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FORMATION OF ION-ION PLASMAS BY ELECTRON MAGNETIC FILTERING: 2D FLUID SIMULATION

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Abstract. A two-dimensional magnetized plasma fluid simulation is developed to investigate the electron magnetic filtering in an electronegative plasma and the formation of an ion-ion plasma (electron-free plasma). The model uses the three first moments of the Boltzmann equation, namely the continuity equation, the conservation of momentum approximated by the drift-diffusion equation and an energy equation for the electrons. The various reaction rates, mobility and diffusion constants (accounting for the presence of an axial magnetic field) are calculated from experimental cross-sections by using a Boltzmann solver. Preliminary results and applications to space plasma propulsion are presented.

1. FLUID MODEL

For every species s of the plasma, the time evolution of the density is described by the continuity equation

$$\frac{\partial n_s}{\partial t} + \boldsymbol{\nabla} \cdot \boldsymbol{\Gamma}_s = S_s, \tag{1}$$

where n_s is the density, $\boldsymbol{\Gamma}_s$ is the flux and S_s is the net source term (creation and loss) of the considered species s (electron, ion or neutral particle). The particle flux $\boldsymbol{\nabla} \cdot \boldsymbol{\Gamma}_s$ is given by the momentum balance

$$m_s n_s \left[\frac{\partial \boldsymbol{u_s}}{\partial t} + (\boldsymbol{u_s} \cdot \boldsymbol{\nabla})\boldsymbol{u_s}\right] = q_s n_s(\boldsymbol{E} + \boldsymbol{u_s} \times \boldsymbol{B}) - \boldsymbol{\nabla} P_s + \boldsymbol{f_s}\big|_{\boldsymbol{c}}, \tag{2}$$

where m_s, $\boldsymbol{u_s}$ and $\boldsymbol{\nabla} P_s$ are the mass, the average velocity and the kinetic pressure gradient of the species s, respectively, while $\boldsymbol{E}$, $\boldsymbol{B}$ and $\boldsymbol{f_s}\big|_{\boldsymbol{c}}$ are the electric field, the magnetic field and the rate of momentum transfer due to collisions with other species. The left hand side of the momentum equation ("inertial" terms) is neglected so that equation 2 can be approximated by the drift-diffusion equation

$$\boldsymbol{\Gamma}_s = \mathrm{sgn}(q_s)\mu_s \boldsymbol{E} n_s - D_s \boldsymbol{\nabla} n_s, \tag{3}$$

where $\mathrm{sgn}(q_s)$ indicates the sign of the charge of the considered species. The coefficients μ_s and D_s are the transport coefficients (mobility and diffusion coefficients) and are respectively given by $\mu_{s,\parallel} = |q_s|/(m_s \nu_s)$ and $D_{s,\parallel} = k_B T_s/(m_s \nu_s)$ along the magnetic field lines and by $\mu_{s,\perp} = \mu_{s,\parallel}/(1+\Omega^2)$ and $D_{s,\perp} = D_{s,\parallel}/(1+\Omega^2)$ across the lines, where $\Omega = |q_s|B/(m_s\nu_s)$.

In equation 3, $\boldsymbol{f_s}\big|_{\boldsymbol{c}}$ was taken equal to $m_s n_s \nu_s \boldsymbol{u_s}$ and isothermal conditions were assumed ($\boldsymbol{\nabla} P_s = k_B T_s \boldsymbol{\nabla} n_s$). The first term of equation 3 represents the flux due to the electric field (drift), while the second term represents the flux due to the density gradient (diffusion). Equation 3, that is derived from a local balance between the forces and the collisional momentum loss, holds rather well for conditions where the mean free path is small with respect to the plasma dimensions and gradient lengths.

The reaction rates and the transport coefficients are supposed to be functions of the reduced electric field (E/N) for heavy species and functions of the electron mean energy $\bar{\varepsilon}$ for electrons. The electron mean energy, $\bar{\varepsilon}$, which is obtained by solving the continuity equation for the electron energy

$$\frac{\partial n_\varepsilon}{\partial t} + \boldsymbol{\nabla} \cdot \boldsymbol{\Gamma}_\varepsilon = -e\boldsymbol{E} \cdot \boldsymbol{\Gamma}_e - L + H, \tag{4}$$

where the first term of the right-hand side is the Ohm heating, the second term is the power lost in the various collision processes and the last term represents inductive heating. On the left-hand side, n_ε is the electron density energy and the electron mean energy is then given by $\bar{\varepsilon} = n_\varepsilon / n_e$. The energy flux $\boldsymbol{\Gamma}_\varepsilon$ can be approximate by an expression similar to equation 3.

The transport equations are coupled to Poisson's equation to determined the electric field which depends on the space charge density, ρ

$$\boldsymbol{\nabla} \cdot (\epsilon \boldsymbol{E}) = -\nabla \cdot (\epsilon \boldsymbol{\nabla} \Phi) = \rho, \tag{5}$$

where Φ is the potential, and ρ is given by

$$\rho = \sum_s q_s n_s. \tag{6}$$

The equations above are implemented for a two-dimensional system in cylindrical coordinates. Any geometry with various materials (electrode, dielectric etc.) can be simulated. A chemistry module allows an unlimited number of species and reactions to be taken into account.

2. PRELIMINARY RESULTS

For the preliminary results presented below, an oxygen plasma in a 5 cm long and 20 cm diameter grounded cylinder was simulated. The various species O_2, O, O_2^+, O^- and 14 reactions between them were taken into account (momentum transfer, dissociative attachment, dissociation, ionization, electron impact detachment, dissociative recombination, mutual neutralization etc.). The magnetic field is uniform and parallel to the system revolution axis. The inductive power was 250 W with a heating profile maximum on the axis of the cylinder and exponentially decaying from the center of the discharge. Finally, the neutral pressure was 10 mTorr. In the following we investigate the effect of the magnetic field strength on the structure of the plasma.

Figure 1(a) shows the various radial steady-state charged species densities for a position $x = 2.5$ cm when the magnetic field is completely switched off. In this situation, we can observe the usual stratification of electronegative plasmas, where

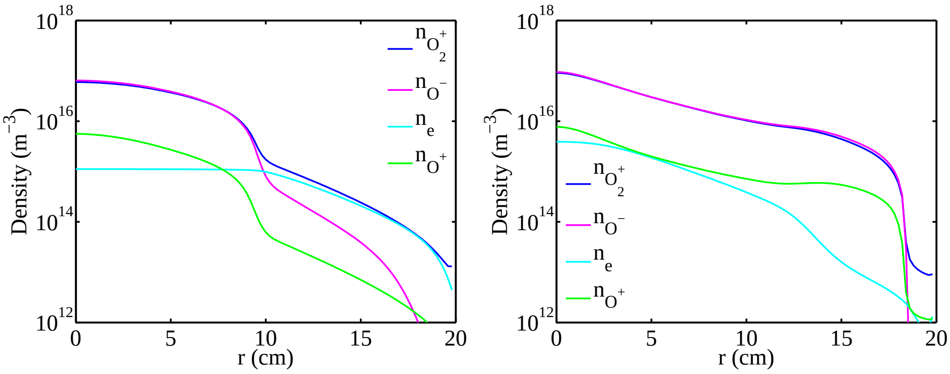

Figure 1: Density of the charged species along the radius r in the middle of the discharge (for$x = 2.5$ cm).

the core of the discharge is essentially electronegative (the two dominant species are the positive ions and the negative ions), while the periphery of the plasma is essentially electropositive (the two dominant species are positive ions and electrons). This is a well known result and it is attributed to the fact that negative ions are electrostatically confined in the core of the discharge by the ambipolar electric field of the plasma and the electrons are the only negative species being able to reach the walls.

Figure 1(b) shows the various radial steady-state charged densities for a position $x = 2.5$ cm when the magnetic field is fixed to 100 G. In this situation, the plasma remains highly electronegative along the whole radius (the dominant species are positive and negative ions and the electron density is at least an order of magnitude lower). This completely different situation is due to the fact that the mobility of the electrons is much smaller across the magnetic field lines than along them. As a result, electrons are confined in the region where they are mostly created i.e. in the center of the discharge (where they are the hottest).

Figure 2 shows the radial electronegativity (or negative ion fraction) $\alpha = n_-/n_e$ as a function of r for a position $x = 2.5$ cm. The blue and pink lines correspond to $B = 0$ and $B = 100$ G, respectively. This figure confirms what was just mentioned: for low or null magnetic field, the plasma presents a usual stratified structure with an electronegative core (α large) and an electropositive periphery (α almost null), while for a sufficiently large magnetic field strength, the plasma appears to be electronegative along the whole radius. In addition, for $r > 12$ cm the negative ion density becomes several orders of magnitude larger than that of the electrons, hence forming an ion-ion plasma at the periphery of the discharge.

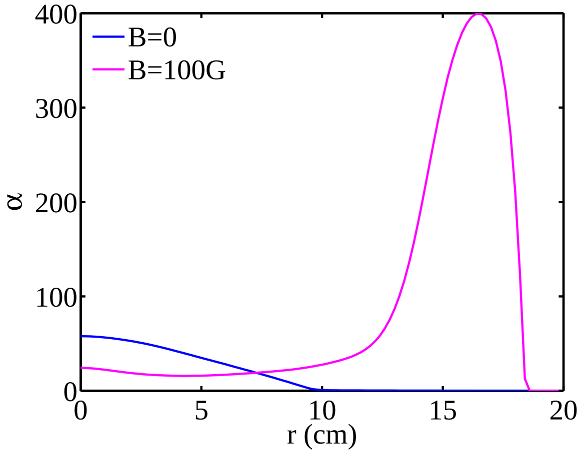

Figure 2: Negative ion fraction $\alpha = n_-/n_e$ along the radius r in the middle of the discharge (for $x = 2.5$ cm), for $B = 0$ (thick line) and $B = 100$ G (thin line).

3. CONCLUSION

We have developed a two-dimentional fluid simulation of a magnetized oxygen plasma. The preliminary results have shown the possibility to create an ion- ion (electron-free) plasma at the periphery of the discharge, hence confirming our earlier experimental results.