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Positive Self-bias in a Magnetized CCP Discharge

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Radio frequency (RF) plasmas are commonly used for surface treatments and plasma heating processes. Controlling the heat flux from the plasma to the RF electrode is a crucial issue for optimizing these processes and is, therefore, the subject of considerable research in the low- and high-temperature plasma physics communities. In an asymmetric Capacitively Coupled Plasma (CCP) discharge, the ions accelerated by the Direct Current (DC) self-bias are the prime factor of the wall heating process. In the presented work, investigations have been performed with the aim to act on the DC self-bias in a linear magnetized RF environment. The lateral side and one face of the electrode have been covered by ceramic in order to limit the electron flux towards these surfaces. The variations in DC self-bias voltage as a function of the gas pressure, coupled RF power and tilt angle between the RF electrode and the axial magnetic field have been studied. A new regime was discovered at low pressures, higher magnetic fields and grazing angles, for which the self-bias is positive. An analytical model was developed, which is in agreement with the experimental results.

Capacitive coupled plasma discharges are still one of the widely used techniques in plasma physics and have been thoroughly studied mainly without magnetic field^{1,2}. The addition of magnetic field to the system makes physics more complex, especially for the RF (Radio-frequency) sheath structure in front of the electrode as a function of the electrode tilt angle. In unmagnetized plasma, the asymmetry between the area of the capacitive electrode and grounded wall of the vacuum vessel results in a net self-bias voltage on the electrode connected to an RF power supply¹, or a net direct current (DC) bias of the plasma in direct coupling discharges^{3,4}. In the case of a small active electrode and large grounded wall discharge, the self-bias is strongly negative due to the higher electron mobility. On the contrary, it can be positive when the RF electrode is much larger than the wall⁵. In most plasma devices, the DC self-bias potential is negative and accelerates ions towards the electrode, also known as cathode. This behavior is exploited in etching and sputtering applications.

In high-power magnetized plasmas like in magnetized fusion, the main goal is to mitigate the heat flux to the wall or active RF surfaces on which hot spots can dramatically damage the material⁶. The magnetic field reduces the particle flux perpendicular to its direction so that the potential drop inside the sheath decreases with the magnetic field strength⁷ and the tilting angle of the electrode^{8–10}.

The particular case when the magnetic field is perfectly parallel^{11,12} to the surface rarely happens in complex reactors such as tokamaks or stellarators, where magnetic field lines are slightly tilted with respect to the wall¹³. Nevertheless, some parts of the wall, like active antenna (or electrode in magnetrons, for instance⁷) can be quasi-parallel to the magnetic field, hence changing the boundary condition of the plasma locally.

As a result, the electric field inside the sheath at grazing angles^{14,15} can reverse at low enough electron mobility (at high magnetic field and low collisionality). This has been observed in PIC simulations for well magnetized ions, i.e. $\varepsilon = \rho_i/\lambda \ll 1$ where ε is the gyroradius to mean free path ratio for ions^{16,17}. It occurs as soon as the ion flux is higher

than the electron flux, leading to a positive bias of the wall with respect to the plasma.

In the same way, the self-bias of an RF capacitively coupled electrode parallel to the magnetic field could be positive despite of the perturbations due to the oscillating sheath which enhances microinstabilities and stochastic heating⁷. The possibility of a positive self-bias on the active RF electrode has been already reported in magnetron systems using the magnetic asymmetry effect¹⁸. In the present work, a general case study in a system with a uniform magnetic field has been explored, a situation of practical interest in various configurations, notably in magnetic fusion reactors. Here, the positive biasing has been observed with a one-face RF electrode and investigated as a function of gas pressure, magnetic field, RF power and tilt angle of the electrode for well-magnetized electrons and almost unmagnetized ions (Table 1).

The experiments have been held in ALINE, a cylindrical magnetized RF experimental reactor (1 m long and 30 cm in diameter)¹⁹. Power from the RF generator is coupled to the plasma either directly via an RF electrode, or via a matching box connected to an RF electrode at the frequency of 25 MHz. The coupled RF power, RF voltage and current are measured using an Octiv Mono IV probe from Impedans. At the maximum magnitude of the magnetic field of 0.1 T, electrons are well magnetized, but the ions are not. DC self-bias developed on the RF electrode was measured using a probe connected to the electrode through an inductor of high inductance to reduce the RF perturbations in the system. ALINE is equipped with an RF compensated Langmuir probe and IR camera to characterize the plasma and heat flux measurements²⁰. A tungsten RF electrode has been placed at the geometric centre of the cylinder. The rotor to which the RF electrode is attached enables its rotation along its diameter, defining (α) an angle with the axial magnetic field (Figure 1). When the plasma is on, the electrode is in contact with the plasma and starts collecting flux. The experiments have been performed by covering the lateral side and one of the circular faces of the electrode with ceramic to limit the particle flux to the electrode.

For each angle (α) and gas pressure, the magnetic field

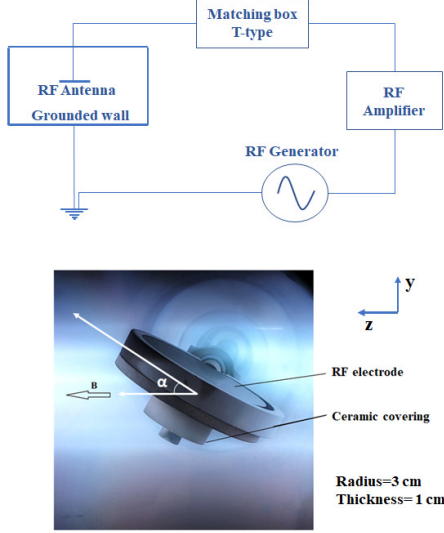


FIG. 1. Schematic of the RF circuit and picture of the RF electrode in ALINE.

was varied from 0.024 T to 0.096 T, and measured self-bias voltages have been analysed to understand the influence of the magnitude of the magnetic field on it. Measurements with different RF powers were performed at a constant magnetic field of 0.1 T. Plasma parameters corresponding to each variable were determined using RF compensated Langmuir probe. These results have been compared with the developed analytical model.

The ion and electron fluxes to the RF electrode can be modelled to deduce the angle at which the averaged sheath collapses, meaning the DC potential drop in the sheath is zero, and the collected ion and electron fluxes are naturally equal. Due to the presence of the magnetic field, the parallel and perpendicular fluxes to the electrode have to be calculated separately as a function of the tilt angle of the electrode. Considering a homogeneous plasma density and magnetic field, with some poorly magnetized ions ($\omega_{ci}/v_{iN} \leq 1$) and well magnetized electrons ($v_{eN} \ll \omega_{ce}$), with $\omega_{ci,e}$ and $v_{i,eN}$ the ion and electron cyclotron frequencies and ion and electron-neutral collision frequencies, the ion flux is merely Bohm flux but electron flux has parallel and perpendicular components. The last component is mainly driven by electron-neutral collisions through the perpendicular mobility μ_{\perp} ⁵ and the perpendicular electric field E_{\perp} in the RF sheath: $E_{\perp} = \bar{E} + \tilde{E} \sin(\omega t)$, with the driving RF amplitude \tilde{E} and the DC component \bar{E} due to the self-bias of the capacitive electrode. The diffusion due to density gradients and the drift velocities ($E \times B$ and diamagnetic drift) are neglected here. In the whole modelling, the plasma potential is assumed to be close to zero (actually of the order of the plasma floating potential), which usually occurs in unequal capacitive discharges¹. Finally, the parallel electron flux connected to the electrode can be estimated directly (Chodura model¹⁰) for an angle α , but another component has to be taken into account for zero angles. All electrons closer than two electron gyro radii $2r_L$ will intersect the

electrode surface so that the electrons in the layer of thickness $2r_L$ above the surface will be collected²¹. In the end, equating ion flux (Γ^i) and electron flux, it follows :

$$\Gamma^i = n\mu_{\perp}E_{\perp} + \Gamma_{\parallel}^e \left(\frac{4r_L}{\pi R} + \sin \alpha \right) \quad (1)$$

with n the plasma density, $\mu_{\perp} = \mu / (1 + \frac{\omega_{ce}^2}{v_{eN}^2})$ with ω_{ce} and v_{eN} the electron cyclotron and electron-neutral frequencies, $\Gamma_{\parallel}^e = nc_e$ ¹³ with $c_e = \sqrt{\frac{k_B T_e}{2\pi m_e}}$, k_B the Boltzman constant, T_e the electron temperature, m_e the electron mass. R is the electrode radius.

From this equation, the angle at which the ion and electron fluxes are equal can be deduced. According to the literature,^{14,15} this angle is usually less than 5° , so that $\sin(\alpha)$ can be approximated as α . Assuming that $\Gamma^i = nC_s$ with C_s the Bohm velocity :

$$\alpha = \frac{C_s - \mu_{\perp} \langle \tilde{E} \rangle}{c_e} - \frac{4r_L}{\pi R} \quad (2)$$

In this equation, the DC component of E_{\perp} , i.e. \bar{E} is null because the DC self-bias of the electrode is supposed equal to the DC plasma potential, which means there is no DC sheath potential drop. Electrons can be accelerated towards the electrode surface by the RF electric field during half a period (when the electric field is directed towards the electrode surface). Then the time average effective electric field over 1 period is $\langle \tilde{E} \rangle = \frac{1}{2} \int_0^{T/2} \tilde{E} \sin(\omega t) dt = \tilde{E} / \pi$. The electric field can be simply deduced from \tilde{V}/s with s the sheath thickness defined by the Child-Langmuir law as follows :

$$s = \gamma \lambda_{De} \left(\frac{V_{rf}}{T_e} \right)^{3/4} \quad (3)$$

The Debye length λ_{De} depends on the plasma density at the entrance of the sheath, V_{rf} is the amplitude of the rf potential and γ is a coefficient which has been chosen at 0.4 to match the experimental measurements. Due to their higher mass, ions do not respond to the high frequency RF oscillations, and therefore they are not accelerated in the RF electric field of the sheath, while the DC part is supposed to be 0, so that they are neither accelerated nor repelled. Hence the ion flux can be simply expressed as the classical Bohm flux. The results have been compared to the experiments in the next sections. Similar observations on the angles have been reported already in the case of tokamak plasmas with a cross-field anomalous diffusion¹⁵ and in the case of pure ambipolar diffusion in higher collisionality plasmas¹⁴. These angles apply in steady-state plasmas, not in the case of an RF-driven sheath. Another crucial parameter is the B (magnetic field in Tesla) and p (the pressure in Pa) pair, in the case of a straight electrode ($\alpha = 0$) for which the DC self-bias is zero. To obtain these parameters, the following polynomial needs to be solved.

$$v_{eN}^2 - v_{eN} \frac{e\tilde{E}}{me \left(C_s - c_e \left(\frac{4r_L}{\pi R} + \alpha \right) \right)} + \omega_{ce}^2 = 0 \quad (4)$$

There are two solutions for this equation, but the acceptable one is the one which satisfies $v_{eN} \ll \omega_{ce}$, in which the electrons remain well magnetized, which is one of the main assumptions of the model. The corresponding pressure p can be deduced from $p = n_g k_B T_e$ and $v_{eN} = \sigma n_g v_{Te}$, where σ is the electron-neutral cross-section, n_g the neutral gas density and v_{Te} is the thermal electron velocity; and the magnetic field B is deduced from $\omega_{ce} = eB/m_e$. The main unknown in this equation is the amplitude of the RF electric field inside the sheath. It can be measured experimentally²² or calculated from the RF electrode potential and the sheath size. The sheath structure can be complex in the presence of a magnetic field. At oblique angles higher than the Chodura angle, the sheath is composed of a magnetic presheath, where the potential drop is still negative (which means the wall is negative with respect to the plasma potential). At grazing angles, the sheath can collapse^{14,15}, hence its thickness depends on either the Debye length for $\omega_{pi} > \omega_{ci}$ or the ion Larmor radius for $\omega_{pi} < \omega_{ci}$; always assuming well-magnetized electrons^{11,12}. The electric field inside the sheath can be as high as several thousands V/m in a non-RF sheath^{14,22}, and it can be much higher in a driven RF sheath in front of a capacitively coupled electrode (up to 10^5 depending on the RF power and the plasma density).

The main parameters of He plasma column in ALINE are displayed in table 1. The plasma is highly non-uniform along the y-direction due to 1) the active RF electrode being at the centre of the chamber, and 2) one of the circular faces and the lateral side of the electrode covered with the ceramic shield. The magnetic field confines the electrons along a thin layer above the active surface of the electrode in which the density can be 10 times higher than the surrounding plasma.

TABLE I. ALINE plasma parameter.

Quantity	Ions (He^+)	Electrons
Density(n)(m^{-3})	$1 - 60 \times 10^{16}$	$1 - 60 \times 10^{16}$
T (eV)	0.026	3-6
$\lambda_{mfp}(cm)$	1.50	1.4-5.2
$v_e (s^{-1})$	380×10^3	3×10^9
$v_p (s^{-1})$	$7 - 23 \times 10^6$	$635 - 2000 \times 10^6$
$\omega_{ce}/v_{(e/i)N}$	0.1-5.6	17-967

The pressure values and the magnetic field varied from 0.3 to 3 Pa and from 0 to 96 mT, respectively. Considering a cross-section of $5 \times 10^{-19} m^2$ for electron-neutral collisions, the magnetization parameter ω_{ce}/v_{eN} for electrons varies from 17 to 967 and for ions from 0.1 to 5.6 showing the poor magnetization of ions except at "high" magnetic field and low pressure. The RF power coupled to the plasma is around 35 W. Figure 2 shows a 'Makuma' interpolation of 6 by 4

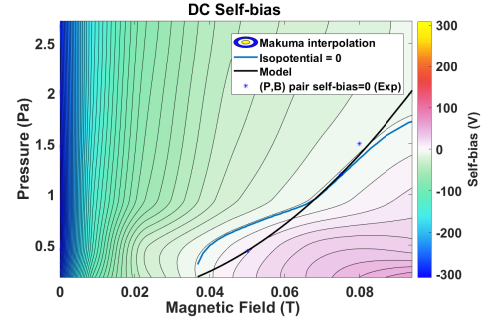


FIG. 2. Interpolated plot of variation of DC self-bias voltage with gas pressure for different magnetic field (He gas, 25 MHz, 35 W coupled RF Power).

points formed by pressure and magnetic field scans. In 3/4 of the domain (low magnetic field and high pressure), the self-bias is negative like usually measured in most experiments. But at a high magnetic field and low pressure (0.3 Pa and 96 mT), the self-bias becomes positive up to values of 55 V. The points where the electrons and ion currents to the electrode are equal (i.e. self-bias null), estimated from the model, have been plotted in the figure. The inputs to the analytical model are the cyclotron frequency, the electron-neutral collision frequency, and the electric field inside the RF sheath, which depends on the electrode RF voltage and also the plasma density (from which the sheath thickness can be measured using Child-Langmuir law). The experimentally measured plasma density using the Langmuir probe via OML theory is between 5×10^{16} to $5 \times 10^{17} m^{-3}$. Hence the corresponding sheath size is less than 1 mm for an RMS RF potential of 100 V, yielding an electric field of the order of 10^5 V/m inside the sheath. The RF voltage at the electrode or the output of the matching box between the RF amplifier and the electrode is measured using the Octiv RF power meter, and it is in the range of 45 to 283 V. In the model, the electric field input is equal to 1.1×10^5 V/m to match the 0 V isopotential in figure 2, which is consistent with the experimental values. Of course, this is a constant value taken for all the domains, but varying the pressure results in density variation as well, hence changing the current collected by the electrode and, in the same way, the RF potential since we operate at constant power. (P,B) pairs at which self-bias values are zero (denoted by * in figure 2) have been added to check the experimental electric field operating along the isopotential = 0. These 3 measurements show an electric field of 1.5×10^5 , 4.3×10^5 and 4.8×10^5 V/m at pressures of 0.44, 1.2 and 1.5 Pa and magnetic field of 0.08, 0.075 and 0.05 T respectively. The densities deduced from OML (which usually overestimates the density) are between 4×10^{16} and $4 \times 10^{17} m^{-3}$. So the electric field value taken in the model (1.1×10^5 V/m) is at least 1.5 times lower than those deduced from measurements. But according to the wide uncertainties in the density and RF potential across the sheath, the trend of the model is quite good. Finally, along with this isopotential, the magnetization parameter ω_{ce}/v_{eN} does not vary much, from 60 to 90 for electrons, which makes this parameter a consistent one to characterize the 0 V biasing.

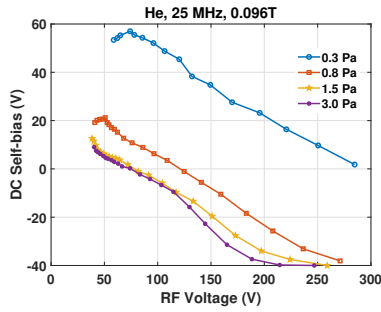


FIG. 3. Variation of DC self-bias voltage with RF voltage on the electrode surface when the RF electrode is parallel to the magnetic field.

Several studies have already reported a linear increase in the magnitude of the self-bias voltage with input RF power/voltage^{18,23}. Here, the variation of the self-bias with the coupled RF power has been studied for four different gas pressures at 0.096 T (Figure 3). A linear decrease in the self-bias values was observed with increasing the coupled power from 3 to 120 W, except at the lowest pressure measurement, which is in accordance with the previously reported studies²³. For 0.3 Pa measurements, the self-bias voltage increases first, reaching a maximum and then decreases linearly. As the coupled power increases, the electron flux (according to the presented model) increases due to its acceleration in the RF electric field inside the sheath, which explains the observed trends at higher pressures. At low pressures, the increase in the RF power enhances the plasma density, and at 0.1 T, the mobility of electrons across the magnetic field is lower compared to that of ions. This explains the maximum positive biasing (57 V) at 74 V on the RF electrode.

In the next study, the angle between the electrode and the magnetic field has been varied from 0° to 90° for four different magnetic field values (0.024 to 0.096 T). Since the lateral and one of the circular sides of the electrode are covered with ceramic, at 0°, the total flux to the electrode is only due to the perpendicular mobility and the contribution due to the gyration of electrons (the electrode collects all the electrons in the layer of thickness of Larmor radius above it). At 0.1 T, the DC potential developed is still positive for grazing angles, but as the tilt angle increases from 0 to 5°, there is a significant fall in DC self-bias voltage (Figure 4). The minimum value of the self-bias is surprisingly at the tilt angle of 20°. At grazing angles, the stochastic heating is efficient because electrons are confined along the magnetic field lines close to the electrode surface and can only go out of the electric field in the sheath by transiting axially, which means they are accelerated all over the diameter of the electrode. The energy gain of these hot electrons is then close to the maximum RF potential²⁴. The self-bias of the electrode is proportional to the electron flux, which is proportional to electron temperature. As a result, the minimum self-bias appears at an angle which is low enough to collect these hot electrons and high enough to increase the collecting surface of the electrode. There is an optimum angle at which the electron temperature and the collecting surface are high. While increasing the angle further up to 90°, hot

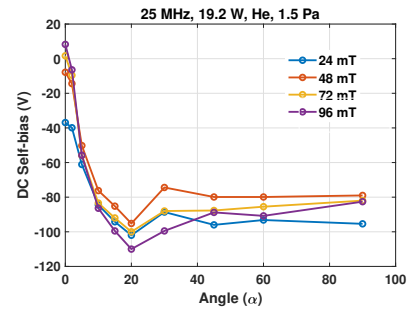


FIG. 4. Variation of DC self-bias voltage with angle of electrode (He gas, 1.5 Pa, 25 MHz, 19.2 W) when the RF electrode is parallel to the magnetic field.

electrons disappear because the electric field inside the sheath tends to be parallel to the magnetic field, and electrons are quickly ejected from the sheath, gaining less energy. This decreases the self-bias while the collecting surface does not vary so much between 45 and 90°. Similar observations have been reported already for a steady-state collisional plasma with an ambipolar model and PIC simulations in¹⁴.

In the last study, the tilt angles at which self-bias is zero for different gas pressures and RF powers have been measured experimentally and compared with the theoretical predictions in figure 5. For three different gas pressures (0.3, 0.6 and 1 Pa) and a range of power from 10 to 120 W (corresponding to RF voltage between 50 and 300 V), the zero self-bias was observed at tilt angles lower than 4°, which is in agreement with predictions from the model based on equation 2. These angles shift to lower values with increasing power. At lower voltage values, the value of the tilt angle deviates from the prediction. This seems to be due to the non-uniformity of the plasma density and the deviation of the electron distribution function from the Maxwellian at lower pressures. It has been observed in the density measurements for the tilted electrode configuration that the high-density region are magnetically connected to the top side of the RF electrode, as seen in figure 1. Unmagnetized ions diffusing from this high-density regime to the electrode surface can be one of the reasons for positive self-bias of the electrode even at higher angles. Electron temperature measurements using the Langmuir probe above the surface of the RF electrode are not easy due to the stochastic heating and generation of hot electrons at grazing angles. A small population of hot electrons results in the shifting of floating potential to negative values and the estimation of high electron temperature values. Hence the average value of the electron temperature is considered to be 3 eV for the whole modelling part. The inputs to fit the experimental curves using the analytical model have been taken from the Langmuir probe (Density) and RF power meter data to estimate the RF voltage and hence the electric field within the sheath in front of the RF electrode. It should be noted that the maximum error on the measured angle is 0.2°.

The possibility of a positive self-bias in an asymmetric

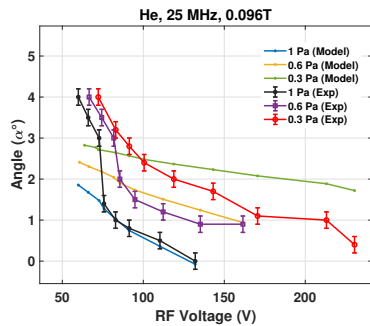


FIG. 5. Angles at which the self-bias voltage developed is zero as function of coupled RF power for a fixed magnetic field and gas pressure.

magnetized CCP discharge has been studied experimentally and analytically. Positive self-bias was achieved using a “one face” electrode surrounded with ceramic at the edge and bottom sides and by limiting the perpendicular electron flow to the electrode in the low collisionality regime and relatively high magnetic field (≈ 0.1 T). Since ions are almost not magnetized, their motion is unaffected by the changes in the B values. Variations in the self-bias voltage with input parameters such as magnetic field, gas pressure, the tilt angle of the electrode and input RF power have been studied and compared with the results from the analytical model. The main results are in good accordance with the model, which shows that the transition angle from a negative to a positive self-bias is mainly lower than 3° and that an increase of the RF power plays the same role as an increase of the pressure or a decrease of the magnetic field. This is due to the oscillating electric field in the sheath, which increases the perpendicular electron flux. The development of a positive self-bias practically repels ions and hence reduces ion flux to the electrode resulting in lower total heat flux at the electrode surface. It would then allow higher power density without excessive heating of the electrode able to enhance the plasma density in smaller device.

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