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Plasma expansion from a dielectric electron cyclotron resonance source

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Abstract
The boundary conditions in an electron cyclotron resonance (ECR) source have been modified to mimic the operating conditions where current-free double-layers (DLs) have been recently measured in rf helicon plasmas. The plasma is heated or generated by the ECR at 875 G inside a dielectric source tube, and expands into a grounded diffusion chamber (terminated by a glass plate) by a rapidly decreasing magnetic field. Preliminary studies of the plasma expansion have been performed. For the present conditions (1 mTorr, 500 G and 500 W), no DL is observed near the source exit and the plasma diffusion is well described by a Bolzmann expansion.

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1. Introduction

Ion acceleration in expanding plasmas has been studied experimentally, theoretically and by computer simulations since the 1930s [1, 2]. These studies have been motivated by a wide variety of research fields from space and solar science [3, 4], plasma thrusters [5], material processing and microelectronics [6, 7], etc. As an example, low-pressure (expanding) plasma sources are desired for anisotropic, uniform etching and controlled deposition as they provide independent control of the ion energy and flux density to the wafer surface [8].

As the plasma expands, the pressure gradient, $\nabla(nT_e)$, must be balanced by an electric field or a potential gradient along the expansion axis for electrons in Boltzmann equilibrium. When the ion mean free path is short, i.e. relative high pressure typically above a few mTorr, the ions undergo a large number of collisions in the system. Therefore, although the ions can be accelerated due to the potential gradient along the expansion axis, the ion distribution remains isotropic [9]. The density and potential gradient along the expansion will in this case follow the Boltzmann relation for electrons [10].

$$n(z) = n_0 \exp\left[\frac{e(\phi_z - \phi_0)}{kT_e}\right], \qquad (1)$$

where $n(z)$ and n_0 are the plasma density along the expansion axis and the reference density, respectively, and ϕ_z and ϕ_0 are the potential along the axis and the reference potential, respectively. k is the Boltzmann constant and T_e the electron temperature, which can be assumed fairly constant along the axis of expansion.

On the other hand, when the pressure becomes very low, typically below 1 mTorr, the mean free path for the ions becomes of the order of or larger than the dimension of the plasma. The low collisionality in the plasma may allow a fraction of the ion population to acquire supersonic velocities when accelerated along the expansion. Under these conditions, an electric double layer (DL) can form [9, 11] and the plasma expansion does not necessarily obey the classical Boltzmann relation. If the plasma expands along divergent magnetic field, the $\boldsymbol{v} \times \boldsymbol{B}$ term might also be important in the Vlasov–Boltzmann equation; however, in most laboratory plasmas this effect can be considered as a second-order effect.

A DL is a narrow isolated region in the plasma that can sustain a large potential change and a variety of electrical DLs have been studied in the laboratory and in space for decades [12]. Usually the DLs studied in the laboratory, by computer simulations or in space, have been driven or generated by external currents or voltages [13–15]. However, recently a current-free DL discovered in a low-pressure expanding 'helicon' plasma has drawn new interests into the field of electrical DLs. In this particular DL experiment, there is no imposed currents or voltages

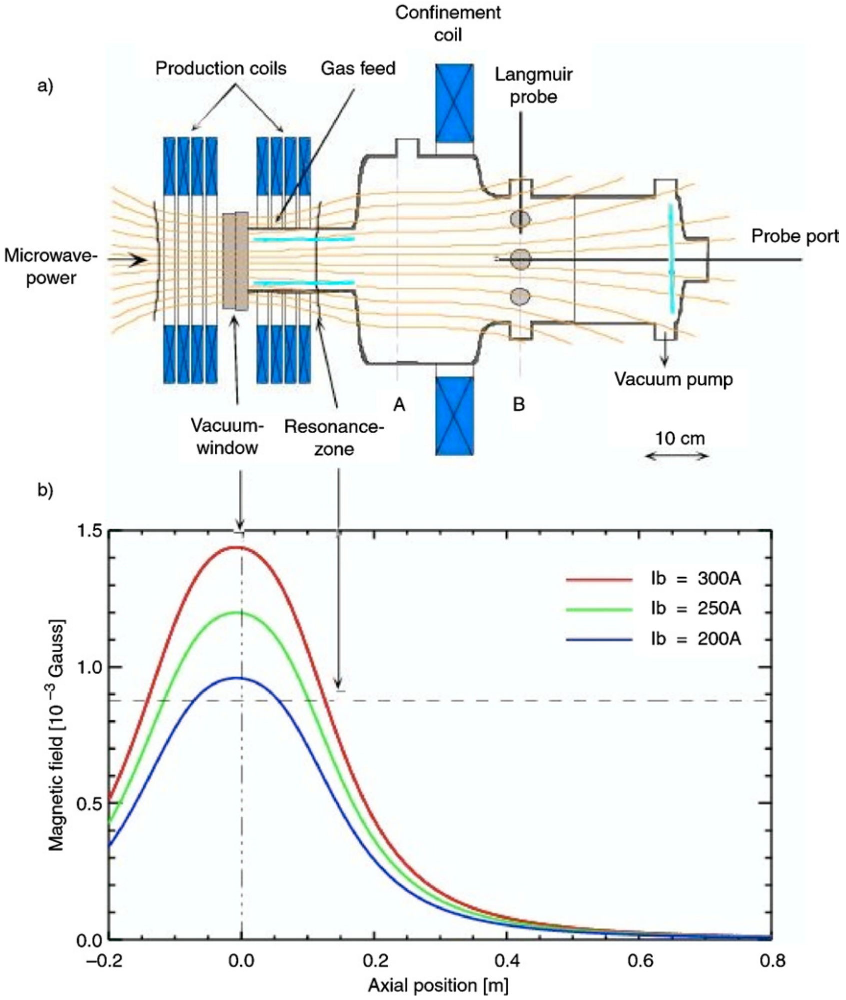

Figure 1. (a) A schematic drawing of the ECR device, ‘Menja’. (b) The magnetic field on axis of the device, where the maximum values are 1450, 1200 and 950 G. Note that the confinement coil in (a) is disconnected, and glass is inserted in the source and at the back of the diffusion chamber.

on the plasma, and the DL is self-consistently created by the plasma [11]. These ‘self-organized’ DLs have now been measured experimentally in a variety of helicon reactors, with different gases spanning from argon, xenon, hydrogen and oxygen, as well as different reactor geometries and sizes [16–18]. The formation of a current-free DL in an inductively heated expanding plasma has also been confirmed by computer simulations [19]. However, all these current-free DLs have been created in expanding plasmas with low-magnetic fields, where the plasma expansion is a consequence of a divergent magnetic field in addition to a sharp volume increase of the vacuum chamber, where typically the diameter of the chamber increase by a factor of two [9]. There have been, to our knowledge, no reports on DL formation in plasmas where the expansion is due to large magnetic fields, such as the one obtained in electron cyclotron resonance (ECR) plasmas with decreasing magnetic fields from about 1000 G in the source (ECR/heating region) to less than 100 G downstream. Although hot ions (downstream) in ECR sources have been measured previously by many authors [8, 20, 24] no DL, comparable to the one obtained in helicon plasmas, has been explicitly measured. Here, we report on experiments aiming to create an electric DL in an expanding low-pressure plasma by use of an insulated ECR source with a divergent magnetic field.

2. Experimental setup

The ECR microwave source, ‘Menja’, has been described in detail previously [21, 22]. A sketch of the system is shown in figure 1, in order to include the modifications done for the experiments reported here. Briefly, TE_{11} microwaves at 2.45 GHz are fed into the vacuum chamber via a circular quartz window. The ECR resonance is obtained at 875 G in the narrow part of the chamber, and its position can be adjusted from 0 to 15 cm from the microwave window, depending on the current in the solenoids. In these experiments only the eight resonance coils surrounding the microwave window are used. The currents in the coils are varied from 200, 260 and 300 A and the corresponding magnetic fields on axis of the reactor are plotted in figure 1(b), showing a rapidly decreasing magnetic field along the main axis. The argon flow is kept at 2 sccm which correspond to a pressure of 1 mTorr, and the microwave power is constant at 500 W where typically 10–20 W is reflected. In order to mimic the experimental

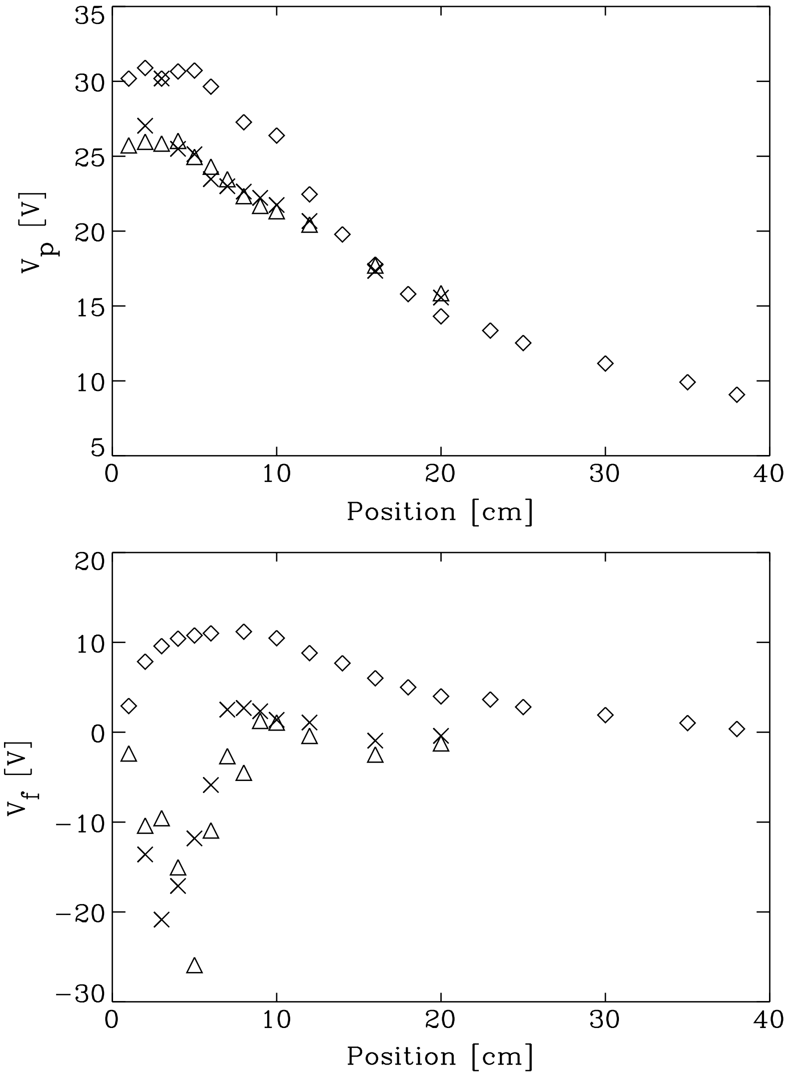

Figure 2. (a) Plasma potential and (b) floating potential as a function of the axial position with respect to the microwave window. Diamonds, crosses and triangles correspond to 200, 260 and 300 A in the coils, respectively.

boundary conditions in the helicon reactors, the narrow part of the stainless steel chamber (source) and the 'back wall' opposite to the microwave window are shielded from the plasma by a 3 mm glass cylinder and plate, respectively, as illustrated in figure 1(a).

The plasma density, n_e, plasma potential, V_p, floating potential, V_f, and the electron temperature, T_e, are measured along the axis of the reactor by a planar Langmuir probe. The data acquisition and analysis have been described previously [23].

3. Results

The plasma parameters are measured as a function of position along the horizontal axis for three different magnetic fields (200, 260 and 300 A). The plasma and floating potentials are shown in figure 2, the electron temperature in figure 3 and the plasma density in figure 4. All positions are given relative to the microwave window and the intersection between the source and diffusion chamber is at 15 cm.

The results show a gradually decreasing plasma potential which is 30–25 V in the source and 10 V in the diffusion chamber. No abrupt jumps in V_p, as would be expected in the presence of a DL, are detected. However, there is a large drop in the floating potential in a narrow region in the source. When the currents in the coils are 260 and 300 A, there is a drop from 0 to −35 V within 2–4 cm. The position where the large negative V_f is measured corresponds to the position of the ECR. At this position the plasma density and the electron temperature are very high as well, indicating large electron heating in this region, which would be expected. At 200 A, the resonance zone is very close to the microwave window and a small drop in V_f is visible also in this case, but not as pronounced as for larger currents.

4. Discussion

Although we did not measure a current-free electric DL in the experiments reported here, it can be interesting to discuss the similarities and discrepancies between the experimental setup,

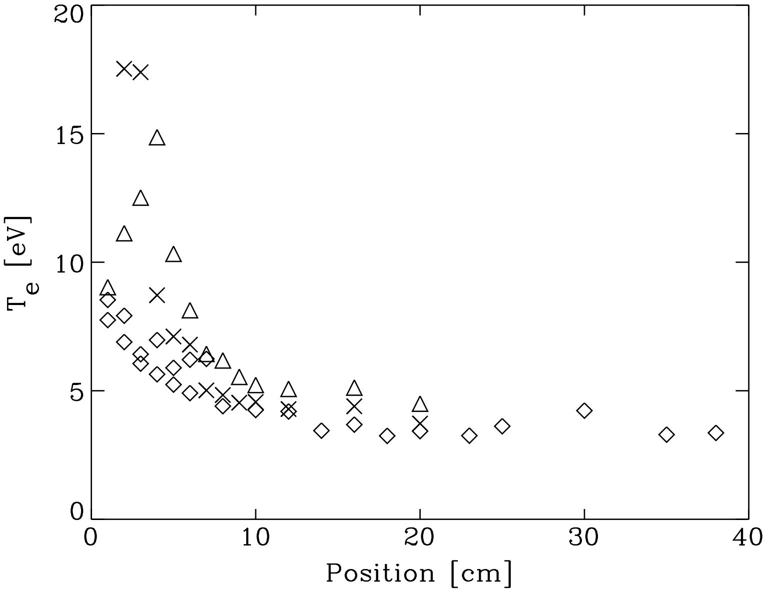

Figure 3. Electron temperature as a function of the axial position. Diamonds, crosses and triangles correspond to 200, 260 and 300 A in the coils, respectively.

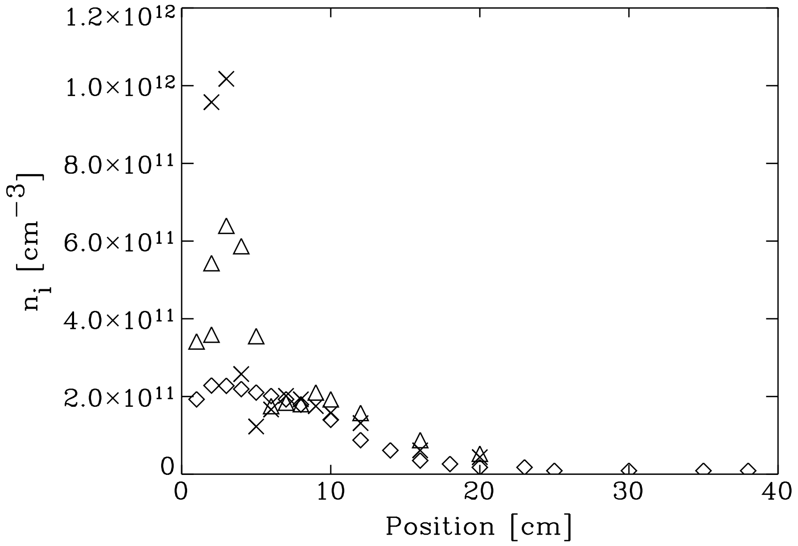

Figure 4. Plasma density as a function of axial position. Diamonds, crosses and triangles correspond to 200, 260 and 300 A in the coils, respectively.

results and physics, between this experiment and the helicon plasma experiments where DLs are formed.

In our case, the electron Larmor radius is very small, $r_{Le} = v_\perp/\omega_{ce} \sim 0.003$ mm, so the electrons can be considered as highly magnetized and will, or should, follow the magnetic field lines. However, the ions have a much larger Larmor radius, 20–100 cm depending on $v_\perp$, and can be considered as weakly magnetized and will naturally cross field lines as they orbit [24]. In a typical ECR plasma, the vacuum chamber is usually made of stainless steel or any other metal, so the walls are electrically grounded everywhere (except for the microwave introduction window). Hence, while the electrons can follow the magnetic field lines along the expansion axis, the ions can be lost to the grounded walls perpendicular to the field or expansion axis. A so-called Simon short circuit current will flow in or on the walls to close the circuit or current loop [25, 26]. In this case, the diffusion coefficients for the electrons and ions parallel and perpendicular to the magnetic field do not have to be equal. However, in this experiment, we mimic the boundary conditions for the helicon plasmas by inserting a glass cylinder inside the source, and terminate the diffusion chamber by a glass plate, in order to isolate the source from the grounded walls, as is commonly the case in helicon plasmas where the rf antenna is surrounding a quartz or glass cylinder. In that case, the Simon current cannot flow and the source would have to charge up considerably to accommodate the density gradient. If the pressure is low enough ($\leqslant$1 mTorr), this might result in a sudden drop in

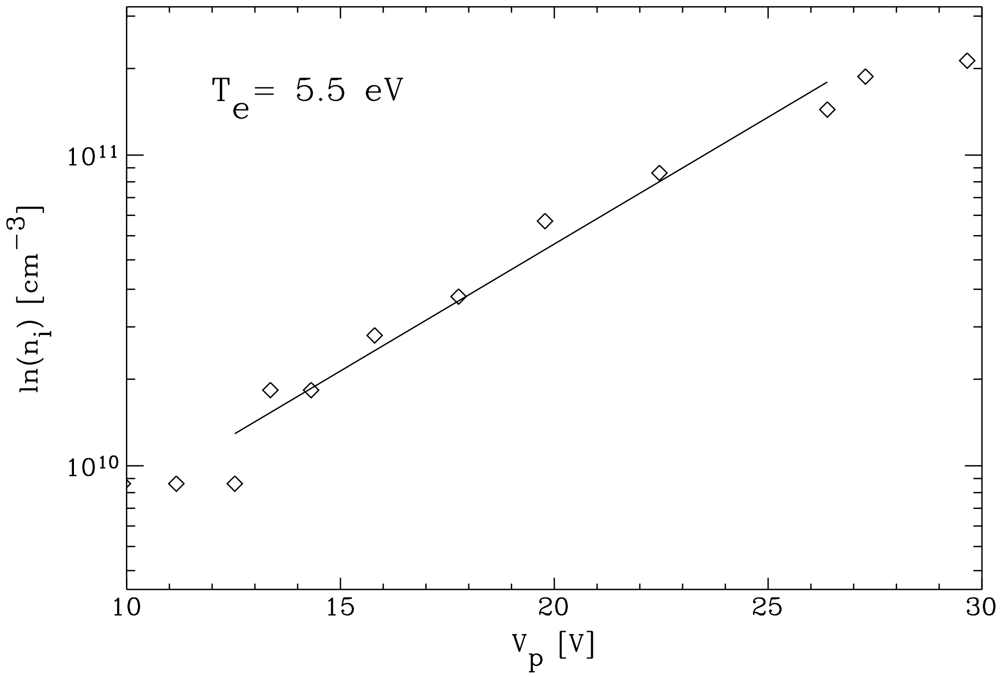

Figure 5. Logarithmic plot of the plasma density as a function of the plasma potential in the case of 200 A in the solenoids.

the potential, such as in the formation of DLs in the helicon plasmas.

As we can see from the results, the floating potential drops to very large negative values in the heating region, the electron temperature also increases dramatically as well as the plasma density. Hence, the ECR heating might induce much stronger gradients in the plasma than what a DL would do in a 1 mTorr plasma. Formation of a DL might therefore simply be ‘masked’ by the ECR heating.

It appears that in the helicon experiments, the density should be less than or of the order of 10^{10} cm^{-3} to obtain the DL [9]. At densities above this value, the plasma follows a normal Boltzmann expansion. Unfortunately, the microwave generator used for this experiment supplies a minimum input power of 500 W, and consequently the plasma density becomes high. This problem might be limited by reducing the pressure below 1 mTorr [27]; however, as we have shown previously, the ECR source might have unstable regimes and mode changes at lower pressures [21].

The magnetic field in this experiment is approximately five times higher than in the ‘equivalent’ helicon experiments. To the first order, the magnetic field simply forces the plasma to follow the magnetic field lines and the expansion is typically an area expansion following approximately $1/r^2$. Figure 5 shows a logarithmic plot of the plasma density versus the plasma potential in the case where the ECR heating takes place as close to the microwave window as possible. The data fits very well to a straight line downstream of the source, where the slope can be addressed to an electron temperature of 5.5 eV (from equation (1)). This is in good agreement with the temperature deduced from the Langmuir characteristics, and suggests that the plasma follows a normal or classical Boltzmann expansion. These experiments show that formation of a DL in ECR sources need an operating pressure below 1 mTorr.

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References

[1] Hairapetian G and Stenzel R L 1991 *Phys. Fluids* B **3** 899, and references therein
[2] Manheimer W M and Fernsler R F 2001 *IEEE Trans. Plasma Sci.* **29** 75
[3] Torven S 1981 *Phys. Rev. Lett.* **47** 1053
[4] Paschman G, Haaland S and Treumann R 2002 *Space Sci. Rev.* **103** 415
[5] Chang-Diaz F R 1997 *Bull. Am. Phys. Soc.* **42** 2057
[6] Charles C 1993 *J. Vac. Sci. Technol.* A **11** 157
[7] Boswell R W and Chen F F 1997 *IEEE Trans. Plasma Sci.* **25** 1229
[8] Trevor D J, Sadeghi N, Nakano T, Derouard J, Gottscho R A, Dow Foo P and Cook J M 1990 *Appl. Phys. Lett.* **57** 1188
[9] Charles C and Boswell R W 2004 *Phys. Plasmas* **11** 1706
[10] Lieberman M A and Lichtenberg A J 1994 *Principles of Plasma Discharges and Materials Processing* (New York: Wiley) chapter 6
[11] Charles C and Boswell R W 2003 *Appl. Phys. Lett.* **82** 1356
[12] Raadu M A 1989 *Phys. Rep.* **178** 27, and references therein
[13] Coakley P and Hershkowitz N 1979 *Phys. Fluids* **22** 1171
[14] Saeki K, Iizuka S and Sato N 1980 *Phys. Rev. Lett.* **45** 1853
[15] Sato N, Hatekeyama R, Iizuka S, Mieno T, Saeki K, Rasmussen J J, Michelsen P and Schrittwieser R 1981 *Phys. Rev. Lett.* **46** 1330

[16] Charles C 2004 *Appl. Phys. Lett.* **84** 332

[17] Cohen S A, Siefert N S, Stange S, Boivin R F, Scime E E and Levinton F M 2003 *Phys. Plasmas* **10** 2593

[18] Sun X, Biloiu C, Hardin R and Scime E E 2004 *Plasma Sources Sci. Technol.* **13** 359

[19] Meige A, Boswell R W, Charles C, Boeuf J-P, Hagelaar G and Turner M M 2005 *IEEE Trans. Plasma Sci.* **33** 334

[20] Matsuoka M and Ono K 1988 *J. Appl. Phys.* **64** 5179

[21] Aanesland A and Fredriksen Å 2001 *J. Vac. Sci. Technol.* A **19** 2446

[22] Aanesland A and Fredriksen Å 2003 *Rev. Sci. Instrum.* **74** 4336

[23] Aanesland A, Charles C, Boswell R W and Fredriksen Å 2004 *J. Phys. D: Appl. Phys.* **37** 1334

[24] Sadeghi N, Nakano T, Trevor D J and Gottscho R A 1991 *J. Appl. Phys.* **70** 2552

[25] Simon A 1955 *Phys. Rev.* **98** 317

[26] Drentje A G, Wolters U, Nadzeyka A, Meyer D and Wiesemann K 2002 *Rev. Sci. Instrum.* **73** 516

[27] Hussein M A and Emmert G A 1990 *J. Vac. Sci. Technol.* A **8** 2913