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Neutral gas depletion mechanisms in dense low-temperature argon plasmas

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Abstract

Neutral gas depletion mechanisms are investigated in a dense low-temperature argon plasma—an inductively coupled magnetic neutral loop (NL) discharge. Gas temperatures are deduced from the Doppler profile of the 772.38 nm line absorbed by argon metastable atoms. Electron density and temperature measurements reveal that at pressures below 0.1 Pa, relatively high degrees of ionization (exceeding 1%) result in electron pressures, $p_e = kT_e n_e$, exceeding the neutral gas pressure. In this regime, neutral dynamics has to be taken into account and depletion through comparatively high ionization rates becomes important. This additional depletion mechanism can be spatially separated due to non-uniform electron temperature and density profiles (non-uniform ionization rate), while the gas temperature is rather uniform within the discharge region. Spatial profiles of the depletion of metastable argon atoms in the NL region are observed by laser induced fluorescence spectroscopy. In this region, the depletion of ground state argon atoms is expected to be even more pronounced since in the investigated high electron density regime the ratio of metastable and ground state argon atom densities is governed by the electron temperature, which peaks in the NL region. This neutral gas depletion is attributed to a high ionization rate in the NL zone and fast ion loss through ambipolar diffusion along the magnetic field lines. This is totally different from what is observed at pressures above 10 Pa where the degree of ionization is relatively low ($<10^{-3}$) and neutral gas depletion is dominated by gas heating.

1. Introduction

Plasma uniformity over large areas has long been recognized as an important factor in processing reactors and is increasingly important with the desire for larger wafers. For the micro-electronics industry, plasma etching is based on synergistic effects of ion bombardment and reactive neutral species such as radicals and excited particles [1]. Excited metastable particle densities play an important role in both plasma sustainment, through two-step ionization, and also in plasma surface interactions. Etching rates and etch anisotropy are key parameters in technological devices motivating low-pressure high-density reactors. Whereas the homogeneity of ion bombardment has long been a topic of research, sometimes overlooked has been the spatial distribution of neutral reactant particles. Typical operation regimes of such low-pressure

discharges can reach ionization degrees up to several per cent [2, 3]. Relatively high electron densities can lead to elevated gas temperatures and thus of course depletion of the neutral gas (for example, see [4] and references within). Less research has concentrated on depletion through high ionization rates [5–11]. Low gas pressures in combination with high ionization degrees can result in an ‘electron pressure’, defined as $p_e = kT_e n_e$, exceeding the neutral gas pressure resulting in a depletion of the neutral gas density. It should, therefore, not be assumed that the neutral gas profile is uniform, in particular not in discharges where the electron pressure profile is non-uniform. There has been some recent theoretical investigation [6, 7] on this depletion phenomenon; however direct experimental measurements are lacking.

Here, we experimentally investigate the underlying mechanisms governing neutral species uniformity in one such

dense low-pressure plasma—a magnetic neutral loop discharge (NLD). We investigate depletion, through both gas heating and high ionization rates, and quantify the importance of each in different pressure regimes. Langmuir probe and Thomson scattering are employed to measure electron temperatures and densities to determine the effect of depletion through high ionization rates. Diode laser absorption spectroscopy on metastable argon atoms is used to measure metastable densities and gas temperatures. Neutral gas depletion in the region of the neutral loop (NL) is investigated by spatially resolved laser induced fluorescence (LIF) measurements on argon metastables. From these investigations we can draw conclusions regarding the relevance of both neutral depletion mechanisms, through elevated gas temperatures and high ionization rates.

2. Experimental set-up

A detailed description of the discharge design can be found in [2, 3]; a brief description is given here. Three coaxial coils, of different diameters, surrounding the chamber produce the desired magnetic field configuration for the creation of the NL [2]. The currents in the top and bottom coil flow in the same direction and the current in the middle coil is opposite in direction to the other two. This arrangement produces a quadrupole magnetic field configuration bent into a torus structure with a magnetic null along a ring in the torus—the so-called NL. An oscillating radio-frequency (rf) electric field is induced along this NL through a planar, four-turn, ICP antenna, of diameter 200 mm. The antenna is operated at 13.56 MHz and separated from the plasma by a quartz dome. The magnetic null ring is located just below the quartz dome, close to the ICP antenna for efficient plasma production. The discharge is primarily operated at low gas pressure (<1 Pa) with relatively high plasma densities. Various diagnostics are installed with direct access to the main plasma production region of the discharge, the NL plane.

A Langmuir probe system (Scientific Systems) is installed for electron temperature and density measurements radially resolved in the NL plane [3] up to RF powers of 1000 W. Due to comparatively high plasma densities and the relatively weak magnetic fields (of the order of millitesla) the electron Larmor radius is much greater than the sheath width around the probe, hence the magnetic field can be neglected in analysing the probe data. Measurements show that the electron energy distribution function (EEDF) is Maxwellian [2]. Above powers of 1000 W measurements can no longer be performed due to thermal heating of the probe tip.

Thus, a Thomson scattering system for measurements above 1000 W has been setup. It does not, however, provide spatially resolved information. In the NL, at powers below 1000 W, good agreement between Langmuir probe and Thomson scattering measurements is obtained. Details of the rather complex Thomson scattering system will be published elsewhere. A brief description of the essentials is given here.

A Nd:YAG laser providing a pulse energy of 600 mJ at 532 nm with a 50 Hz repetition rate is focused into the NL region for incoherent Thomson scattering measurements of

electron temperatures and densities. The scattered light is focused onto the entrance slit of a triple grating spectrograph (TGS) [12–14] and detected using an intensified CCD camera with high quantum efficiency (GaAs photocathode). The comparatively high laser power and the highly sensitive detection system in combination with the TGS allows very sensitive measurements with highly efficient stray light reduction (10^{-6}). The resulting signal to noise ratio allows measurements with a lower detection limit of 10^9 cm^{-3} . Raman scattering is used for a calibration of the diagnostic system allowing absolute electron density measurements.

The gas temperature is deduced from the Doppler profile of the 772.38 nm argon line ($\text{Ar}(1s_5-2p_7)$ in Paschen notation), absorbed by $\text{Ar}^*(^3\text{P}_2)$ metastable atoms, using an external cavity diode laser. $\text{Ar}^*(^3\text{P}_2)$ is the most populated excited state of argon and, as will be shown later, in our experimental conditions (large volume, low pressure and high-plasma density) it is populated by electron impact excitation of the ground state atoms and destroyed predominantly through collisions with electrons. With a typical electron density of 10^{18} m^{-3} , the lifetime of $\text{Ar}^*(^3\text{P}_2)$ atoms is short enough ($<10 \mu\text{s}$) to preserve their velocity distribution, i.e. that of the ground state argon atoms, when they are produced. The technique for measuring neutral temperatures in argon is described extensively in [15, 16]. Briefly, the frequency of the external cavity diode laser (Toptica DL100) is slowly scanned (at 50 Hz) around the absorption line centre. The total mode-hop free scan range is about 10 GHz. The laser beam is separated into three parts by a beam splitter. The first beam crosses the NLD and is detected with a photodiode. The second beam crosses a confocal Fabry–Perot interferometer, whose free spectral range is 0.375 GHz, and is detected by a second photodiode. The signal from this photodiode, which has intensity peaks every 375 MHz, acts as a reference for the calibration of frequency shifts. The third beam crosses an about 1 Torr argon reference cell (diameter = 2 cm, length = 20 cm), in which metastable atoms are produced by an about 1 mA, CW discharge, and is detected with a third photodiode. Due to the low input power, the gas in this reference cell remains at room temperature and its absorption signal acts as a reference for the control of the measured temperature. In order to avoid saturation phenomena [17], beams 1 and 3 are attenuated to about $10 \mu\text{W}$ before entering the plasmas. Finally, all three signals from the photodiodes are simultaneously recorded and averaged in different channels of a digital oscilloscope and then treated by a computer. The temperature T_g is deduced from the Doppler width of the recorded profiles γ_D , according to the relation:

$$\gamma_D(\text{FWHM}) = (2\sqrt{\ln 2}/\lambda_0)2\sqrt{k_B T_g/M}, \quad (1)$$

where λ_0 is the wavelength and M is the mass of argon. Figure 1 shows, as an example, treated absorption profiles from the NLD and reference cell. The Gaussian fit corresponds to 330 K in the reference cell and 860 K in the NLD, operated at $p = 0.05 \text{ Pa}$ and $P = 1900 \text{ W}$. The absolute density of $\text{Ar}^*(^3\text{P}_2)$ atoms can also be deduced from the total area of the absorption curve (see [15, 17]). For LIF measurements, the absorption signal from the reference cell was used to set

Figure 1. Absorption profiles with Gaussian fit for gas temperature determination from NLD (0.05 Pa, 1900 W) at 860 K and reference cell at 330 K.

the laser frequency at the centre of the 772.38 nm line. The laser beam entering the NLD chamber was no more attenuated (a few milliwatt power) to be in weakly saturated regime [17]. The optical system imaged the LIF light from the NL region onto an ICCD camera. A spectral filter (VariSpec CRI) located in front of the camera helped to isolate the 810.37 nm, $\text{Ar}(1s_4-2p_7)$, and reject the plasma emission at other wavelengths. The final LIF image of argon metastable atom density distribution has been deduced by subtraction of the image recorded when the laser beam was blocked from the image recorded in the presence of the laser beam. Assuming a constant gas temperature in the NLD volume, the intensity distribution of the LIF image provides the relative variation of the $\text{Ar}^*(^3P_2)$ atom density along the laser beam.

3. Results

We examine the implication of both neutral gas temperature and high ionization rate, hereafter referred to as depletion through electron pressure, on the depletion of neutral particles in the plasma.

Gas temperatures, determined from Doppler profiles of diode laser absorption measurements on metastable argon, show that the temperature increases—quite significantly—with both power (linearly) and pressure, see figure 2. Temperatures reach up to 1500 K at 5 Pa and 2000 W. Even at lower, more typical operating pressures of the NLD (a few tens of Pascal), temperatures of up to 1000 K can be reached. The typical assumption that in low-temperature plasmas the neutral gas is at room temperature is, therefore, clearly not justified under the observed conditions. Heating of the neutral gas must be taken into account when deducing the gas density.

Figure 3 takes the gas temperature into account, but not additional depletion due to electron pressure as will be discussed later, and shows the degree of ionization and electron pressure as a function of neutral gas pressure in an argon plasma at 1000 W. These were determined from Langmuir probe measurements of electron temperatures and densities. As expected, both the degree of ionization and electron pressure strongly increase with decreasing pressure. The degree of

Figure 2. Gas temperatures, determined from diode laser absorption spectroscopy, as a function of power for various pressures in the NLD.

Figure 3. Degree of ionization and electron pressure over neutral gas pressure as a function of pressure in an argon NLD at 1000 W.

ionization reaches values above a per cent, a regime where neutral depletion due to electron pressure is expected. In the NL region the electron pressure not only increases quite significantly with decreasing pressure but at relatively low pressures (<0.1 Pa) can even exceed the neutral gas pressure. In the following, we discuss the influence of various effects on neutral gas depletion in dense low-temperature plasmas.

The depletion through electron pressure D_e can be expressed in the following way [5, 6]:

$$\frac{n}{n_g} = 1 - D_e = 1 - \alpha \frac{p_e}{p}, \quad (2)$$

where n is the depleted neutral density, $p_e = kT_e n_e$ is the electron pressure and n_g is the neutral gas density deduced from the measured pressure p , assuming no electron pressure depletion and p is the total pressure. Balancing diffusion of neutrals into the region of depletion with ambipolar diffusion of the efficiently produced ions results in [5]: $\alpha = \mu_i/\mu_n$, where μ_i and μ_n are the ion and neutral mobilities, respectively. Case studies with numerical examples can also be found in [5]. Using the momentum equations of ions and neutrals predicts a pressure balance, $\alpha = 1$ [6]. This is equivalent to the simple

thermodynamic relation that the sum of electron and neutral gas pressure equals the total pressure that is assumed to be constant throughout the discharge. Both theoretical approaches assume the neutral gas to be at room temperature and the contribution from magnetic fields is neglected. Details of the influence of the magnetic field in the investigated NLD are discussed in appendix A. The analysis shows that the diamagnetic current, known from plasmas confined by magnetic fields, can under certain conditions reduce the effect of the electron pressure on the neutral gas pressure. A detailed quantitative analysis is, however, complicated due to the complex magnetic field structure in the NLD.

Depletion through electron pressure D_e and elevated gas temperatures D_g can be quantitatively combined in a total depletion D in the following way:

$$\frac{n}{n_0} = 1 - D \quad (3)$$

with

$$(1 - D) = (1 - D_e)(1 - D_g). \quad (4)$$

Here n is the depleted neutral gas density and n_0 is the undepleted neutral gas density, calculated from the measured pressure and assuming the neutrals at room temperature. Then $D = 0$ corresponds to no depletion and $D = 1$ to fully depleted, respectively. The gas temperature depletion D_g is defined through the following:

$$\frac{n_g}{n_0} = \frac{300}{T_g} = 1 - D_g, \quad (5)$$

where T_g is the gas temperature.

Figure 4 shows a plot of depletions due to gas heating and electron pressure at 1000 W of rf power (assuming $\alpha = 1$) and also the combined effect of both as a function of pressure. Depletion through gas heating is determined from measurements of the gas temperature, and depletion through electron pressure is calculated using measured electron densities and temperatures. The combination of both depletion mechanisms shows a minimum around 0.5 Pa. It can be observed that with decreasing pressure the gas temperature effect becomes less important while the influence of electron pressure becomes more dominant. At pressures below 0.05 Pa, the electron pressure even becomes the more important depletion mechanism. Similar dependences are observed with varying powers (figure 5). An interesting aspect is that the fractional contribution of the two depletion effects appear to be almost independent of power. This can be understood since both the gas temperature and the plasma density scale linearly with power. Therefore, the ratio of electron pressure and gas temperature should not be sensitive to power.

It has been observed that the spatially resolved electron pressure profile in the NLD is non-uniform [3]. This allows us to distinguish spatially between the two depletion effects. The electron pressure profile peaks in the NL, dips in the centre of the discharge and significantly drops to the edge of the antenna. In the investigated pressure regime, the gas temperature profile, on the other hand, can be expected to be a lot more uniform and relatively flat across the discharge

Figure 4. Depletion due to gas heating, electron pressure and total combined depletion of both effects as a function of pressure in NLD at 1000 W.

Figure 5. Depletion of the neutral particle density through electron pressure, gas temperature and combined as a function of power in NLD at 0.05 Pa.

diameter. Therefore, measuring the depletion of neutral particles spatially resolved allows us to distinguish between the two effects. Figure 6 shows spatially resolved LIF measurements of relative densities of argon metastables. The profiles are normalized at the edge of the NL region where it can be assumed that the depletion effect due to electron pressure is minimal, while at this position the depletion due to gas temperature is similar to that in the discharge centre. It can be observed that depletion increases towards the NL region where electron pressures reach their maximum value. Accordingly, this depletion significantly increases with increasing power. The depletion profile, in particular at the highest investigated power of 2000 W, reflects the electron pressure profile [3] with decreasing depletion outside the NL region. As outlined below, the observed profiles cannot be caused by gas temperature gradients. Excitation and depopulation, of the metastable state by electrons, balance and the degree of excitation depends, therefore, only on electron temperature. The electron temperature only slightly increases with power due to reduction of the neutral gas density. A rough estimation shows that at low pressures the ionization rate in the NL and the gas exchange rate are both of the same order

Figure 6. Normalized LIF signal from argon metastable atoms in NLD at 0.05 Pa.

(10^2 s^{-1}). This suggests that localized ground state density depletion can be caused by high ionization rates and fast ion loss through ambipolar diffusion [5] along the magnetic field lines.

Gas heating mechanisms to consider are e–Ar momentum transfer and Ar⁺–Ar charge transfer collisions, and heating through energetic neutrals resulting from surface neutralization of ions. In the first case, the mean free path of an argon atom through a cloud of 10^{18} m^{-3} electrons at $k_B T_e \approx 3 \text{ eV}$ is of the order of 1 mm [23]. However, due to the large mass difference, the kinetic energy gained by the argon atom within $\approx 10 \text{ cm}$ NLD dimensions (≈ 100 collisions) is only 0.01 eV and is hence negligible. Energetic neutrals produced through neutralization of energetic ions at surfaces can also contribute to neutral gas heating. Details of the energy balance during this neutralization process depend critically on the mass ratio of the impinging ions and the surface material [18–20]. In our case, with argon ions and stainless steel chamber walls, the influence on neutral gas heating can be expected to be small in comparison with charge transfer collisions. For charge transfer collisions, with a cross-section of $1 \times 10^{-18} \text{ m}^2$ [21], the mean free path of ions at 0.1 Pa and 750 K (neutral density $1 \times 10^{19} \text{ m}^{-3}$) is about 10 cm. As the ion density is almost homogeneous within the NL [3] the heating of argon atoms within the NL region is also more or less homogeneous. Given that at low kinetic energy, the Ar–Ar momentum transfer cross-section is about $3 \times 10^{-19} \text{ m}^2$ [21], at 0.1 Pa and 750 K, this would lead to a mean free path of about 30 cm for the ground state argon atoms. As this length is comparable to the plasma dimensions, we conclude that the neutral temperature gradient will not be significant. Thus, depletion due to gas heating is normalized out of the profiles.

In the following we discuss how the measured metastable density profile reflects the profile of neutral ground state density. A detailed kinetic treatment of this problem can be found in [22]. Under our conditions a simple balance equation model is justified. Metastable production, through electron impact excitation, is balanced with destruction of metastables through electron impact de-excitation, collisions with the

background gas as well as losses to the wall:

$$\frac{dn_m}{dt} = n_g n_e k_m(T_e) - n_m n_e k_e(T_e) - n_m n_g k_0 - n_m K_{\text{wall}} \equiv 0. \quad (6)$$

Examining the ratio of metastable density to ground state density we obtain the following:

$$\frac{n_m}{n_g} = k_m(T_e) \frac{1}{k_e(T_e) + \frac{n_g}{n_e} k_0 + \frac{K_{\text{wall}}}{n_e}} \approx \frac{k_m(T_e)}{k_e(T_e)} \propto k_m(T_e), \quad (7)$$

where k_m , k_e , k_0 are the rate coefficients for electron impact excitation into metastables, electron impact de-excitation of metastables and collisions with the background gas, respectively. The EEDF has been measured in the NLD and shown to be Maxwellian [2]. The different destruction terms of metastable atoms can be estimated. For T_e higher than 0.2 eV, the rate coefficient for electron impact quenching k_e is about $2 \times 10^{-13} \text{ m}^3 \text{ s}^{-1}$ [25]. Diffusion frequency is $K_{\text{wall}} = D_0/(n_g \Lambda^2)$, where $D_0 = 1.8 \times 10^{20} (T_g/300 \text{ K})^{0.5} \text{ m}^{-1} \text{ s}^{-1}$ [24] and $\Lambda = 0.1 \text{ m}$ is the fundamental diffusion length of the plasma chamber. The square root in D_0 accounts for the temperature dependence of the mean velocity of atoms. For a neutral density n_g ranging between 10^{19} and 10^{20} m^{-3} (0.1 and 1 Pa at 750 K) and a plasma density of $1 \times 10^{18} \text{ m}^{-3}$, K_{wall}/n_e ranges below $1.5 \times 10^{-15} \text{ m}^3 \text{ s}^{-1}$ and is therefore two orders of magnitude smaller than k_e . Quenching of metastables by three and two body collisions with argon atoms results in $(n_g/n_e)k_0 < 2 \times 10^{-20} \text{ m}^3 \text{ s}^{-1}$ [24, 25] and is also negligible. Since under the conditions of interest here the electron density is large, both diffusion and quenching by neutrals can be neglected and it can be assumed that electron quenching is the dominant destruction mechanism. Both electron impact excitation and de-excitation scale with electron temperature. However, the electron temperature dependence of electron quenching through low energetic electrons is much less pronounced than the excitation rate determined by energetic electrons. It can, therefore, be assumed that the electron quenching rate is almost constant in the investigated parameter regime. The metastable density is, therefore, a convolution of the ground state density and excitation rate governed by the electron temperature. $k_m = 3.7 \times 10^{-14} \exp(-15 \text{ eV}/k_B T_e) \text{ m}^3 \text{ s}^{-1}$ [25] for the excitation to the metastable state and $k_i = 2 \times 10^{-13} \exp(-5 \text{ eV}/k_B T_e) \text{ m}^3 \text{ s}^{-1}$ [25] for the ionization and $k_t = 2 \times 10^{-13} \text{ m}^3 \text{ s}^{-1}$ [25] for the transfer to the resonant state of metastable atoms by electron impact. The radiative lifetime of the resonant Ar^{*}(³P₁) state is a few nanosecond; however, due to resonant radiation trapping, the effective radiative lifetimes reach a few microsecond and consequently the density of Ar^{*}(³P₁) atoms becomes almost comparable to that of the metastable state [26, 27] and consequently the reverse process (electron impact transfer from ³P₁ to ³P₂), which has 5/3 times larger rate coefficient, partly compensates the depletion of the Ar^{*}(³P₂) state. Therefore, the overall depletion rate by population transfer must be smaller than k_t . A simplified assumption is to consider that the total population destruction of the Ar^{*}(³P₂) metastable state is given by $k_d = k_i + \rho(\%)k_t$, where $\rho(\%)$ is the effective percent contribution of collisional transfer to

Figure 7. Ratio of k_m/k_d as a function of electron temperature for different ρ (%).

Figure 8. Metastable density and ratio of metastable density to ground state density as a function of pressure.

the depletion of the metastable state. Figure 7 shows the ratio k_m/k_d versus T_e for different values of ρ (%).

Metastable density as a function of pressure is plotted in figure 8 (black squares). The metastable density is deduced from the diode laser absorption spectroscopy measurements, under the assumption of a homogeneous density. Deconvoluted with the ground state density and taking the gas temperature depletion into account, n_m/n_g is also plotted (grey circles) and reflects the typical dependence of the electron temperature on pressure [2]. Table 1 gives the values of this ratio, n_m/n_g , at various pressures and also the electron temperature deduced from figure 7, making the assumption that about 50% of the electron impact transfers to the 3P_1 state effectively contribute to the depletion of metastable states. The $k_B T_e = 2.15$ eV deduced at 1 Pa is very close to the 2.4 eV measured in the NL region [3].

In principle the ground state density could be calculated; however, the dependence on electron temperature and also the electron impact transfer contribution would need to be more accurately known. The excitation rate is a monotonically increasing function with electron temperature. Since the electron temperature peaks in the NL [3] it can be expected that the depletion of the ground state density is even more

Table 1. Values of k_m/k_d and electron temperature for different pressures.

P (Pa)	k_m/k_d	$k_B T_e$ (eV)
0.05	0.002 05	3.1
0.1	0.0013	2.8
0.2	0.0008	2.55
0.5	0.000 45	2.3
1	0.000 28	2.15
2	0.000 18	2
5	0.000 08	1.8

pronounced than for the metastable density. Of course direct measurements of the ground state density profiles would be desirable. We have, therefore, carried out preliminary TALIF measurements on ground state krypton. First results seem to support localized depletion of the ground state density. However, more detailed investigations are necessary. Nevertheless, the work presented here clearly shows that under certain conditions neutral gas depletion through high ionization rates can play an important role in low-pressure, low-temperature plasmas.

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Appendix A

In the following the influence of the electron and ion pressure on the neutral gas pressure in the presence of a magnetic field is discussed. The discussion is limited to an isotropic pressure tensor for the neutral gas. A more precise treatment based on an anisotropic pressure tensor is beyond the scope of this paper. Details on differences between an isotropic and anisotropic treatment can be found in [29] and references therein. The following calculation is based on applying the static momentum balance equations for all three species: the influence of the electron and ion pressure on the neutral gas pressure in the presence of a magnetic field can be calculated applying the static momentum balance equations for all three species:

$$-en_e(\vec{E} + \vec{u}_e \times \vec{B}) - \nabla p_e - \sum_{ce} = 0, \quad (8)$$

$$en_i(\vec{E} + \vec{u}_i \times \vec{B}) - \nabla p_i - \sum_{ci} = 0, \quad (9)$$

$$-\nabla p_n - \sum_{cn} = 0. \quad (10)$$

The terms $\sum_{ck}$ denote the sums of all collisional momentum transfer of the species k to the other two species. Charge exchange collisions between ions and neutrals can be included but the details are not of importance since here only the sum of all three equations matters. In the sum of all three equations, the collisional terms cancel out since in the total ensemble of

all particles momentum is conserved and cannot be lost by transfer between different species. Further, assuming quasi-neutrality, i.e. $n_i = n_e = n_p$, the electric field terms cancel out. This leads to

$$-en_p(\vec{u}_e - \vec{u}_i) \times \vec{B} - \nabla(p_e + p_i + p_n) = 0. \quad (11)$$

The term on the left-hand side of the cross product is the current density in the plasma. In general, this current density can lead to the generation of additional magnetic fields in the plasma B_p :

$$\nabla \times \vec{B}_p = -en_p(\vec{u}_e - \vec{u}_i)\mu_0. \quad (12)$$

Representing the local magnetic field through the sum of the external field B_e and the magnetic field generated by plasma currents yields

$$-en_p(\vec{u}_e - \vec{u}_i) \times \vec{B}_e + \frac{1}{\mu_0}(\nabla \times \vec{B}_p) \times \vec{B}_p - \nabla(p_e + p_i + p_n) = 0. \quad (13)$$

Only velocities vertical to the magnetic field contribute. In the case of the investigated NLD the vertical fluid velocity is given by the diamagnetic drift [28]:

$$\vec{u}_{e,i}^{(D)} = \pm \frac{\nabla p_{e,i} \times \vec{B}}{en_p B^2}. \quad (14)$$

Inserting the diamagnetic current and performing some vector algebra give the final result:

$$\frac{1}{\mu_0}(\vec{B}_p \cdot \nabla)\vec{B}_p - \nabla \frac{B_p^2}{2\mu_0} - \nabla_{\parallel}(p_e + p_i) - \nabla p_n = 0. \quad (15)$$

Here the gradient of the sum of electron and ion pressure is taken in the direction parallel to the external magnetic field. The second term represents the plasma magnetic field pressure gradient. In our set-up drift velocities in the order of 10^5 ms^{-1} have been measured using Thomson scattering and phase resolved optical emission spectroscopy (PROES) [28]. The ion drift is negligible due to the much lower ion temperature resulting from thermalization between ions and neutrals.

Using this drift velocity, $n_p = 10^{18} \text{ m}^{-3}$ and a typical scale length for magnetic field changes of $a = 1 \text{ cm}$ gives by the use of equation (12) a plasma magnetic field of $B_p \approx 0.2 \text{ mT}$. This field is comparable to the external field only very close to the neutral line where the external field vanishes. Outside this region the external field is typically one order of magnitude larger. Since the numbers used for the density and drift velocity represent upper values measured in our experiments which cannot be reached simultaneously one can conclude that the magnetic field generated by the diamagnetic current can be neglected except very close to the neutral line where no external field exists. With the above estimation, the magnetic field pressure is of the order of 10^{-2} Pa , which is negligible compared with the gas pressure except at the very low-pressure operation limit.

The first term in equation (15) describes the change in the plasma magnetic field along the direction of the field and this term is generally even smaller than the second term. This leaves the gradient of the charged particle pressure along the external magnetic field and the gradient of the neutral gas pressure to be balanced.

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