Plasma drift in a low-pressure magnetized RF discharge

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A bright strip-like structure has been observed in a low-pressure 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. The strip results from the E×B drift of the plasma that is intercepted by the dielectric walls of the discharge tube. Measurements indicate that the strip acts as a path for the electrons to cross the magnetic field. The strip intensity is strongly reduced when switching from a capacitive to an inductive discharge. That indicates the strip characteritics are mostly governed by the electric field properties within the magnetic barrier.

A magnetic barrier is a crucial element for the generation of negative ions in plasma sources running with electronegative gases. The 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 [1]. The PEGASES thruster concept is one of the numerous example of negative ion sources that rely on a transverse magnetic field to cool down and filter out electrons. The PEGASES thruster is an attractive new type of electric propulsion device in which an ion-ion plasma is accelerated to a high velocity through a set of biased grids [2]. 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 plume. While studying different magnetic field configuations for the PEGASES thruster, we have observed the formation of a stationary two-dimensional pattern in the region of high magnetic field strength, see Fig. 1a. The luminous structure was called a “strip” according to its peculiar shape [3].

The plasma source used in this work is outlined in Fig. 2. A three-turn planar spiral antenna is operated at 13.56 MHz. The antenna is located at the end of a 5 cm in diameter quartz tube with a flat end to transmit the power into the gas. A Faraday shield built after the design described by Mahoney, can be placed between the antenna and the discharge tube. The gas is injected through a feed line which is mounted on the side of the discharge tube. A magnetic field, perpendicular to the direction of the plasma flow, can be applied by placing permanent neodymium magnets on either sides of the discharge tube. In the experiments the magnetic north pole was placed behind the tube (see Fig. 2). The tube is mounted to a vacuum chamber equipped with a turbumolecular pump, which can sustain a background pressure in the order of 10^{-3} mbar at a gas flow rate of 20 sccm in argon. A Langmuir probe, which is passively compensated for the RF frequency with chokes, has been used to measured quantities like n_e, T_e and V_p. The probe was 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.

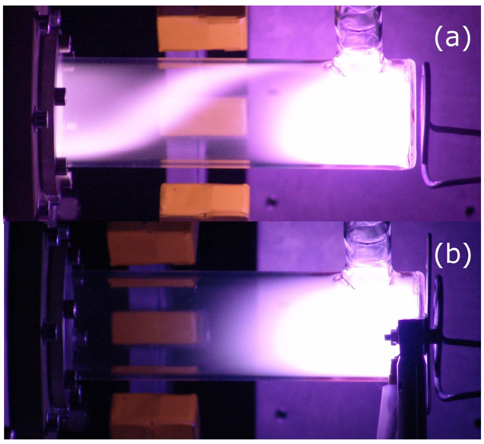

Fig. 1 Pictures of the RF discharge with 20 sccm argon, 300 W input power, at a background pressure of around 10^{-3} mbar and 500 G magnetic field without (a) and with (b) a Faraday shield. The strip is clearly visible in case (a).

The strip structure has been observed over a broad range of discharge parameters [3]. The first observation was made in SF_6. Later the strip was also seen during experiments in Ar, Xe, He, O_2 and N_2. The strip formation is therefore not connected with the nature (atomic vs molecular), mass and electronegativity of the gas. The gas flow rate has been varied between 1 and 120 sccm in Ar, thus varying the pressure between 10^{-4} mbar and 10^{-1} mbar. The frequency has been tuned from 10 MHz to 60 MHz and the transmitted power

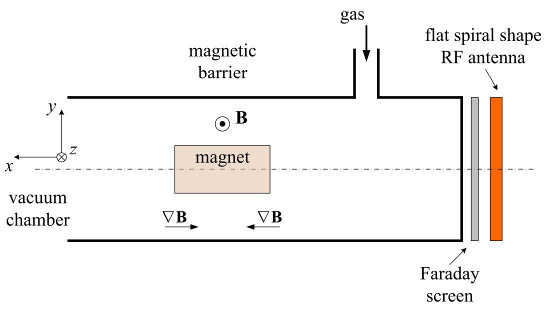

Fig. 2 Layout of the quartz tube with the magnetic field, the planar RF antenna and the Faraday shield.

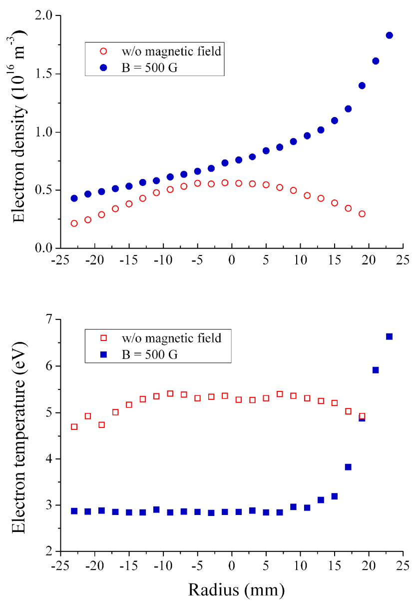

Fig. 3 Radial distribution of n_e and T_e in Ar at the tube outlet with magnetic field and strip formation and without a magnetic field.

varied between 10 W and 600 W. Modifying the discharge parameters did not influence the formation of the strip and its shape although the strip was brighter at higher power. An increment in the inclination of the strip could also be observed by the naked eye while increasing the strength of the magnetic field from 50 G up to 1200 G. Measurements carried out with a Langmuir probe at the exit of the tube, see Fig. 3, indicate that the strip is a region of large electron density and high electron temperature. The ion current is also larger within the strip [4].

Experiments indicate that the appearance of the strip originates in the E×B 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. The electron drift current in the y direction reads:

$$j_{e,\text{drift}} = -en_e\mathbf{v}_e = -en_e\frac{\mathbf{E}\times\mathbf{B}}{B^2} \approx -en_e\frac{E_x}{B_z} \qquad (1)$$

With our standard setup the electric field is due to the capacitive coupling between the high-voltage part of the antenna and the grounded walls of the vacuum chamber (the ambipolar field is negligible in comparison). A way of reducing the capacitive coupling is to place a Faraday shield between the antenna and the discharge tube to force the inductive mode [5]. Inserting a shield has indeed a great influence on the plasma, as can be seen in Fig. 1b. The generation of the plasma now happens in the first few centimeters of the tube and no more strip is visible by the naked eye within the magnetized region. A large capacitive probe plunged into the plasma shows the amplitude of the RF induced oscillations is greatly reduced with the shield, which indicates an inductive coupling is achieved [4]. Besides, measurements along the tube axis with a floating emissive probe reveal a smooth decrease of V_p from the upstream plasma production area to the tube exhaust without the characteristic signature for the strip, i.e. a jump in V_p [4].

The strip-like structure is especially visible under our discharge conditions because of the existence of a strong electric field in capacitive mode. However, the strip appears to be a general phenomenon that occurs in all types of magnetized discharges wherein the configuration permits an E×B drift without a closed loop, as recently demonstrated by means of computer simulations [5]. 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 plasma, which can affect ion extraction and acceleration, but it also reduces the efficiency of the plasma source in terms of energy conversion and negative ion production yield.

References

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