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Triggering of Buneman instability and existence of multiple double layers in laboratory plasma

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A B S T R A C T

We report experimentally observed triggering criteria for Buneman instability and boundary conditions for existence of multiple double layers (MADL) in glow discharge plasma. The MADLs are generated by accelerating plasma electrons towards a positively biased electrode submerged in it. The boundary conditions for the formation and existence of MADL are obtained from the experiment in terms of electron drift velocity (v_d) and electron thermal velocity (v_{te}). The MADL is found to exist within the range $3v_{te} \geq v_d \geq 1.3v_{te}$. For the condition $v_d \geq 1.3v_{te}$, rise of an instability and simultaneous formation of MADL is observed in the experiment. The analysis of fluctuations in floating potential showed that the instability has all the characteristics of Buneman instability.

1. Introduction

Double layers (DLs) in plasma represents a non-neutral region of opposite charges separated by a small distance with a potential drop of the order of $|\phi_0| \geq kT/e$ across the layer [1]. They are suggested to be responsible for energizing auroral particles in ionosphere, solar flares, acceleration of charged particles in space plasma etc. The investigation on DL are frequently reported in space plasma [2–7], numerical simulation [8–12], theoretical plasma study [13–16] and also in a series of different types of laboratory plasma devices [17–20]. In addition, DLs have received enormous interest in the recent past because of its interdisciplinary nature and are known to play significant role in electrochemical super-capacitors [21], biological systems such as amphiphilic bilayers [22], heterogeneous fluid-based systems such as blood [23], paint etc. In laboratory, DL is generally produced by applying a potential drop or passing a current through plasma or by injecting an electron beam into plasma which often leads to current driven or beam related instabilities. Singh and Schunk, in a numerical simulation relevant to auroral plasma, showed the recurring formation of moving DL in a current driven plasma and demonstrated the role of Buneman instability in the reformation process through one dimensional model [24]. Studies carried out by Smith and Goertz [25] shows that excitation condition for Buneman instability exactly match with the Bohm criteria, i.e., $v_d \geq 1.3v_{te}$ where v_d is the electron drift velocity and v_{te} is the electron thermal velocity. In this article, we present experimental results from MADL, an experimental analog of auroral DL. Results clearly demonstrate, for the first time experimentally, that the triggering of Buneman instability leads to formation of MADL in the present experimental conditions. Our results are closely matching with findings of numerically simulated double layers in auroral plasma by Singh et al. [24].

The MADL in the present investigation consisting of more than one concentric layers and are generated by accelerating plasma electrons towards a positively biased electrode submerged in it. Analysis of satellite data by Temerin et al. [26] suggested that in auroral region, electrons are accelerated to large energies by a multiple double layer comprised of a series of many DL, rather than by a single DL. Computer simulations [27] also produced such a series of DLs, which somewhat resemble the proposed auroral structure. Bailey et al. demonstrated experimentally that a multistep DL or multiple DL (MDL) structure resembles very much to those data inferred from satellite measurements of auroral DL [28–31]. The understanding of DL in auroral region was greatly aided by Viking [32], S3-3 [33] and FAST [34] satellite including observation of parallel electric field, characterization of downward current region by electron drifting in the anti-earthward direction etc. But the issues concerning the formation and existence condition, relevance of instability in DL dynamics are far from complete. Also in space one is often limited to remote observations or data from a single pass of a spacecraft from which it might be difficult to even distinguish between spatial and temporal variations. Due to these reasons+

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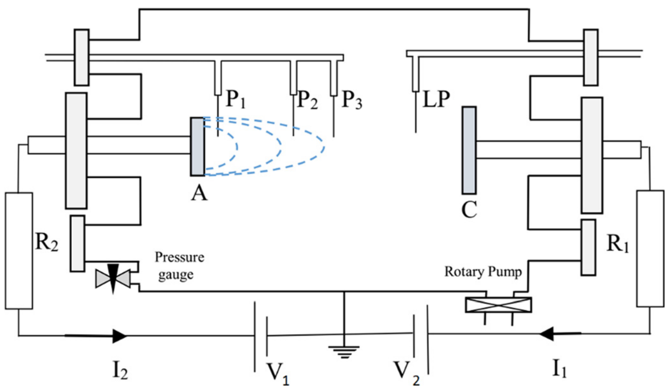

Fig. 1. Schematic of the experimental setup. A typical ADL profile with concentric DL structure is schematically shown in front of the anode. V_1 and V_2 = DC power supplies, A = anode, C = cathode, R_1 and R_2 = current limiting resistor, I_1 and I_2 = current measured through R_1 and R_2. P_1, P_2 and P_3 = floating probes. P_L = Langmuir probe.

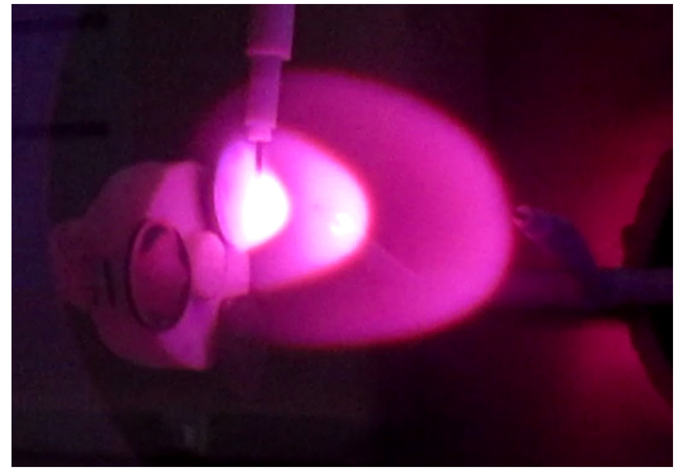

Fig. 2. (Multimedia view), experimental observation of multiple anodic double layer consisting of three layers at 0.2 mbar pressure.

MADL in the present investigation can be used as a testbed for studying auroral DL. The study provides the experimental boundary condition for the formation and existence of MADL obtained in terms of drift velocity and discharge parameters. The requirement of drift velocity condition gives rise to a lower limit for the formation of MADL which is consistent with Buneman instability condition, $v_d \geq 1.3 v_{te}$. We have obtained an experimental upper limit, at which DL vanishes. The obtained upper limit is in agreement with the condition, $v_d \geq 3 v_{te}$, given by Quon and Wong for ordinary simple DL produced in double plasma machine [35]. The time dependent floating potential fluctuations, obtained using floating probes, showed the excitation and growth of an instability with features similar to that of nonlinear evolution of Buneman instability [36].

The findings of the present investigation, mainly the condition for triggering Buneman instability and existence of MADL, provide a fundamental understanding of DLs. These results can be extended to improve the understanding of basic governing processes of DLs in space science, astrophysical system, solar corona, supercapacitors, biological system etc.

2. Experimental setup and generation of MADL

The experiment was performed in a modified dc glow discharge plasma set-up as shown in Fig. 1. Two disk shaped electrodes made of iron (Fe) and tungsten (W) used as cathode and anode respectively and are kept at a distance of 300 mm from each other. A high voltage DC power supply V_1 was used for application of negative bias up to −1 kV between cathode C and the grounded chamber. Another DC power supply V_2 was used for application of positive bias on anode in the range of 0–200 V. Two current limiting resistors, R_1 (100 Ω) and R_2 (100 Ω) were connected across the power supply V_1 and V_2 respectively. The variation in current I_1 (cathode discharge current) and I_2 (anode discharge current) through the resistors R_1 and R_2 had been measured when the anode bias V_2 changes from 0–200 V. The experiment was conducted in a low vacuum with air as the working gas.

In the present study MADLs were produced in the following way. Glow discharge plasma was initially produced between cathode and chamber by keeping the cathode at very high negative bias of −700 V. Once a steady plasma is achieved, an electron current is then driven through plasma by applying a positive bias to anode electrode fixed at a distance of 300 mm from cathode. The application of positive bias leads the electrons to stream towards anode from cathode side in the background of stationary cold ions. At certain lower critical value of anode bias denoted as V_{LC}, a sudden rise of an instability cause the charges self-organize to form MADL with three alternate dark and bright regions having a cone-in-cone geometry forms as shown in Fig. 2 (multimedia view), the geometry of the structure including the diameter of the layers, number of layers were attributed to the length of the chamber, size of electrodes, separation between electrodes etc. The MADL with three successive layers remained till the anode voltage reaches an upper critical value (V_{UC}). Beyond this upper critical value, the MADL transform or decay into other MADL states with reduced number of layers and size. For very large value of, V_2, all the DLs vanish and completely transform into a highly intense anode glow (AG). The complete evolution of this triple DL including transition from triple to double, double to single, single to anode glow (AG) and reverse can be obtained by monotonically increasing and decreasing V_2 in the range of 0–200 V.

Three floating probes P_1, P_2, and P_3 fixed distance of 3 mm, 30 mm and 80 mm from anode and a Langmuir probe P_L were used to measure the floating potential and plasma parameters respectively. The floating probes were fixed in such a way that any two of the three probes will sit at opposite layer of charges of the MADL with variation in DL dimension for a change in either pressure or voltage as schematically shown in Fig. 1. The floating probes were also used to record the fluctuations in floating potential by connecting the floating probes to a Lecroy 500 MHz wavejet oscilloscope having a sample rate of 2 GS/s using high impedance passive probe (10 MΩ) with system attenuation of 10× ± 2% to record the signal. More details about the experimental set-up can be found in [37].

3. Characteristics of MADL

In this section, we are focusing on two major characteristics of MADL in glow discharges mainly current–voltage characteristics and floating potential characteristics. Investigations carried out by Conde and Leon (1994) in constricted glow discharge [38] on the I–V characteristics revealed that discharge current, I_{dis} and discharge voltage, V_{dis} remain unaffected by the disappearance or upsurge of a new plasma corona or double layer. Later, role of discharge current in the number of plasma corona was studied by M. Strat [39] in a system consisting of two anodes and two cathodes revealed that the current was not steady rather consisted of regular spikes when there was a diffuse luminous plasma formation in front of anode. A sudden jump in current was observed when a nearly spherical intense luminous region with sharply defined boundaries was observed. It was concluded that double layer transforms into two, three or multiple DL structures when the cur-