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Plasma drift in a low-pressure magnetized radio frequency discharge

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Abstract
A bright strip-like structure is observed in a low-pressure capacitively coupled radio frequency discharge with a magnetic field perpendicular to the plasma flow. The structure forms for a broad set of operating conditions in different gases. Measurements indicate that the strip acts as a path for the electrons to cross the magnetic field, which makes the discharge inhomogeneous and non-symmetrical. The strip intensity is strongly reduced when switching from a capacitive to an inductive discharge. A theoretical analysis shows that the strip results from a drift of the magnetized electrons perpendicular to the magnetic and electric fields, which is intercepted by the dielectric walls of the discharge tube. In capacitive mode, the drift is mostly governed by the electric field whereas the pressure dominates in inductive mode.

(Some figures may appear in colour only in the online journal)

1. Introduction

A magnetic barrier is a crucial element for the generation of negative ions in low-pressure plasma sources running with electronegative gases. Such magnetized sources find technological applications in various fields such as material processing for etching of microcircuits [1], neutral beam injection for controlled nuclear fusion [2] and space propulsion with the innovative PEGASES (Plasma propulsion with Electronegative GASES) thruster concept [3]. A magnetic field is used to trap electrons and to subsequently cool them down owing to collision events with heavy particles. A low electron temperature leads to a higher electron attachment rate, thus enhancing the production of negative ions [4–6]. The PEGASES thruster concept is one example of negative ion sources that rely on a transverse magnetic field to cool down and filter out electrons in such a way that an electron-free plasma, also called an ion–ion plasma, is obtained. In the PEGASES thruster, both positive and negative ions are created upstream of a magnetic barrier by way of an inductively coupled radio frequency (RF) discharge. Downstream of the magnetic trap, the resulting ion–ion plasma is accelerated to a high velocity through a set of alternately biased grids [3, 7–9]. The device therefore operates cathodeless. In addition, the ion density in the beam is relatively low due to the fast recombination of ion pairs to recreate the parent molecule, which limits the interaction between the host spacecraft and the charged particles.

While studying different magnetic field configurations for the PEGASES thruster trap using a capacitively coupled RF discharge, we have observed the formation of a stationary two-dimensional pattern in the region of high magnetic field strength, as can be seen in figure 1. The luminous structure was called a ‘strip’ according to its peculiar shape [10]. The strip was always present whatever the operating parameters and gas nature, making us believe that it originates from the intrinsic properties of a magnetized RF discharge. After describing the RF discharge assembly together with the magnetic trap and diagnostic techniques (section 2), this paper presents the characteristics of the strip in terms of electron parameters and ion current (section 3). In section 4, a physical mechanism is suggested to explain the origin and features of the strip from a theoretical analysis and recent numerical simulations. In addition, consequences on negative ion source design and beam generation are critically examined.

2. Experimental arrangement

2.1. RF discharge

The plasma source used to investigate the plasma strip formation and properties is outlined in figure 2. A three-turn planar spiral antenna is operated at 13.56 MHz. The antenna is

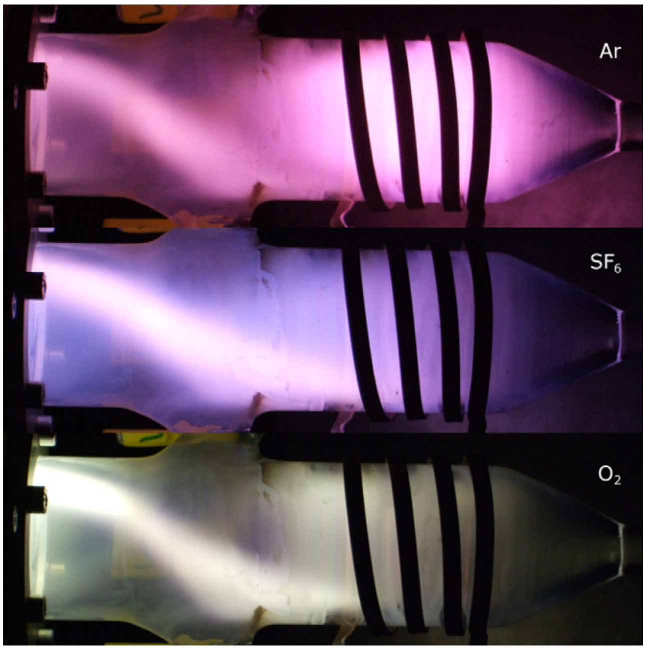

Figure 1. Side view of the strip-like structure in an RF discharge created in argon, SF$_6$ and oxygen (20 sccm, 500 G magnetic field and 250 W input power).

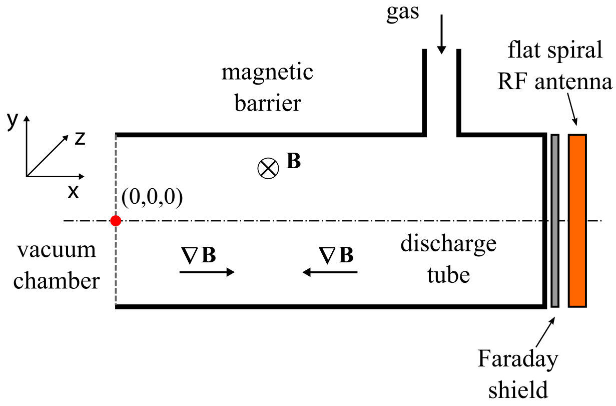

Figure 2. Layout of the RF discharge assembly for experiments with a magnetic barrier (***B*** goes into the page at the cross). This magnetic configuration corresponds to the picture in figure 1.

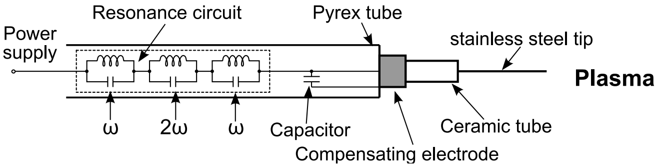

Figure 3. Sketch of the RF-compensated Langmuir probe used to determine electron parameters in the plasma discharge.

located at the end of a quartz tube 5 cm in diameter and 20 cm in length with a flat end to transmit the power into the gas. The tube offers visual access to the whole plasma discharge. A grounded Faraday shield, built according to the design by Mahoney to prevent azimuthal RF current from circulating, can be placed between the antenna and the discharge tube [11]. Without the shield, the RF power is capacitively coupled to the plasma. When the shield is introduced, the discharge runs in inductive mode. The gas is injected through a feed line, which is mounted on the side of the discharge tube. Two RF power supplies were available for these studies. An RF generator operating at a fixed frequency of 13.56 MHz was able to deliver power between 5 and 1000 W. A variable frequency amplifier was used to produce RF power with a maximum output of 200 W. The amplifier was driven by a sine wave function generator. To minimize the reflected RF power, an L-type matchbox was placed between the antenna and the power supply. The fraction of reflected power was typically below 15%. A magnetic field perpendicular to the direction of the plasma flow was created by placing several stacks of permanent neodymium magnets on either side of the discharge tube. Measurements and simulations of the axial distribution of the field showed that it is Gaussian with a full-width at half-maximum (FWHM) between 3 and 7 cm. The field strength was changed by varying the number of magnets, the number of stacks or the gap between the stacks and the tube. The maximum field intensity at the center of the tube was 1200 G. In experiments corresponding to figure 2 the magnetic south pole was placed behind the tube.

The discharge tube was mounted on a vacuum chamber 0.4 m in diameter and 0.75 m in length. The latter was evacuated with a 350 l s^{-1} nitrogen turbomolecular pump connected to a dry primary pump. The chamber had several optical windows, access ports and electrical feedthroughs. It could be equipped with a variety of probes and linear motion stages. A pressure down to 10^{-6} mbar could be reached without any gas flow. The background pressure at a gas flow rate of 20 sccm was typically 10^{-3} mbar depending on the gas.

2.2. *Diagnostic tools*

(i) A major challenge with Langmuir probe measurements in RF discharges is to overcome the high-frequency fluctuation of the plasma potential, which leads to a distortion of the I–V probe curve. Here a passively compensated Langmuir probe is used to measure the plasma parameters [12]. The probe was built after the design proposed by Chen [13]. It is outfitted with two chokes in series of which the resonance frequencies are 13.56 MHz and 27.12 MHz, respectively. The frequency corresponds to the main frequency and second harmonic frequency of the RF wave. The chokes isolate the probe tip by blocking high-frequency currents, therefore ensuring that the probe follows the sheath potential fluctuations. Moreover, in order to ensure that the probe tip draws enough current to fill the stray capacitances, a coupling capacitor connected to an external metal ring is added. This capacitor allows the collection of a large amount of charge. The probe tip is a stainless steel wire 5 mm in length and 0.125 mm in diameter. The tip is electrically insulated from the plasma by an alumina cover. A sketch of the probe is shown in figure 3. The voltage sweep and the resulting probe current measurement are performed using the ALP System™ manufactured by Impedans. The probe is installed on a motorized linear stage unit and placed at the exit of the discharge tube where the strength of the magnetic field is negligible.

(ii) The plasma potential V_p was also assessed using a floating emissive probe [14]. The emitting part of the probe consisted of an 8 mm long loop of thoriated tungsten wire 150 μm in diameter. The ends of the wire were mechanically crimped to copper wires and inserted into two parallel holes of an alumina tube 100 mm in length and 4 mm in diameter [15]. The filament was heated with a dc power supply up to the regime of electron emission. In the ideal case, the floating potential of a sufficiently emitting probe is equal to the plasma potential. In this case, the electron current is completely compensated by the emission current from the probe, therefore no net current flows through the probe and there is no sheath around the probe [16]. In fact, the sheath never fully vanishes. The probe voltage must then be corrected using the electron temperature to obtain a more accurate value of the plasma potential. An emissive probe has the advantage of being barely sensitive to a magnetic field, contrary to a Langmuir probe. In principle, an emissive probe can follow high-frequency fluctuations of the discharge. However, due to the capacitive part of the electrical circuit, our probe is limited to frequencies below 100 kHz. It is thereby employed to measure V_p across the large magnetic field region where the strip forms and develops.

(iii) A capacitive probe was constructed to determine the RF fluctuations of the potential inside the plasma [17]. This probe consists of an insulated wire, which is inserted into a copper cylinder 1 cm in diameter. There is no electrical contact between the wire and the cylinder. This probe works like a capacitor. It measures the fluctuations in the plasma without draining electrical charges in its surroundings. The probe is directly connected to the 50 Ω input of an oscilloscope to acquire the potential waveform. A calibration of the system is necessary to obtain the real value of the fluctuation amplitude at the measurement location.

(iv) The ion current is measured at the discharge tube exhaust by means of a planar Faraday probe equipped with a guard ring. The probe is made of graphite to withstand ion bombardment. The probe active area is 1 cm^2. The gap between the ring and the collector is 1 mm. The probe is negatively polarized at −50 V. The current is captured with a 10 Ω load to minimize the disturbance of the plasma sheath. A low-pass amplifier with a gain of 10 dB delivers the output signal.

3. Plasma characteristics with the strip

3.1. Capacitive discharge

As mentioned in section 1, a strip structure with its S-type shape was observed over a broad range of parameters with the discharge operated in capacitive mode, i.e. without the Faraday screen [10]. The first observation was made in SF_6, a strongly electronegative gas used for the PEGASES prototype [3]. Afterwards the strip was also seen when running the RF discharge with Ar, Xe, He, O_2 and N_2, see figure 1. The strip formation is therefore not connected with the nature (atomic versus molecular), mass and electronegativity of the gas. The gas flow rate was varied between 1 and 120 sccm in Ar, thus varying the pressure between 10^{-4} and 10^{-1} mbar. The frequency was tuned from 10 to 60 MHz and the transmitted power varied between 10 and 600 W. Modifying the discharge parameters did not influence the formation of the strip although the strip was brighter at higher power. When a transverse magnetic field is added to the RF discharge, whatever its magnitude between 50 and 1200 G, a luminous strip forms. At low field strength, only electrons are magnetized. At large strength, both electrons and ions are magnetized. A small increment in the inclination of the strip is observed while increasing the strength of the $\boldsymbol{B}$ field. The inflection point of the strip along the tube axis is always slightly downstream of the maximum of the field. The direction of the strip changes when the direction of the magnetic field is reversed. According to the sketch in figure 2, the strip is oriented upward, respectively downward, when $\boldsymbol{B}$ goes into the page, respectively comes out of the page.

Measurements were carried out with a compensated Langmuir probe at the exit of the discharge tube with argon as the working gas, see figure 4. In this figure the strip ends on the positive radial position side. Without a magnetic field, there is no visible structure in the plasma. The radial distribution of the electron density (n_e) and the electron temperature (T_e) is symmetrical about the tube axis as expected. When a transverse magnetic field is added, the radial profiles are no longer symmetrical. The electron density is much higher in the region where the strip exits. Similarly, T_e is larger inside the strip. The thickness of the strip can be deduced from the T_e radial profile. It is around 1 cm, in agreement with visual inspection. Note that figure 4 reveals the efficient cooling of an electron fluid across a magnetic barrier.

The ion current was also measured inside and outside the strip with the RF discharge operated with argon. Two planar probes were placed on either side of the discharge tube in such a way that one probe sees the strip while the other one sees the plasma bulk. The results are displayed in table 1. The ion current is larger by a factor of about three inside the strip. When the direction of the magnetic field is reversed, the strip horizontally flips but the ion current inside the filament stays unchanged.

3.2. Inductive discharge

A way of reducing the capacitive coupling of the RF power is to place a grounded Faraday shield between the coil and the plasma, see figure 2 [17]. The shield localizes the electrostatic field between the antenna without disturbing the induced electromagnetic field that drives the plasma. Note that the plasma no longer ignited itself when the shield was used, clear proof of good inductive coupling. A capacitive probe was used to measure the RF potential fluctuations with and without the shield in an argon plasma with a 500 G magnetic field and 300 W input power [17]. Inserting a shield has a great influence on the oscillation of the potential in the plasma. For instance at $x = 4$ cm (see figure 2 for the coordinate system) the peak-to-peak voltage amplitude drops from 188 V without, to 45 V

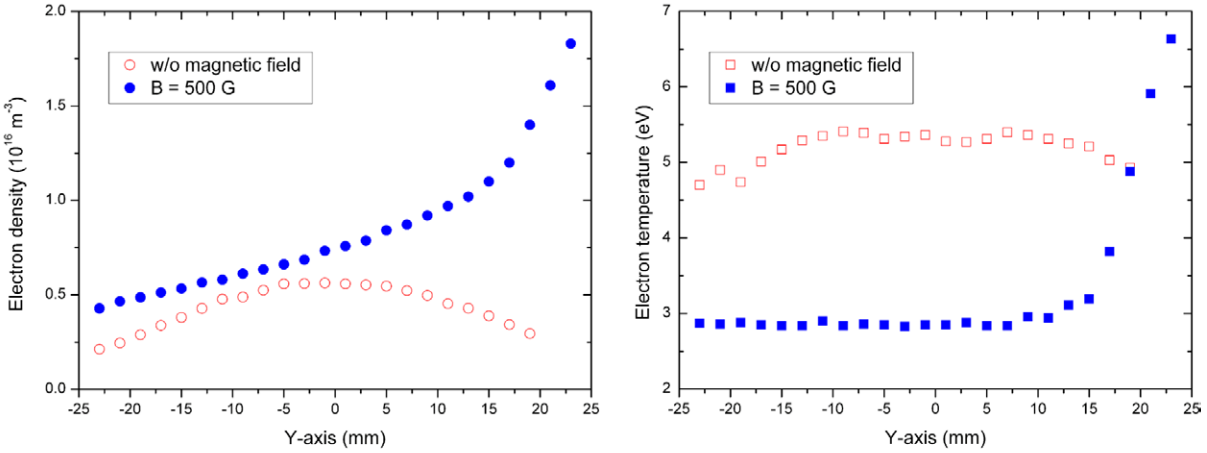

Figure 4. Distribution of the plasma density (left) and electron temperature (right) along the y-axis at the tube outlet with magnetic field and strip formation and without magnetic field (argon, 150 W).

Table 1. Ion current inside and outside the strip measured with two planar probes for the two strip directions (argon, 150 W).

	Upward strip (A)	Downward strip (A)
Top probe	1.91×10^{-4}	8.48×10^{-5}
Bottom probe	7.7×10^{-5}	2×10^{-4}

with a shield. A low fluctuation level indicates inductive power coupling.

When the magnets were placed around the discharge tube in inductive mode, no strip was formed whatever the operating conditions. Figure 5 illustrates the difference observed by the naked eye between a capacitive and an inductive discharge. Measurements performed with a compensated Langmuir probe at the tube exit in the case of the magnetized inductively coupled plasma revealed symmetrical electron parameter profiles contrary to what was observed in the capacitive mode, see figure 4. Similarly, planar probe measurements indicated that there is no radial dependence for the ion current when a Faraday shield is added.

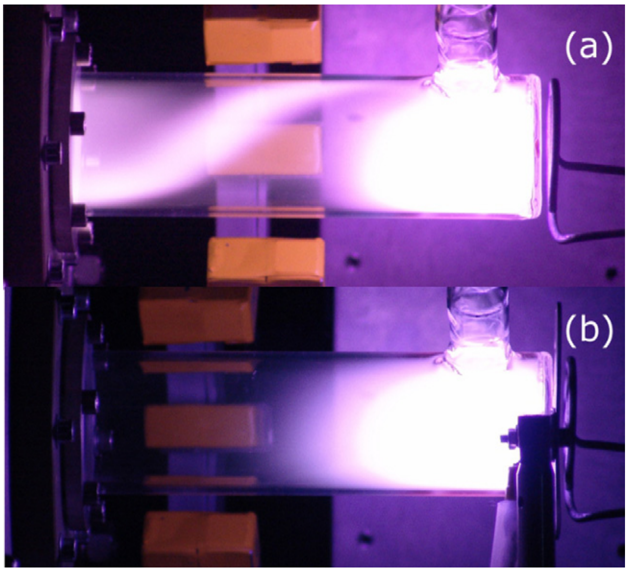

Figure 5. Picture of the RF plasma discharge with 20 sccm argon, 300 W input power, at a background pressure of around 10^{-3} mbar and 500 G magnetic field (*a*) without and (*b*) with a Faraday shield. The magnetic field points out of the page.

Measurements were also carried out with an emissive probe along the axis of the discharge tube for the four possible operating conditions, namely with and without a $\boldsymbol{B}$ field and with and without a Faraday screen. The results are shown in figures 6 and 7. The position $x = 0$ mm refers to the tube outlet. The peak of the $\boldsymbol{B}$ field distribution is located at $x = 80$ mm. The plasma potential development along the axis is displayed in figure 6. V_p is assumed here to correspond to the potential of the hot emitting probe [15]. The heating current is fixed to 4 A. The plasma potential is lower in the inductive mode. Without $\boldsymbol{B}$, V_p decreases when moving away from the region wherein the energy is deposited, i.e. the back section of the tube. With $\boldsymbol{B}$, V_p is low and it is independent of the axial coordinate in the inductive mode. The most interesting profile is, however, obtained in the capacitive regime. The plasma potential jumps suddenly when the probes goes throughout the strong magnetic field region, which means when the probe crosses the strip, see figures 1 and 5. When the probe moves outside the strip, V_p drops. The electron temperature T_e was also inferred from the emissive probe data. T_e can be estimated from the hot and cold probe potentials. In the latter case the potential is the floating one. In argon at low pressures, T_e is given by [18]

$$T_e = \frac{V_{\mathrm{hot}} - V_{\mathrm{cold}}}{5.4} \qquad \text{in eV}. \tag{1}$$

In figure 7, the cooling of the electron fluid due to the magnetic barrier is visible for the two discharge regimes. The rapid increase in T_e is a signature for the existence of the strip in capacitive mode. As previously explained, the strip is a region of large electron temperature. The emissive probe measurements show that the strip structure divides the plasma into two regions where the electron properties differ.

4. Origin of the strip

One way to understand the mechanism at the origin of strip formation is to consider the equation of motion for the electron

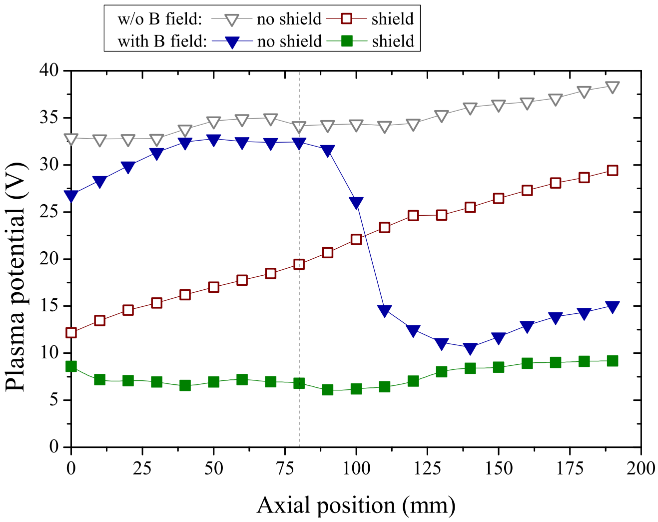

Figure 6. Plasma potential distribution along the discharge tube axis for four operating conditions. The position $x = 0$ mm refers to the tube exit. The dashed line indicates the $\boldsymbol{B}$ field peak.

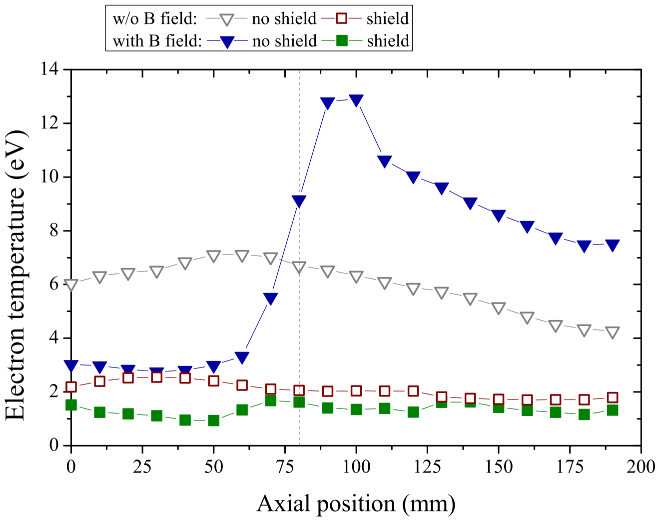

Figure 7. On-axis development of T_e for four operating conditions. The position $x = 0$ mm refers to the tube exit. The dashed line indicates the $\boldsymbol{B}$ field peak.

fluid in a magnetized plasma [19]. For simplicity we do not take ions into account. A more complete treatment of the problem is discussed below. Let us assume a steady state so that the convective derivative terms can be removed. In addition, the pressure p_e is also assumed to be isotropic. The electron fluid equation of motion then reduces to

$$en_e(\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B}) + \nabla p_e = 0, \tag{2}$$

where e is the elementary charge. Taking the cross-product of equation (2) with $\boldsymbol{B}/B^2$ and rearranging the terms, one obtains an expression for the electron drift velocity across the magnetic field. The drift velocity can be divided into two components: the $\boldsymbol{E} \times \boldsymbol{B}$ drift $\boldsymbol{v}_{\boldsymbol{E}\times\boldsymbol{B}}$ and the diamagnetic drift $\boldsymbol{v}_{\text{dia}}$:

$$\boldsymbol{v}_{\boldsymbol{E}\times\boldsymbol{B}} = \frac{\boldsymbol{E}\times\boldsymbol{B}}{B^2} \qquad \text{and} \qquad \boldsymbol{v}_{\text{dia}} = \frac{\nabla p_e \times \boldsymbol{B}}{en_e B^2}. \tag{3}$$

The electron drift current can then be written as

$$\boldsymbol{j}_e = -en_e(\boldsymbol{v}_{\boldsymbol{E}\times\boldsymbol{B}} + \boldsymbol{v}_{\text{dia}}). \tag{4}$$

A reasonable approximation in the case of our magnetized RF discharge is to consider that the three vectors $\boldsymbol{E}$, $\boldsymbol{B}$ and ∇p_e have only one component, namely E_x, B_z and $\partial p_e/\partial x$ according to the coordinate system in figure 2. Therefore, the electron current becomes

$$j_{e,y} = en_e \frac{E_x}{B_z} + \frac{\frac{\partial p_e}{\partial x}}{B_z}. \tag{5}$$

This equation indicates that the drift current is transverse to both $\boldsymbol{E}$ and $\boldsymbol{B}$ fields. This is in agreement with the strip direction in figure 1 as well as in figure 5. The strip, therefore, originates from the transverse drift of the electron fluid that is intercepted by the dielectric walls of the discharge tube. In other words, the drift does not form a closed loop in this situation, contrary to what is realized in, e.g., Hall thrusters [20]. This picture is supported by recent computer simulations carried out by Hagelaar and Oudini [21]. An interesting part of their work is the modeling and simulation of a low-pressure RF ITER negative ion source. With its magnetic filter, this source has a configuration similar to our inductive RF discharge. Numerical outcomes indicate that the electron flux creates a strip-like structure in the high $\boldsymbol{B}$ field region because the electron drift is confined by the chamber walls. Ion transport is included in the model. However, as ions are weakly magnetized in comparison with electrons, they do not contribute significantly to the formation of the strip.

The strip, with its typical S shape, therefore appears to be a general phenomenon that occurs in RF discharges with a transverse magnetic field for which the geometrical configuration does not permit the electron drift to close up. The strip is especially visible for a capacitively coupled RF discharge because of the existence of a strong electric field. In that case the appearance of the strip is mainly due to the electron $\boldsymbol{E} \times \boldsymbol{B}$ drift, wherein the electric field results from the capacitive coupling between the high-voltage part of the antenna and the grounded walls of the vacuum chamber. In inductive mode, the electric field is linked to the ambipolar diffusion, and pressure effects dominate [21].

5. Conclusion

In low-pressure discharges, the strip structure corresponds to an open drift of magnetized electrons that interacts with the reactor walls. In capacitive mode, the strip lights up due to collisions between the hot electrons and the gas particles. Light is emitted when atoms de-excite. Electrons are not hot enough in inductive mode to create a large amount of visible radiation. The origin of hot electrons, however, remains an open question. They could be heated locally in the strip, but the mechanism at work has to be identified, or they are just hot electrons from the upstream region crossing the magnetic barrier. Although it is always present, the strip intensity depends on the discharge features in terms of field strength and gradients. The strip is of course a path for electrons, as well as energy, to escape the magnetic barrier. Moreover, the interaction between the strip and walls creates losses. As a consequence, the strip not only leads to an inhomogeneous and asymmetrical plasma, which can affect ion extraction and acceleration processes, but it also reduces the efficiency of the source, e.g. in terms of negative ion yield, since the magnetic confinement becomes less efficient. For instance, plasma drift with strip formation in the filter of the negative ion source for neutral beam injection in controlled nuclear fusion is certainly at the origin of the observed nonuniformity in the extracted ion beam [22].

Acknowledgments

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