The magnetized discharge with dust: negative and positive space charge modes

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The structure of a discharge across a magnetic field in a dusty plasma is analysed. The dust macroparticles are negatively charged, but are unmagnetized because of their high mass. The electrons are highly magnetized, and the ions have intermediate magnetization. This results in different transport rates of the different species across the magnetic field. Depending on the size of the magnetic field, and the relative charge on the different species, the dust grains can be the dominant current carrier. The space charge clouds near the electrodes will then be determined by the relative mobility of the different species. The discharge can operate in one of two modes, a positive space charge (PSC) mode, characterized by a strong cathode fall, and a negative space charge (NSC) mode, characterized by a broad anode fall. Features unique to the dust particles can also play a role in the structure of the discharge, such as the variable equilibrium charge on the grains, dependent on the local potential and species temperatures, the effect of gravity on the grain dynamics, and the rate of charging of the grains. The dust grains can also form an ordered structure, the dust-plasma crystal. A fluid model of the different species is used to calculate the structure of the resulting discharge, incorporating the above effects. The transition from the PSC mode to the NSC mode as the magnetic field, pressure and dust properties are varied is demonstrated.

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I. INTRODUCTION

A Particle-in-Cell/Monte-Carlo (PIC/MC) simulation (van der Straaten et al. 1994, 1997) and semi-analytic treatment (Cramer, 1997) of the radial structure of a low pressure DC cylindrical magnetron discharge has revealed a potential and electric field structure highly dependent on the pressure and magnetic field. As either the pressure was reduced or the magnetic field was increased, the steady state discharge was found to exhibit a transition from a positive space charge mode (PSC), characterised by a strong cathode fall as occurs in an unmagnetised glow discharge, to a negative space charge mode (NSC) characterised by a broad anode fall. The reason for the transition to the NSC mode is the strongly reduced (according to classical theory) transport of electrons across the magnetic field in a low pressure, strongly magnetised plasma. These two modes of the magnetised discharge have been discussed by Thornton and Penfold (1978).

There is little conclusive experimental evidence for the NSC mode. The cathode fall is always observed in planar magnetron experiments, even at very low pressures (Rossnagel and Kaufmann 1986, Gu and Lieberman 1988). Experiments by Yeom et al. (1989) with a cylindrical magnetron with pressures and magnetic fields similar to those considered in this paper and in the PIC simulation study (van der Straaten et al. 1997) showed a distinct cathode fall and no anode fall over the entire range of discharge parameters. Langmuir probe measurements in a cylindrical magnetron were also reported by van der Straaten et al. (1997) with the same discharge parameters as used in the simulation, but the results did not agree with the simulation results in that no anode fall was observed at low pressures and high magnetic fields. However, Hayakawa and Wasa (1965) reported the existence of a stable discharge operating in what appeared to be the NSC mode. The discharge featured a broad anode fall for a magnetic field strength greater than 4kG, which is considerably higher than the field strength predicted by the fluid model and the simulations (≈ 100kG) for the onset of the NSC mode. In order to explain the persistence of the cathode fall in the experimental results it would be necessary for the electron transport across the magnetic field, at low pressures and high magnetic field strengths, to be considerably higher than is predicted by the classical transport coefficients. It has been postulated (eg Sheridan and Goree 1989) that turbulence or nonlinear coherent modes induced by instabilities in the partially ionized plasma in crossed electric and magnetic fields (Simon 1963) may increase the diffusion and drift of electrons, thus increasing their effective transport coefficients.

Dust macroparticles in a discharge are negatively charged, but are unmagnetized because of their high mass. The electrons are highly magnetized, and the ions have intermediate magnetization. This results in different transport rates of the different species across the magnetic field. Depending on the size of the magnetic field, and the relative charge on the different species, the dust grains can be the dominant current carrier. The space charge clouds near the electrodes will then be determined by the relative mobility of the different species. The two modes of the discharge will then be affected by the charge on, and the current carried by the dust grains. Features unique to the dust particles can also play a role in the structure of the discharge, such as the variable equilibrium charge on the grains, dependent on the local potential and species temperatures, the effect of gravity on the grain dynamics, and the rate of charging of the grains. The dust grains can also form an ordered structure, the dust-plasma crystal. A fluid model of the
The electrons have two components of drift velocity, $v_{Te}$ transverse to the magnetic field in the $x$-direction, and $v_{\perp e}$ perpendicular to both the electric field $E$ and to $B$, where

$$v_{Te} = -\frac{e}{m} \frac{E}{\nu^2 + \omega_c^2}$$

$$v_{\perp e} = -\frac{e}{m} \frac{E \omega_c}{\nu^2 + \omega_c^2}$$

(1)

where $E$ is the $x$-component of $E$ (negative in this case), $\omega_c$ is the electron-cyclotron frequency and $\nu$ is the collision frequency of electrons with background gas atoms. The resultant drift of the electrons is at an angle $\theta$ to the $x$-axis given by

$$\tan \theta = \frac{\omega_c}{\nu}. \quad (2)$$

The basic equations used are those of Davies and Evans (1980), modified to include the magnetic field and the dust. Thus we use Poisson’s equation in one dimension, i.e.

$$\frac{dE}{dx} = \rho/\epsilon_0 \quad (3)$$

where $\rho$ is the net charge density and $\epsilon_0$ is the permittivity of free space. This equation may be rewritten as

$$\frac{dE}{dx} = \frac{1}{\epsilon_0} \left( \frac{J_i}{v_i} + \frac{J_e}{v_{Te}} + \frac{J_d}{v_d} \right), \quad (4)$$

where $v_i$ is the ion drift velocity in the $x$-direction (negative in this case), $v_d$ is the dust grain drift velocity, and $J_i$, $J_e$ and $J_d$ are the ion, electron and dust current densities in the $x$-direction.

The dust current density is

$$J_d = n_d v_d Q_d = n_{d0} v_{d0} Q_d \quad (5)$$

where we assume a constant flux of dust particles, with initial density and velocity $n_{d0}$ and $v_{d0}$. The dust charge varies in the discharge due to the varying local potential.

Writing the total current density as $J = J_i + J_e + J_d$, and assuming $|v_i| \ll |v_d|$, we have

$$\frac{dE}{dx} = \frac{J}{\epsilon_0 v_i} \left[ 1 - \left( 1 + \frac{|v_i|}{v_{Te}} \right) j_e \right] + \frac{n_d Q_d}{\epsilon_0} \quad (6)$$

where $j_e$ is the fraction of the total current density due to electrons. A boundary condition that can be applied is that the electron current at the cathode is due solely to secondary emission of electrons caused by ion impact on the cathode. The secondary emission coefficient $\gamma = j_e/j_i$ at the cathode is assumed known.

The second basic equation we use is the electron charge conservation equation, or ionization avalanche equation. The electrons drift through the background neutral gas at the angle $\theta$ to the $x$-axis and ionize the neutral gas molecules, and electron avalanches are formed. These avalanches are therefore also inclined at the angle $\theta$ to the $x$-axis. If the coordinate along this direction is $\zeta$, the normalized electron current density in this direction is $j_{\zeta e}$ and the electric field in this direction is $E_{\zeta}$, and the ionization equation may be written

$$\frac{dj_{\zeta e}}{d\zeta} = \alpha j_{\zeta e}, \quad (7)$$

where $\alpha$ is Townsend’s 1st ionization coefficient (Llewellyn-Jones 1966),

$$\alpha = AP \exp(-C(P/|E_{\zeta}|)^s) \quad (8)$$

where $A$ and $C$ are constants depending on the gas, $P$ is the gas pressure and $s = 1/2$ for a monatomic gas. Since $\zeta = x/\cos \theta$, $j_{\zeta e} = j_e/\cos \theta$ and $E_{\zeta} = E \cos \theta$, becomes

**FIG. 1:** The discharge geometry.
\[ \frac{dj}{dx} = a' j_e = \frac{AP}{\cos \theta} \exp \left( -C(P/|E| \cos \theta)^{1/2} \right) j_e. \quad (9) \]

The only difference in equation (9) to the unmagnetized case is therefore the replacement of the pressure \( P \) by the "effective pressure" \( P/\cos \theta \).

The ion mobility is assumed unaffected by the magnetic field, so we assume, as do Davies and Evans (1980), that

\[ |v_i| = k(|E|/P)^{1/2} \quad (10) \]

where \( k \) is a constant. This gives a good representation of the experimental ion drift (Ward 1962). However we note that this means that the ion and electron drift velocities have different \( E \) dependences, so \( r \) is not strictly independent of \( E \) as we have assumed so far. A dependence of \( r \) on \( E \) would prevent the application of the analysis used here, so we neglect it, noting that it could cause an error in our results at high magnetic fields.

The charge of a (negatively charged) dust particle is determined by the current balance equation

\[
\sqrt{\frac{\pi}{8n_i(z)}v_i(z)} \left[ 1 - \frac{2eQ_d(z)}{am_i\bar{v}_i^2(z)} \right] = n_0v_e \exp \left[ \frac{eQ_d(z)}{aT_e} + \frac{e\varphi(z)}{T_e} \right].
\]

\[(11)\]

### III. RESULTS

The equations have been solved for a number of cases, using the above prescription, to illustrate the effect on the discharge of increasing the magnetic field and the density of dust particles. The parameters used in the numerical examples are those of van der Straaten et al (1994), viz. \( d = 2.2 \text{cm} \), \( P = 5 \text{mTorr} \) and \( 50 \text{mTorr} \), and Argon gas, for which \( A = 29.22 \text{cm}^{-1} \text{Torr}^{-1} \), \( C = 26.6V^1/2\text{cm}^{-1/2} \text{Torr}^{-1/2} \), electron mobility for zero magnetic field \( \mu_e = 3 \times 10^2 \text{cm}^2\text{TorrVs}^{-1} \) and \( k = 8.25 \times 10^4 \text{cm}^3\text{Torr}^{-1/2} \text{Vs}^{-1} \). The corresponding electron collision frequency is \( \nu = 6 \times 10^9 \text{Ps}^{-1} \) where \( P \) is in Torr. The ratio of ion and electron mobilities in the unmagnetized gas is \( r_0 = 3.3 \times 10^{-3} \) (Ward 1962).

Figure 2 shows the electric field, ion velocity and space charge profiles for a pressure of 5mTorr. There is no magnetic field or dust.

In figure 5 a magnetic field is present, with \( \cos \theta = 0.2 \), but no dust is present, and the potential drop = 392V. The negative space charge region is now due to the magnetic field.

In figure 6 a magnetic field is present, with \( n_{d0} = 10^3 \), and the potential drop = 392V. The negative space charge region is more prominent, due to the dust. Dust charges negative near the NSC.
FIG. 3: The electric field, ion velocity, space charge and dust particle charge profiles. There is no magnetic field, but $n_{d0} = 10^3$.

In figure 7 a stronger magnetic field is present, with $\cos \theta = 0.5$, and dust is present with $n_{d0} = 10^3$, and the potential drop = 524V. The negative space charge region is wide. Dust charges positive over most of the discharge.

FIG. 4: There is no magnetic field, but $n_{d0} = 3 \times 10^3$.

IV. DISCUSSION AND CONCLUSIONS

A numerical solution of the electron, ion and dust fluid transport equations for a magnetized discharge has been developed, building on previous work for an unmagnetized steady-state glow discharge. Understanding the transport of charged particles across the magnetic field is important for modelling the operation of magnetron devices used in plasma processing for industry. The effects
of charge on the dust particles on the transition from a positive space charge mode to a negative space charge mode as the magnetic field is increased or the pressure is reduced has been demonstrated.

The presence of dust can create a negative space charge region near the anode, which enhances or mimics the effect of a magnetic field. If however the field is so strong that the ions are magnetized (future work), the dust grains may carry most of the current, which will enhance the positive space charge region.

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FIG. 7: A magnetic field is present, with cos \( \theta = 0.5 \), and dust is present with \( n_{d0} = 10^3 \).