SPECTROSCOPIC INVESTIGATION OF A LOW-TEMPERATURE PLASMA IN MAGNETIC FIELD

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Introduction

The flow of the plasma in a non-homogeneous magnetic field is a very important subject in the high-temperature fusion plasma, where it is essential for the plasma confinement. There is also much interest in the case of the behavior of the low temperature plasma in a magnetic field, which is very important in the development of plasma thrusters. In thrusters, the magnetic field is used for separating the electrons from ions and for accelerating the ions (if it is not already essential for creation of the plasma, as in the helicon device).

One of the novel approaches to the plasma propulsion is the PEGASES project, where the plasma containing only positive and negative ions is to be used [1]. In this case, plasma is created in the helicon device, and the electrons are filtered out of it by the magnetic barrier. This paper features the simplified version of Pegasus device, with RF plasma source and radial magnetic barrier, proposed for confining the electrons inside the antenna region.

Experimental setup

The experimental setup consists of a vacuum tank pumped by a main dry pump and turbomolecular one with the minimum pressure of approximately 10^{-5} mBar and the plasma source attached to one of the ends of the tank. The plasma source consists of a 5 cm diameter and 20 cm length quartz tube with the 4-coil antenna around about 6 cm of the tube. Gas tubes are attached to the end of the quartz tube, so the gas flows through the plasma region in the direction of the vacuum tank due to the gradient of pressure. The antenna is connected to the power supply (RF generator and amplifier) by a matchbox which adjusts the coupling between antenna and plasma to improve the power transfer into the plasma. The parameters are as following: 100-200 W RF power, coupling up to 90%, with frequency between 12 and 16 MHz. Plasma can be created using many gases, those used were argon, helium, air and SF_6. Pressure in the tank during the plasma operation can be between 10^{-4} and 10^{-2} mBar, but in most cases presented here the pressure was around 10^{-3} mBar.

The spectra were recorded by a computer-controlled small spectrometer of 1 nm resolution, with optic fiber transmitting the light from the plasma to the spectrometer. The integration time of the spectrometer had to be long to average out the disturbances arising from the interaction of the RF field with the equipment.

Magnetic traps were tested in many positions and the main idea was to put the traps both before and after (in the direction of the gas flow) the antenna, but the interesting feature of the plasma appeared in the trap between the antenna and the vacuum tank.

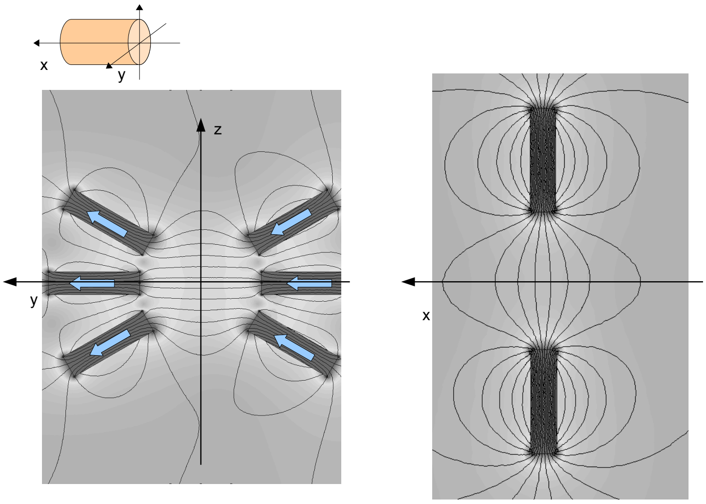

Figure 1: Configuration of the magnetic field in the trap.

Magnetic field configuration

The magnetic trap was built on the circular aluminum support to which six piles of strong neodymium magnets were attached. The magnetic field of this trap is presented in fig 1. The strong field in the direction transverse to the plasma cylinder forms a barrier that should stop the electrons from escaping the antenna and let the ion-ion plasma be produced in the after the trap region (when the working gas is SF_6, so the ion-ion plasma can be produced at all). The field is relatively uniform in the middle of the trap, but the gradients exist both in the axial as in radial directions. The strongest gradients are in the axial direction (denoted in figures as x), where the field drops from around 1700 Gauss to 0 on the distance of several centimeters.

Stripe mode

It appeared, that the plasma in the presence of the magnetic trap can be in two modes - in one of them, the plasma is really trapped before the maximum of the magnetic field, and in the other the plasma flows through the trap, compressed in the flat stripe positioned diagonally from the lowest point of the quartz tube to the highest. The angle of the stripe depends on the axial gradient of the magnetic field and the direction (from up to down or from down to up with the respect to the plasma flow) depends on the direction of the magnetic field in the trap.

In the trap all the visible plasma is very much affected by the magnetic field, but as the magnetic field can affect easily only the charged particles, it suggests, that the emission from the plasma is created in the processes involving charged particles - either by exciting the emitters by collisions with electrons concentrated in the strip or in the more complex three-body processes (charge exchange, recombination or reattachment).

The motion of the charged particles in the nonhomogeneous magnetic field in the plasma can be divided into two parts - the basic gyro motion around the magnetic field lines and the much slower diffusion due to the magnetic field gradients, described by the equation:

$$\vec{v_B} = \vec{v_R} + \vec{v_\nabla} = (v_\parallel^2 + \frac{1}{2}v_\perp^2)\frac{\vec{B}\times\nabla B}{\omega_g B^2} \tag{1}$$

where the $v_\parallel$ and $v_\perp$ are the particle velocity along and across the field lines and ω_g is the gyro frequency of the particle motion. This velocity is visibly independent on the particle mass, so in the equilibrium plasma the velocity should be the same for ions and electrons and differ only in

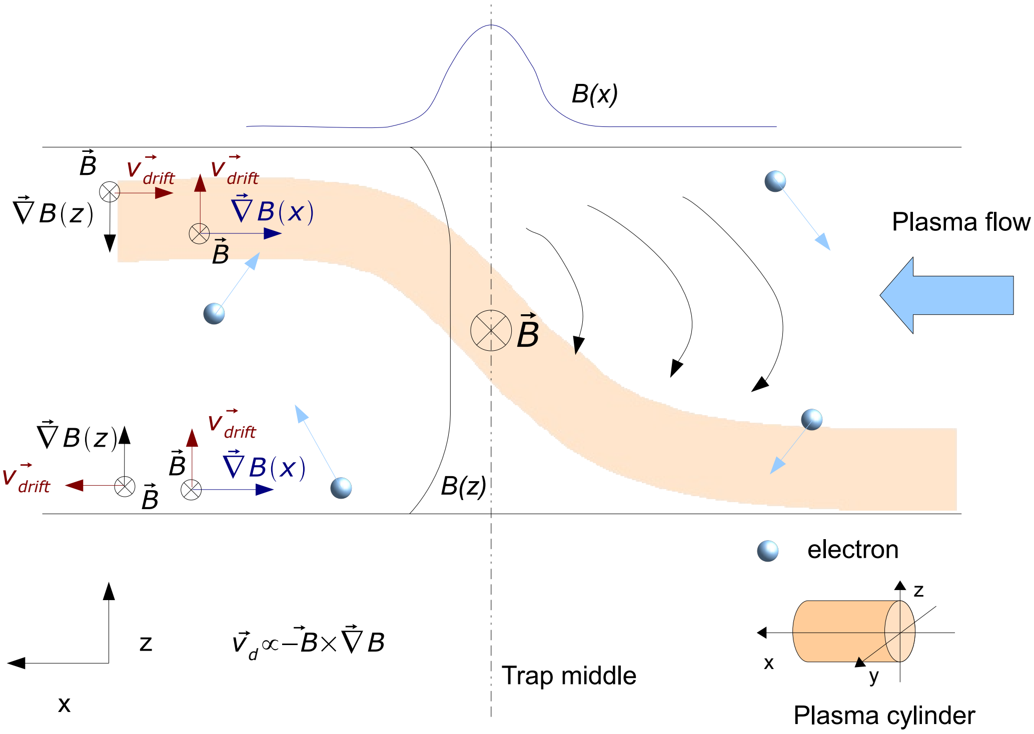

Figure 2: Direction of the electron diffusion - calculation of the drift in the right side of the figure is analogical to the left.

direction. In the plasma source described here, though, the electron temperature is of the order of several eV, when the gas temperature is not much higher than the room temperature (so, several hundredths of eV), which makes the electron velocity an order of magnitude higher than the ion velocity, so the diffusion velocity will be two orders of magnitude higher for electrons than for ions. This suggests, that the direction of the plasma shift in the trap is decided by electrons.

The formation of the stripe is explained in fig. 2, showing the direction of the diffusion velocities due to the gradients in both directions perpendicular to the direction of the magnetic field. The vertical gradients are much smaller than the axial ones, so the velocity of the diffusion along the stripe is much slower than the diffusion to the walls forced by the axial gradient.

Emission spectra

In many gases (Ar, He, air) the emission from different parts of the stripe is different even for the naked eye, because of the differences in color - argon plasma in its main part is pink, and the ends of the stripe appear bluish, orange air plasma turns violet in the stripe ends, and off-white helium discharge is in this region emerald. All this color differences can be correlated with the differences in the spectra shown in fig 3. Spectra presented there were normalized to the low-excited features - in the case of the air plasma to the first-positive band, in the case of the argon and helium plasmas to the red or yellow strongest lines. It can be seen, that the color differences arise: in the case of air, from first negative bands of nitrogen (bands of the molecular ion) which is much stronger in the stripe ends than anywhere else, in the case of argon, the blue color originates both from the high-excited atomic lines and from the much stronger there argon ion lines and the emerald color of the helium plasma is caused by the 501 nm helium singlet line and some blue singlet lines, much stronger in this region of the stripe than elsewhere.

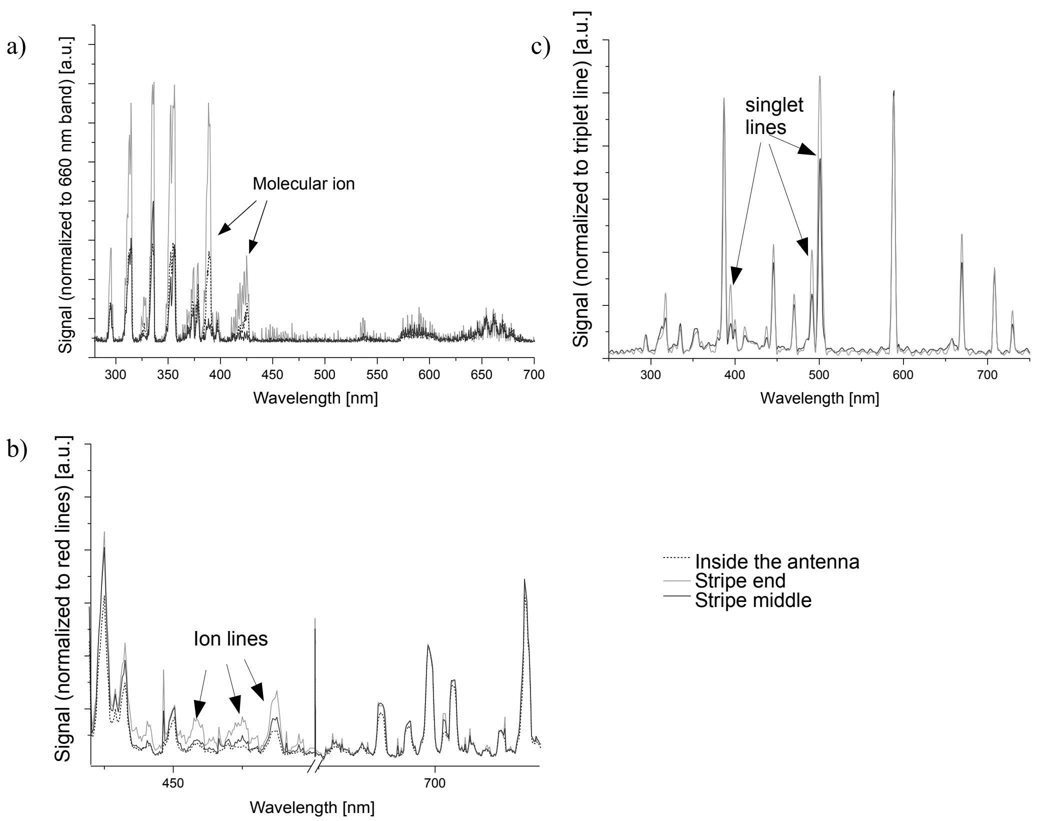

Figure 3: Spectra of the emission from different parts of the plasma: a) air, b) argon, c) helium.

The ends of the stripe are different from the rest of the plasma in the stripe for two reasons - the ends are more concentrated, because the volume of the ends is smaller (due to the round shape of the quartz tube) and also the ends directly touch the glass wall. In this case any processes facilitated by the proximity of the wall (most of the three-body processes) should be much more common there than anywhere else in the stripe. This is probably responsible for the stronger singlet lines in helium in this region - either the recombination prefers the antiparallel spin configuration or the emission from the rest of the plasma is dominated by the collisional excitation from the metastable levels, which favorizes the triplet configuration (one of the lowest excited levels in the singlet configuration has resonant transition to the ground level).

Conclusions

Creation of the stripe mode is an interesting, if not foreseen (and decidedly unpleasant in the case of the thruster) feature of the RF plasma flowing through a strong transverse magnetic field. Two interesting features are, that the stripe mode appears not always, it is possible to completely trap the plasma with the help of this magnetic trap and moreover, the stripe mode appears only in the trap after the plasma. Interesting would be also to see if the stripe would appear also in the plasma with different gas supply configuration.

References

[1] A. Aanesland, A. Meige, P. Chabert, Journal of Physics: Conference Series, **162** 1, (2009).