c), starting from z=6 cm (solid line), 6.5 cm (dashed line), 7 cm (dashed-dotted line), for B=200 G, α_B=65° and T_e=10 eV.

appears. The number of n_e-peaks and distance between them depends on ratio of T_e/B, Debye length and geometry of the chamber. The potential drop over the sheath near the wall (difference between plasma potential and wall potential) $\delta\phi_w \approx T_e$. The existence of plasma stratification found in PIC simulations well agrees with experimental observation of electron current behavior measured near the wall in oblique magnetic field.

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