Effect of magnetic field on double layer in argon helicon plasma

Kaiyi Yang | Ruilin Cui | Wanying Zhu | Zhiwen Wu | Jiting Ouyang

1School of Physics, Beijing Institute of Technology, Beijing, China
2School of Aerospace Engineering, Beijing Institute of Technology, Beijing, China

Correspondence
Jiting Ouyang, School of Physics, Beijing Institute of Technology, Beijing 100081, China. Email: jtouyang@bit.edu.cn
Associate Editor: Heping Li

Funding information
National Natural Science Foundation of China, Grant/Award Number: 11077047

Abstract
The electric double layer in argon helicon plasma by using floating electrostatic probe and local optical emission spectroscopy under different external magnetic field was investigated. Results show that electrons generated in the plasma source can be magnetized by the magnetic field and transported by the gradient of diverging magnetic field in the diffusion chamber, giving rise to the hollowed distribution of electron temperature. The electron temperature on axis has a sudden decrease, leading to the sudden decrease of plasma density as well as the plasma potential, forming a double layer structure. The position of double layer moves along with the position of diverging magnetic field, and the potential drop increases along with the strength of magnetic field. The structure of the external magnetic field plays the decisive factor for the double layer in helicon plasma.

1 | INTRODUCTION

Helicon plasma is known as a type of high-density plasma generated by radio frequency (RF) discharge in a specially made helicon antenna at low gas pressures in a magnetic field. Helicon plasma undergoes three discharge modes at increasing RF power, that is, capacitively coupled plasma mode (or E-mode), inductively coupled plasma mode (or H-mode) and wave coupled mode (or W-mode). One of interesting phenomenon in helicon plasma is electric double layer (DL) occurred under specific experimental conditions, in which the plasma potential has an abrupt drop in a short axial distance but no current flowing through an external circuit (or current-free DL) [1]. Such a potential drop of DL can accelerate ions downstream, achieving a kind of DL thruster [1–4]. For this reason, many researches have been carried out on the characteristics of DL [5–11] and the performance of helicon plasma thruster [12–18].

Usually, the DL forms in a helicon plasma device when the plasma suddenly expanded from a narrow source tube into a wide diffusion chamber together with abruptly diverging magnetic field [19]. Formation of DL was accompanied with a sharp gradient of axial density [1] and an ion beam generated in the downstream [20]. Although various factors may contribute to the formation of the current-free DL in helicon plasma, diverging magnetic field is one of the most essential factors therein. In the past few years, many studies were carried out in order to figure out how this diverging magnetic field affects the DL. For example, Keese et al. suggested that the ion flow speed in the downstream, which represented the strength of the DL, increased with decreasing neutral pressure and increasing magnetic field strength [21]. Takahashi et al. proposed that the magnetic field threshold for the formation of a DL increases with the decrease of the source tube diameter and the DL forms when the ion Larmor radius is smaller than the source tube radius [22]. Fredriksen et al. used the Njord helicon plasma device in which the diffusion chamber was spherical to study the effect of downstream magnetic field on DLs and the ion beam. They suggested when all the magnetic field lines in the source are passing through the intersection between source tube and diffusion chamber without intersecting the wall, the downstream density and the plasma potential increased significantly [23]. Ghosh et al. created the transition from single to multiple axial potential structure by forming a cusp magnetic field in the downstream of the diffusion chamber. They pointed out that only when geometric and magnetic expansions closely coincide with each other could single and multiple DL-like structures appear [24]. Charles [25] found a two-dimensional (2D) high-density conic along the most diverging magnetic field lines exiting the source in helicon plasma device, which was also reported by Saha et al. [26] that radial density profile in the downstream was peaked on the periphery appearing a hollow profile. Similar plasma profile was also observed in the other
dense plasmas like plasma jet [27, 28]. In the past, most researches were done with one-dimensional (1D) measurement or simulation, owing the formation of DL simply to the plasma expansion in diverging magnetic field, or the density reduction by some loss mechanisms [23]. But 1D theories were not appropriate to explain DL formation since 2D structure was discovered in experiment and simulation. Rao et al. proposed by 2D simulation that the density conic in helicon plasma was due to the magnetized electrons following the diverging magnetic field while the unmagnetized ions flowing directly downstream, resulting in a radial electric field which accelerated ions to the conical surface [29]. Nevertheless, the mechanism of DL formation was not clear yet.

The effect of external magnetic field on the electric DL in argon helicon plasma was investigated. The aim is to study how the diverging magnetic field contribute to the formation of a DL structure and the key factor to influence the DL.

2 | EXPERIMENTAL SET-UP AND DIAGNOSTIC METHOD

Experimental setup is shown schematically in Figure 1. The device is comprised of a quartz plasma source tube and a stainless-steel diffusion chamber. Pure argon is introduced from the top of the source tube controlled by a gas mass flow controller and the pressure is monitored by a vacuum gauge. A 13.56 MHz RF power source connected to a self-optimizing matching network is employed to provide RF power supply for a hollow copper helical antenna. The external magnetic field $B$, generated by two sets of copper solenoids electrified by DC power source, is axially uniform in part of the quartz tube including the region of antenna and diverges in diffusion chamber, as shown in Figure 2 as example of 150 G. A molecular pump together with a mechanical pump is assembled at the bottom side of the diffusion chamber to pump the gas pressure to 10$^{-4}$ Pa as a base pressure. The instruments described above have a set of water-cooling system if needed.

To obtain the characteristics of plasma potential, a floating electrostatic probe [30] instead of the traditional Langmuir probe was used. It comprised three parts: a single probe inserting in the diffusion chamber, an RF filter circuit and an electrometer voltmeter. The single probe was made by tungsten wire with radius of 0.1 mm covered by two layers of ceramic tubes and the exposed length of tungsten wire was 4 mm. The end of the probe was connected to the electrometer voltmeter through the RF filter circuit. The probe is fixed on a movable platform to take spatial measurement. One advantage of the floating electrostatic probe is that there is no current flowing through the probe system and the stability of the plasma will not be greatly disturbed. The potential value on the electrometer voltmeter represents the floating potential of the plasma and need to be corrected by the relation,

$$V_f = V - \frac{kT_e}{2e} \ln \left( \frac{2M}{\pi m} \right),$$  \hspace{1cm} (1)

where $k$ is the Boltzmann constant, $T_e$ is the electron temperature, $M$ is the ion mass, $m$ is the electron mass and $e$ is the elementary charge. With this method, the plasma potential can be obtained and applied into the analysis of the DL.

The method for measuring the optical spectrum of Ar helicon plasma is local optical emission spectrum [31, 32]. The optical spectrum is collected by a probe comprised of a hollow cylindrical tube 5 mm in diameter and a thin optical fibre fixed inside. Two symmetrical small holes are located at the head of the ceramic tube at both sides to collect the emitted spectral lines from the local area only. The tube is mounted on an electric movable platform so that it can do translation movement axially and radially. A spectrometer is connected to the probe to acquire the information of optical spectrum.

In low pressure RF plasma, when the electrons collide with ground state atoms (one-step electron collision) and metastable state atoms (two-step electron collision), the excited state atoms will be produced. The excited state of atoms will be quenched through the radiative de-excitation from excited state to lower state and the collision with neutral atoms. For the excited state particle Ar* at the j-level, the intensity of the spectral line radiated by the transition to the relatively low l level is [33]:

$$I_{ji} = \frac{n_{Ar}K_{ji}n_{Ar}b\lambda}{A_{Ar}},$$  \hspace{1cm} (2)

where $K_{ji}$ is the factor set in the spectrometer, $A_{Ar}$ is the Einstein’s Coefficient, $n_{Ar}$ is the density of Ar atoms on excited state, $b$ is the Planck constant, $\lambda$ is the speed of light in vacuum and $\lambda$ is the wavelength of certain spectral line emitted by transition. At steady state, the generation and quenching of the excited atoms is going to be equal for equilibrium, then the density of the excited state atoms Ar* can be obtained by

$$n_{Ar^*} = \frac{n_e \left( n_{Ar}K_{dir}^{Ar^*} + n_{Ar}^{m}K_{m}^{Ar^*} \right)}{k_{rad}^{Ar^*} + n_{Ar}K_{Ar}},$$  \hspace{1cm} (3)

where $n_e$, $n_{Ar}$, and $n_{Ar}^{m}$ are the density of electrons, ground state atoms and metastable state atoms respectively, $K_{dir}^{Ar^*}$, $K_{m}^{Ar^*}$, $k_{rad}^{Ar^*}$ and $k_{Ar}$ are the reaction rate coefficient of the excitation of ground state and metastable state and the reaction rate coefficient of the collisional quenching of excited state and the quenching of radiative de-excitation of excited state respectively. Combining Equations (2) and (3), we can obtain

$$I_{ji} = n_e \left( \frac{n_{Ar}K_{dir}^{Ar^*} + n_{Ar}^{m}K_{m}^{Ar^*}}{k_{rad}^{Ar^*} + n_{Ar}K_{Ar}} \right) K_{ji}A_{Ar} \frac{b\lambda}{\lambda}.$$  \hspace{1cm} (4)

Seen from Equation (4), the intensity of spectral lines correlates with the densities of particles and the rate coefficients in excitation and de-excitation reaction. By means of adopting two certain spectral lines and applying their intensities
into Equation (4) and comparing the ratio of each side of the equation, the value of electron temperature can be obtained.

3 | RESULTS AND DISCUSSION

3.1 | Experiments and results

In experiment, mode transition could be seen at increasing RF power, with a significant increase of plasma density and emission intensity of spectral line of 811.53 nm. As the input power was increased to certain values, the main way of power coupling was changed from capacitive-coupling at E-mode to inductive-coupling at H-mode and wave-coupling at W-mode sequentially. The efficiency of ionization was promoted accordingly. This characteristic of mode transition was reported previously by our group [30–32] as well as the others [34–36].

The DL was observed when the helicon discharge is in wave-mode. The distribution of plasma potential along the central axis is shown in Figure 3a. The operation conditions are of gas pressure $p = 0.2$ Pa, magnetic field $B = 150$ G and input RF power $P = 1500$ W. It is seen that significant potential drop begins from $z = 0$ cm where the largest gradient of magnetic field is located. The total potential drop of DL is around 10 V.

The DL distribution is consistent with the electron temperature and the emission intensity of 811.53 nm, as shown in Figure 3b,c. Drops of electron temperature and intensity of 811.53 nm also occur in the DL region. The electron temperature upstream is 30% higher than the electron temperature downstream, decreasing from 4.1 eV at $z = 0$ cm to 3.3 eV at $z = -3$ cm. The spectral line of 811.53 nm decreases its intensity by 21%, from 57,000 at $z = 0$ cm to 44,900 at $z = -3$ cm. Since 811.53 nm emission from the transition $3p^5(3P_{3/2})4p[5/2] \rightarrow 3p^5(3P_{3/2})4s[3/2]^3P_0$ is correlated with the density of metastable state argon atoms as well as the electron density [30], result of Figure 3b also approximately indicates the distribution of electron density, roughly the plasma density, across
the DL on axis. Besides, the intensity of 811.53 nm line can be converted to the electron density by certain relations [31, 32]. Hence the corresponding electron density is also displayed here in Figure 3b.

Generally, DL can only be obtained in W-mode, as shown in Figure 4. And the potential drop in DL increases with the RF power. In E-mode (at power below 600 W) or H-mode (at 900 W), the plasma potential changes very little (less than 2 V). Similar result was also reported in Gao et al. [30].

The plasma potential in the DL region is not uniform in radial direction. 2D contour of the potential is shown in Figure 5. At z = 0 cm or below, the equipotential lines are broader in radial direction evidently. From 0 to −3 cm in the central z-axis, the equipotential lines become relatively denser comparing to the lines on other axial positions, indicating a stronger field there. These denser equipotential lines in the centre are located at the same area where the DL exists as well as that the magnetic field lines begin to diverge significantly, showing a U-shaped DL. Similar phenomenon was previously reported by Charles et al. [25].

Displayed in Figure 6 is the 2D contour of measured intensities of 811.53 nm emission. As expected, the 811.53 nm emission intensities resemble the similar distribution as the plasma potential, with peaked values inside the tube (z ≥ 0 cm) and decreased in the diffusion chamber (z < 0 cm) where the magnetic field is diverged. Correspondingly, the density of the metastable atoms and hence the plasma should be higher in the high-potential region and decrease in the downstream of the DL.

Also, Ar II spectral lines ranged in 400–550 nm were observed when the W-mode is achieved, although the intensities of these lines are generally lower comparing with that of 811.53 nm (not shown here). Since the excitation energy for Ar II lines is higher (at least 19.2eV), it indicated that more electrons with high energy existed in helicon plasma in W-mode.

Figure 7 shows the radial profiles of electron temperature at different axial positions. In the upstream of the DL (e.g. z = 1 cm), the electron temperature is nearly constant in radial direction. In the downstream, the electron temperature appears...
lower in the centre but higher in the edge. Also, the electron temperature drops faster in the centre than the edge in axial directions. Such a hollowed distribution of the electron temperature represents a hollowed distribution of the energy of electrons. It reveals that the electrons derived from the plasma source have more energy at the outward region where the magnetic field diverged in the diffusion chamber.

A higher magnetic field results in a larger DL. Figure 8 gives a comparison of potential drop, 811.53 nm emission (and the corresponding electron density) and electron temperature at $B = 150$ G, $200$ G and $300$ G. The potential drop of DL increases from 10 V at $150$ G to 12 V at $200$ G and to 15 V at $300$ G. The same trend is shown for the plasma density and electron temperature. The radial distribution of electron temperature at higher magnetic field is also similar to that of Figure 7, but with larger value in general. It indicates that DL is accompanied by the drop of electron temperature.

In experiments, the potential gradient of DL increases along with magnetic field strength, as shown in Figure 9 which is a plot of the potential drop $\Delta V_p$ along the central axis from $z = 0$ cm to $-3$ cm against the magnetic field $B$. A potential drop larger than 10 V can be obtained when the magnetic field is higher than $200$ G. When the field is less than $50$ G, it was generally no significant potential drop can be observed in experiment.

To investigate the DL changing with the structure of the magnetic field, we moved the two copper solenoids downwards. Figure 10 shows the distribution of plasma potential, 811.53 nm emission (and the corresponding electron density) and electron temperature when maximum magnetic field 2 cm downwards together with the original one. It is seen that the beginning position of the plasma potential drop moves 2 cm downwards, that is, the drop begins at the maximum gradient of the magnetic field. So do the spectral intensity of 811.53 nm and electron temperature, that is, the profiles of plasma potential, emission intensity and temperature follow the movement of the solenoids which determines the structure of the magnetic field.
3.2 | Discussions

As seen above, the electric DL appears in the diverging magnetic field when helicon discharge is in W-mode. The potential drop increased with RF power and magnetic field strength. The DL region moved according to the position of the magnetic field gradient. We therefore suggested that the electric DL in helicon plasma should relate to the diverging magnetic field.

In a magnetic field, the charged particle in motion is affected by Lorentz force and moves circularly in Larmor radius. The cyclotron radius $r_c$ of the electrons in magnetized plasma can be calculated by

$$r_c = \frac{m_e v}{eB}$$

where $m_e$ is the mass of the electron and $v$ is the mean electron velocity $v = \left( \frac{8kT_e}{\pi m_e} \right)^{\frac{1}{2}}$.

Then, the Larmor radius of electrons ($r_{L,e}$) is about 0.32 mm under $B = 150$ G, and electrons can be well confined by the magnetic field (i.e. magnetized). Similarly, the Larmor radius of argon ion $r_{L,i}$ is calculated to be 40 mm, much larger than $r_{L,e}$ and in the same order of the tube. Therefore, argon ions are unmagnetized. The hollowed distribution of electron temperature represented that the energy of electrons is higher along the diverging magnetic field lines. As electrons derived from the source could be magnetized by magnetic field, they were confined around the magnetic field lines and were transported through strong gradient of diverging magnetic field (VB) into the diffusion chamber. Such transportation was proposed to be grad-B drift [37], in which the electrons rotated in azimuthal direction with little loss of energy. Hence the electron energy was higher at the periphery below the discharge tube and the electron temperature was peaked off-axis. Since the electron temperature was correlated with the enthalpy which could be transferred into potential energy [38], the electrons gathered at outward region contributed to the broad distribution of plasma potential, as shown in Figure 5. Besides, the electrons with higher energy at outward region could enhance the ionization due to the grad-B drift effect [37]. This contributed to the radially broad distribution of the plasma density, as shown in Figure 6. As stated above, the electrons were well confined by magnetic field and their cross-field diffusion was limited. But since the ions were unmagnetized, they could attract the electrons to move outwards by ambipolar field effect. This also contributed to the broad distribution of plasma density.

As discussed above, in a diverging magnetic field, the electrons were transported outwards along diverging magnetic field lines. This gave rise to a hollow-distributed electron temperature, in which the electron temperature on $z$-axis dropped faster. The ionization of plasma was enhanced in the periphery but dropped quickly on $z$-axis. Hence the axial plasma density decreased greatly, forming a large density gradient. Also, the plasma potential had a sudden drop in a short distance on $z$-axis, which was identified as a DL. On the contrary, when there was no diverging magnetic field, like in the discharge region where the magnetic field was nearly uniform, the radial transportation of the electrons was not so much and most of them was transported downwards. Hence most of the generated plasma was centred on axis and the axial variation of density was not obvious. Thus, no significant potential drop would be found.
As the strength of the magnetic field was increased, shown in Figure 8, the plasma density increased. This might be due to the improved coupling of helicon wave which caused a larger fraction of the wave power to be absorbed. The electrons were heated due to the improved power absorption, causing the increase of electron temperature. The increased electron temperature then leads to enhance the ionization of plasma. Also, according to the dispersion relation of helicon plasma [2], the plasma density in source region increased along with magnetic field strength for a fixed wave number. Thus, when the magnetic field was higher, the upstream plasma density increased. This leads to a larger axial gradient of plasma density as well as the plasma potential. Therefore, the strength of DL increased with the magnetic field strength as indicated in Figure 9.

As the position of the diverging magnetic field moved downwards, the position of DL moved downwards correspondingly. Since the magnetic field could magnetize the electrons, the electrons in diverging magnetic field would be transported outwards by grad-B drift, forming a hollow distribution of electron temperature. Thus, when the position of the diverging region of magnetic field was moved downwards (and so was the maximum of grad-B), the position where the hollow electron temperature distribution appeared was moved downwards as well, then the formation of DL would locate below the original position. Moreover, because there existed the geometrical expansion of plasma, part of charged particles was lost when expanding in the diffusion chamber before contributing to the DL formation. This is demonstrated in Figure 10, in which the strength of DL was smaller as the solenoids were moved downwards.

DL is a peculiar structure in helicon plasma. The sharp potential drop in DL can accelerate ions and generate thrust, achieving the helicon plasma thruster. For one respect, the helicon thruster needs high input RF power to generate high plasma density in the source region in order to form the DL by large density gradient. For another respect, the diverging magnetic field can influence the DL structure and can be considered as an essential factor for the helicon thruster. Increasing magnetic field strength gives rise to the increase of DL strength which has stronger ability for ion acceleration. The relative position between the diverging magnetic field and the DL facilitates the alternative locations of the DL thruster controlled by the locations of diverging magnetic field.

4 CONCLUSIONS

In summary, we have investigated the electric DL in argon helicon plasma. The DL appeared in region of diverging magnetic field when the helicon discharge was in W-mode. The axial potential drop in DL was coincided with the drop of electron density and electron temperature. The electron density showed the same 2D distribution as the plasma potential. The electron temperature exhibited a hollow distribution in radial profiles, in which the axial electron temperature decreased fast. Then the gradient of plasma density was increased and so was the gradient of plasma potential. The characteristics of DL were suggested to be affected by the external magnetic field. Increasing the strength of magnetic field gave rise to the increasing strength of DL. The position of the DL moved accordingly to the position of the diverging magnetic field. It is concluded that the external magnetic field should be one of the most important factors for the DL. These results and conclusions are helpful for designing the DL thruster.

ACKNOWLEDGEMENTS

This work was partly supported by the National Natural Science Foundation of China (No. 11975047).

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