3D model of the magnetic filter region in tandem plasma sources

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Abstract. Based on a three-dimensional model developed within the fluid-plasma theory, the study presents results on the spatial structure of hydrogen discharges in the magnetic filter region of tandem plasma sources and an analysis on its formation by transport processes – particle and electron-energy fluxes – both across and along the magnetic field.

1. Introduction
The magnetic field is a tool for controlling the plasma parameters in different type of devices used in plasma physics applications. In the sources of negative hydrogen ions developed for nuclear fusion [1], the magnetic field appears as an electron cooler. It separates two regions in the source: regions of high- and of low-energetic electrons. This is considered as necessary for providing proper conditions for the two-step reaction of negative ions production by electron attachment to vibrationally-excited molecules. Because of coupling two regions, the source it known as a tandem source and the magnetic field is called a magnetic filter. The filter field is weak so that the electrons are magnetized and the ions are left unmagnetized. Transport processes across the magnetic field and filtering of the fast electrons based on the temperature dependence of the electron-electron collision frequency have been involved in the understanding of the filter operation since the early years of the modelling of the source [2]. A recent study [3], also developed within the fluid plasma theory and stressing transport processes across the magnetic field, has provided extended analysis based on a two-dimensional (2D) modeling of the filter operation. The model involves only the electron-neutral collision frequency in the charged particle and electron-energy transport coefficients. Reduced nonlocality in the electron heating combined with diffusion and thermal diffusion and completed by (E×B)- and diamagnetic- drift action outline the complicated structure of the discharge in the filter region, shown also in experiments [4].

This study extends the analysis in Ref. [3] towards a detailed three-dimensional (3D) description of the discharge structure. The difference in the fluxes across and along the filter field both in the charged-particle and electron-energy balances specifies the formation of different types of distribution of the plasma parameters in the three directions.

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2. Model description

Figure 1(a) shows the modeling domain, with the magnetic filter centered at \( z = 10 \text{ cm} \). The discharge is produced by a rf power input \( P_w \) with a maximum \( P_{w0} \) at \( z = 0 \) and a super-Gaussian profile in the \( z \)-direction (figure 1(b)). The magnetic field is homogeneous in the \( x \)- and \( y \)-directions and has a Gaussian profile along the \( z \)-direction. Thus, the plasma is produced in the region before the filter (i.e., close to \( z = 0 \)) and expands along the discharge vessel (i.e., in the \( z \)-direction) across the filter located in the \((x-y)\)-plane at \( z = 10 \text{ cm} \). The species in the hydrogen discharge considered are electrons, the three types of positive ions (\( \text{H}^+, \text{H}_2^+ \) and \( \text{H}_3^+ \)), and hydrogen atoms (H) and molecules (\( \text{H}_2 \)).

The initial set of equations numerically solved by employing COMSOL Multiphysics consists of the continuity equations, the electron-energy balance and the Poisson equation:

\[
\text{div} \Gamma_\alpha = \frac{\partial n_\alpha}{\partial t}, \quad (1a)
\]

\[
\text{div} \mathbf{Q}_e = P_w - P_{\text{coll}}, \quad (1b)
\]

\[
\Delta \phi = \frac{\varepsilon}{\varepsilon_0} \left( n_e - \sum_{\alpha=1}^{3} n_\alpha \right). \quad (1c)
\]

Here \( n_\alpha \), with \( \alpha \) denoting electrons (\( \alpha = e \)), the three types of positive ions (\( \alpha = i_l, \ l = 1-3 \)) and hydrogen atoms, are the particle densities, \( e \) and \( \varepsilon_0 \) are, respectively, the elementary charge and the vacuum permittivity and \( n_\alpha \) is the potential of the dc field in the discharge (\( E_{dc} = -\Delta \phi \)). The charged particle fluxes \( \Gamma_\alpha \) and the electron energy flux \( \mathbf{Q}_e \) are, respectively:

\[
\Gamma_\alpha = -Z_\alpha n_\alpha \mathbf{b}_\alpha \cdot \text{grad} \phi - \mathbf{D}_\alpha \cdot \text{grad} n_\alpha - \frac{n_\alpha}{T_\alpha} \mathbf{D}_\alpha^\gamma \cdot \text{grad} T_\alpha, \quad (2a)
\]

\[
\mathbf{Q}_e = -\mathbf{\hat{\chi}}_e \cdot \text{grad} T_e + \frac{5}{2} T_e \mathbf{\Gamma}_e. \quad (2b)
\]

In (2), \( \mathbf{b}_\alpha \) and \( \mathbf{D}_\alpha \) are, respectively, the mobility- and diffusion- tensors, \( \mathbf{D}_\alpha^\gamma = \mathbf{D}_\alpha \) is the thermal diffusion tensor and \( \mathbf{\hat{\chi}}_e \) is the thermal conductivity tensor [5]. Their components along the magnetic field (i.e., in the \( y \)-direction) are, respectively, \( b_{\alpha y} = e/\mu_\alpha \nu_\alpha \), \( D_{\alpha y} = T_\alpha/\mu_\alpha \nu_\alpha \) and \( \mathbf{\hat{\chi}}_e = (5/2) n_e D_{\alpha y} \) whereas \( b_\alpha = b_{\alpha y} \left[ 1+(m_\alpha \Omega_u/\mu_\alpha \nu_\alpha)^2 \right], D_\alpha = D_{\alpha y} \left[ 1+(m_\alpha \Omega_u/\mu_\alpha \nu_\alpha)^2 \right] \) and \( \mathbf{\hat{\chi}}_e = \chi_e \Omega_u \left[ 1+(m_\alpha \Omega_u/\mu_\alpha \nu_\alpha)^2 \right] \) are the corresponding components perpendicularly to the magnetic field (i.e., in the \( x \)- and \( z \)-directions). In addition, the components \( b_{\alpha y} = b_{\alpha y} \left[ 1+(m_\alpha \Omega_u/\mu_\alpha \nu_\alpha)^2 \right] \) and \( D_{\alpha y} = D_{\alpha y} \left[ 1+(m_\alpha \Omega_u/\mu_\alpha \nu_\alpha)^2 \right] \) account, respectively, for the \((\mathbf{E} \times \mathbf{B})\)- and diamagnetic-drifts; \( \mathbf{\hat{\chi}}_e = \chi_e \Omega_u \) is the thermal conductivity coefficient related to the diamagnetic drift. The other notations are as follows: \( T_e \) is the electron temperature, \( \Omega_u = eB/m_e \) are the gyro-frequencies and \( m_\alpha \) and \( \mu_\alpha \) are the mass and the reduced mass in elastic collisions with neutrals with frequency \( \nu_\alpha \), the latter specified by \( \mu_\alpha \nu_\alpha = \sum_j \mu_{\alpha j} \nu_{\alpha j} \) with \( j \) denoting atoms and molecules; \( Z_\alpha = \pm 1 \) for positive ions and electrons. The flux of the hydrogen atoms is a diffusion flux and the density of...
the molecular component is determined by the equation of state. In 1(a) \( \delta n_\alpha / \delta t \) describes the production and the losses of charged particles and hydrogen atoms, and \( P_{\text{coll}} \) in 1(b) summarizes the electron energy losses in collisions. The boundary conditions are for the fluxes at the walls where a zero-potential is assumed (metal walls). For more details see [3].

3. Results and discussions
The results presented here are for discharge vessel size \( 2L_x = 2L_y = L_z = 20 \text{ cm} \), maximum value of the magnetic field \( B_0 = 20 \text{ G} \), power density applied \( P_w = 10^4 \text{ W/m}^3 \), widths \( \sigma_B = 1.581 \text{ cm} \) and \( \sigma_p = 4.729 \text{ cm} \) of the \( B \)- and \( P_w \)-profiles and gas temperature \( T_g = 300 \text{ K} \). For the gas-pressure \( p = (5-10) \text{ mTorr} \) considered, the mean free paths of the charged particles are smaller then the dimensions of the discharge vessel, justifying applicability of the drift-diffusion approximation.

![Figure 2](image1)

Figure 2. Spatial distribution of the electron temperature in the \((x-z)_{y=0}\) (a), \((y-z)_{x=0}\) (b) and \((x-y)_{z=10 \text{ cm}}\) (c) planes.

The discharge structure is illustrated by the distribution of the electron temperature \( T_e \) (figure 2) and density \( n_e \) (figure 3) in the \((x-z)_{y=0}\), \((y-z)_{x=0}\) and \((x-y)_{z=10 \text{ cm}}\) planes obtained at \( p = 8 \text{ mTorr} \). A complicated structuring of the discharge due to the spatial interplay of particle- and electron-energy fluxes across the magnetic field replaces the smooth spatial variation of the plasma parameters (smooth decrease of \( n_e \) towards the walls and almost constant \( T_e \), due to comparatively high electron density combined with comparatively long mean free path, resulting in high thermal conductivity), well known for plasmas without magnetic field and shown here by the changes along the magnetic field (the y-direction) in figures 2(b), 2(c), 3(b) and 3(c).

![Figure 3](image2)

Figure 3. The same as in figure 2 but for the plasma density.

Starting with a slight variation of in the region of the rf power deposition at \( z = 0 \), \( T_e \) drops sharply in the \( z \)-direction (figures 2(a) and 2(b)) due to the reduction of the thermal conductivity coefficient across the magnetic field. The result is a reduced electron energy flux and, thus, reduced nonlocality of the electron heating. The axial drop of \( T_e \) drives the thermal flux in the \( x \)-direction which is related to the diamagnetic drift and leads to an increase of \( T_e \) in the \((+x)\)-direction (figures 2(a) and 2(c)). The latter drives a thermal flux again related to the diamagnetic drift, but now in the \( z \)-direction which
leads to electron heating behind the filter and formation of a groove in the filter region (figure 2). Thus, the reduced – by the filter field – electron-energy flux and thermal fluxes related to the diamagnetic drift are responsible for the electron cooling by the filter with formation of a minimum of \( T_e \).

The changes of \( n_e \) caused by the magnetic field (figure 3) are not so drastic as those of \( T_e \). A formation of a maximum of \( n_e \) in the filter region is the main effect of the magnetic field. It results from simultaneously acting thermal diffusion and diffusion: Thermal diffusion related to the axial gradient of \( T_e \) drives the electrons along the discharge (in the \( z \)-direction) and the reduced – by the filter field – diffusion permits the accumulation of electrons in the filter region (figures 3(a) and 3(b)). Therefore, the filter operation, involving strong reduction of \( T_e \), is an example of the importance of the thermal diffusion that usually appears to be smaller than the diffusion.

Figure 4.

![Figure 4](image)

**Figure 4.** Changes in the axial profiles (at \( x = 0, y = 0 \)) of the electron temperature and density as the gas pressure is varied.

Figure 4 shows the changes in the axial variations of \( T_e \) and \( n_e \) under varying gas pressure. With the increase of \( p \), \( T_e \) and its axial gradient in the filter region decrease and the maximum of \( n_e \) there becomes less pronounced. This is in agreement with the results of probe diagnostics along the discharge axis [4].

4. Conclusions

The analysis of the results of the 3D model of the magnetic filter operation in the sources of negative hydrogen ions, developed for describing the complete plasma structure in the filter region in the source, emphasizes the formation of a minimum of the electron temperature and a maximum of the electron density in the filter region. The former is due to suppressed – by the magnetic field – electron energy flux causing a drop in the electron temperature and consequent action of thermal fluxes related to the diamagnetic drifts, and the latter is formed by thermal diffusion and diffusion fluxes. Accounting for the negative ions and, respectively, for the vibrationally excited molecules, including rovibrational excitation [6], would be the further extension of the work.

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