Ion accumulation in an electron plasma confined on magnetic surfaces

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Accumulation of ions can alter and may destabilize the equilibrium of an electron plasma confined on magnetic surfaces. An analysis of ion sources and ion content in the Columbia Non-neutral Torus (CNT) [T.S. Pedersen, J.P. Kremer, R.G. Lefrancois, Q. Marksteiner, N. Pomphrey, W. Reiersen, F. Dahlgreen, and X. Sarasola, Fusion Sci. Technol. **50**, 372 (2006)] is presented. In CNT ions are created preferentially at locations of high electron temperature, near the outer magnetic surfaces. A volumetric integral of $n_e \nu_{iz}$ gives an ion creation rate of 2.8×10^{11} ions/s. This rate of accumulation would cause neutralization of a plasma with 10^{11} electrons in about half a second. This is not observed experimentally, however, because currently in CNT ions are lost through recombination on insulated rods. From a steady-state balance between the calculated ion creation and loss rates, the equilibrium ion density in a 2×10^{-8} Torr neutral pressure, 7.5×10^{11} m^{-3} electron density plasma in CNT is calculated to be $n_i = 6.2\times10^{9}$ m^{-3}, or 0.8%. The ion density is experimentally measured through the measurement of the ion saturation current on a large area probe to be about 6.0×10^{9} m^{-3} for these plasmas, which is in good agreement with the predicted value.
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Simultaneous confinement of positive and negative charged particles in a non-neutral plasma can be achieved in magnetic mirrors,[1] combined Penning-Paul traps,[2] or on magnetic surfaces.[3] This feature can be an advantage, for example for creating electron-positron plasmas[4] or antihydrogen.[5,6] However, this feature is a disadvantage when studying pure electron plasmas.[7,8]

If there are no sinks for the ions, a pure electron plasma in a background neutral gas will neutralize on a time scale of $\tau = N_e/R_c$, where N_e is the total number of electrons and R_c is the ion creation rate (in ions per second). If a sink does exist, a steady-state ion fraction may result. Even a small percentage of ions can have an effect on an electron plasma. Ions can cause elevated electron transport[7] or ion driven instabilities.[9–13] Ion driven instabilities are an important topic of research in non-neutral plasmas and they are currently being investigated in the Columbia Non-neutral Torus (CNT).[14] In those experiments it is necessary to know the ion fraction to know the limits of stability and compare it to ion driven instabilities in Penning traps. For example, it was found that electron plasmas are destabilized by the presence of $\geq 1.4\times10^{-7}$ Torr of N_2, or by $\geq 1.0\times10^{-6}$ Torr of H_2. With the method outlined here we were able to determine that these conditions both correspond to ion fractions of $n_i/n_e \approx 0.1$ since the steady-state ion density depends on both the ionization cross section and the square root of the ion mass, as will be shown.

It is therefore desirable to understand the accumulation of ions in an electron plasma confined on magnetic surfaces in CNT. To do this, we consider the ion creation rate both inside and outside the magnetic surfaces (as ions created outside the surfaces will be drawn into the plasma by the space charge). We then consider the mechanisms of ion loss that might lead to a steady state ion fraction, rather than a continuous accumulation of ions. In CNT the main mechanism is the presence of insulated rods in the plasma, on which ions can neutralize. Finally, we compare the ion fraction calculated in this way to experimental measurements in CNT.

This method is directly applicable to the pure electron plasma experiments in Proto-RT,[8,15] which also have insulated rods in the plasma. In the pure electron plasma experiments in the Compact Helical System (CHS) stellarator,[13,16,17] electrons are injected from the outside, but diagnostic rods that are usually used inside the plasma[18] provide a mechanism for ion loss and therefore the ion rate balance is also analogous to that in CNT.

The ion creation rate at any particular location in the plasma is $n_e \nu_{iz}$, the electron density times the ionization frequency. To get a volumetric ion creation rate (in s^{-1}) this quantity must be integrated over the volume. The ionization frequency depends on the neutral number density and the electron temperature and is given by[19]

$$\nu_{iz} = n_n \left(\frac{2}{m_e}\right)^{1/2} \int_0^\infty \left(\frac{2\varepsilon}{\pi^{1/2}(T_e)^{3/2}}\right) Q_{iz} e^{-\varepsilon/T_e} d\varepsilon. \qquad (1)$$

In the above expression $Q_{iz}(\varepsilon)$ is the energy-dependent total ionization cross section (in m^2), and ε and T_e are energy and electron temperature, both in Joules. The cross section for molecular nitrogen is shown in Fig. 1.

An estimate of the ion creation rate can be made by assuming a constant neutral density and electron temperature within the plasma. The ion creation rate is then $R_c = N_e \nu_{iz}$, where N_e is the total number of electrons. In a typical CNT plasma with −200 V electron emitter bias, 0.02 T magnetic field, and a neutral pressure of 2×10^{-8} Torr, $N_e = 10^{11}$, and $T_e = 4$ eV in the bulk of the plasma,[20] which gives

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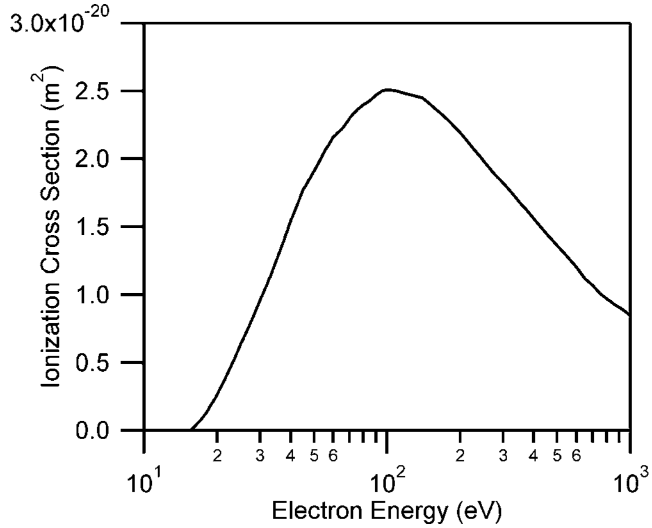

FIG. 1. The cross sections for ionization of molecular nitrogen as a function of electron energy (Ref. 22).

$\nu_{iz}=0.27\ \mathrm{s}^{-1}$. This means that an estimate of the ion creation rate is $R_c \approx 2.7\times 10^{10}\ \mathrm{s}^{-1}$. We will now show, however, that this simple estimate underpredicts the true ion creation rate by an order of magnitude by ignoring the disproportionate effect of areas of high temperature.

A more accurate determination of the ion creation rate is to integrate the local value of $n_e \nu_{iz}$ over the volume of the plasma. Density and temperature profiles have been measured for typical CNT pure electron plasmas.[20] These profiles are used in an equilibrium reconstruction code[21] to calculate the value of density and temperature everywhere in the magnetic surfaces. The temperature values are then used to specify ν_{iz} at each point. Figure 2 shows the calculated contours of $n_e \nu_{iz}$ in the thin and fat cross sections of the magnetic surfaces in CNT.[21] A high temperature near the edge[20] causes the ionization frequency to sharply rise. Therefore, even as the density is dropping sharply in this region,[20] $n_e \nu_{iz}$ is peaking. This is evident in Fig. 2, which shows that the ion creation takes place mainly near the edge. By doing a volume integral of $n_e \nu_{iz}$ over all of the flux surfaces, we find that $R_c=2.8\times 10^{11}\ \mathrm{s}^{-1}$, an order of magnitude greater than the simple estimate presented above.

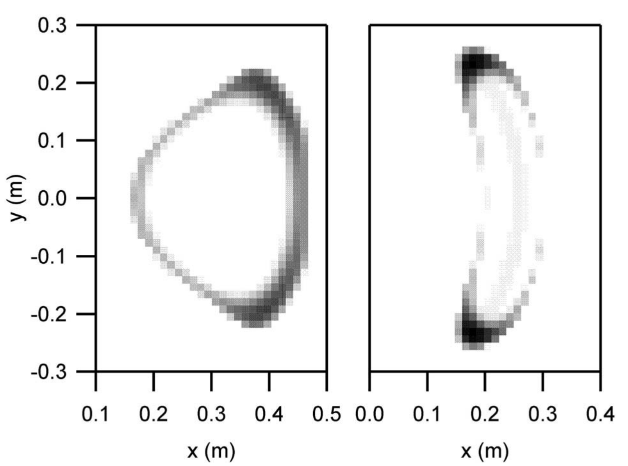

FIG. 2. Contour of $n_e \nu_{iz}$ in the fat and thin cross sections of CNT magnetic surfaces. The scale (from white to black) is $n_e \nu_{iz}$: 0 to $1.27\times 10^{13}\ \mathrm{m}^{-3}\ \mathrm{s}^{-1}$.

Because of the space charge of the pure electron plasma, ions move with a complicated bounce motion in the magnetic surfaces, but the overall effect is that they are confined. In steady state, the total flux of electrons leaving the magnetic surfaces is equal to the emission current from the emitter. We will consider these electrons to no longer have a temperature distribution, but rather a directed energy along the field lines that is due to thermal energy and energy picked up from the approximately 100 V potential difference between the last closed flux surface and the grounded wall.[20] A simple estimate for the ion creation rate outside of the surfaces is then $R_c=(I_e/e)(d/\lambda)$, where $\lambda=1/n_n Q_{iz}$ is the mean free path of electrons for ionizing collisions and d is the field line length to the wall.

A field line following code[23] has been used to determine an approximate average length of stochastic magnetic field lines from just outside the last closed flux surface to the walls of the vacuum chamber and the internal coils. In order to not underestimate the ion creation rate we will consider the highest possible collision cross section, which occurs at a directed energy of about 100 eV (see Fig. 1), and a conservative estimate of $d\approx 5$ m. At $p_n=2\times 10^{-8}$ Torr, and with $Q_{iz}\approx 2.5\times 10^{-20}\ \mathrm{m}^2$, the mean free path is approximately 6×10^4 m. Then with a typical electron loss rate of $I_e=5\ \mu\mathrm{A}$, the ion creation rate outside of the magnetic surfaces is $R_c=2.6\times 10^9\ \mathrm{s}^{-1}$. This is two orders of magnitude less than the ion creation rate in the plasma, so it can be considered an insignificant contribution.

Because of the pure electron plasma space charge, ions created anywhere inside the CNT vacuum vessel will be drawn into the plasma and may remain confined. With $R_c=2.8\times 10^{11}\ \mathrm{s}^{-1}$ and $N_e=10^{11}$, an unperturbed electron plasma should become neutralized in a time scale $\tau=N_e/R_c=0.45$ s. Experimentally, this is not currently observed in CNT, because ions are lost due to recombination on insulated rods that are used to hold the electron emitter and diagnostic probes. In future work on CNT, electron plasmas will be created with a retractable emitter and will be surrounded by copper mesh sectors conforming to the outer magnetic surface. In that case the electron plasma neutralization process may be observed by using the sectors as image charge (or wall) probes, however complications of ion driven instabilities or electron transport[7] may make this measurement difficult.

If we consider that the insulated rods charge up negatively, the flux of ions to the rods is given by

$$R_I=\exp\left[-\frac{1}{2}\right] n_i A_r \sqrt{\frac{T_e}{m_i}}. \tag{2}$$

Because the ions have a background velocity due to their motion in the electron space charge potential, the inherent assumption of cold ions at ∞ is violated. It has been shown, however, that the increase in ion current due to an increased ion velocity is approximately balanced by the effect of ions that enter the sheath but do not strike the rod because of conservation of angular momentum, and the expression above is still reasonably accurate.[24,25] With two rods of 0.3 m length each and 6.35 mm radius inserted into the plasma, the rod surface area, $A_r \approx 0.02\ \text{m}^2$.

Now, since in steady state $R_c = R_l$, we can solve for n_i. With the calculated value of R_c for a $p_n = 2 \times 10^{-8}$ Torr plasma and with $T_e = 4$ eV and N_2^+ as the dominant ion, an estimate of the ion density is $n_i \approx 6.2 \times 10^9\ \text{m}^{-3}$. With $n_e = 7.5 \times 10^{11}\ \text{m}^{-3}$, this is an ion fraction of $f_i \approx 0.8\%$.

In this calculation the profile of electron temperature along the rod length has been ignored. Despite the fact that the ions are preferentially created at the outer surfaces, they then move through the interior surfaces as they complete their bounce motions. In the inner surfaces (along a majority of the rod's length) the electron temperature is constant at about 4 eV.[20]

A series of experiments was conducted to measure the ion density as a function of neutral pressure in CNT. The neutral gas was air, which will be approximated as N_2. The ion density was determined through the measurement of the ion saturation current, I_{is}, as is often done in quasineutral plasmas. The two quantities are related through Eq. (2), where now $R_l = I_{\text{is}}/e$ and A_r is replaced by A_p, the probe area.

For the expected ion densities, the Langmuir probes used in CNT for measurement of electron temperature and density[20] have far too little surface area to produce a measurable ion current. Indeed no ion saturation current was ever seen on these probes. A flat plate 7.4 cm^2 probe was constructed solely for this purpose. It should be noted that even with a probe of this size, and with $B = 0.02$ T, the ions can be considered unmagnetized. The probe was inserted into the magnetic surfaces about halfway between the edge and the axis, and it was elongated and curved and aligned so that the plate intercepted a minimum fraction of the surfaces to minimize the disturbance to the electron plasma. It will be shown below that this probe also did not significantly perturb the steady-state ion fraction in these plasmas.

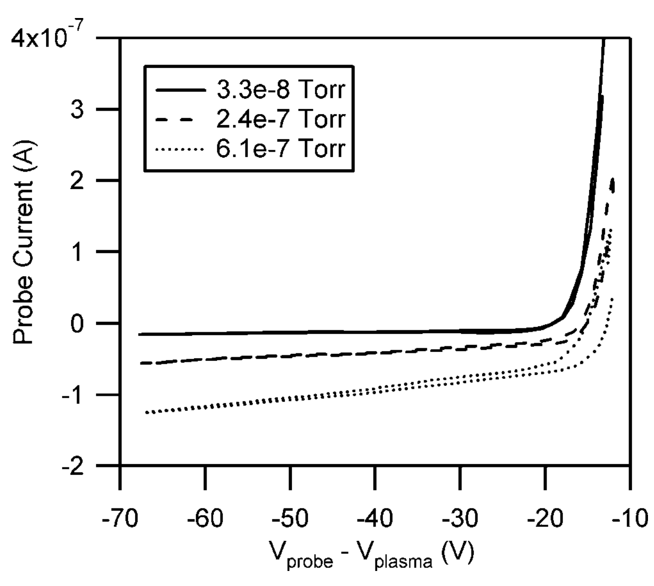

FIG. 3. The probe current measured on the ion density probe for $p_n = 3.3 \times 10^{-8}$ Torr, 2.4×10^{-7} Torr, and 6.1×10^{-7} Torr neutral pressure. All three current-voltage characteristics were produced with $B = 0.02$ T, and $V_{\text{bias}} = -200$ V.

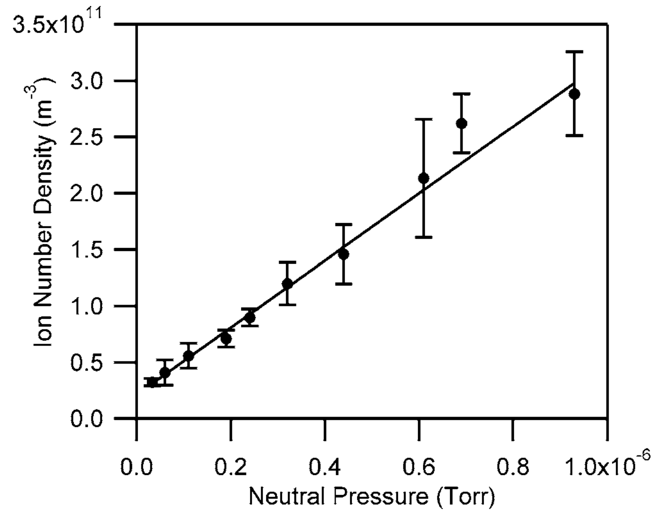

FIG. 4. The ion density measured as a function of the neutral pressure for $B = 0.02$ T and $V_{\text{bias}} = -200$ V.

Current-voltage characteristics for three different values of p_n are shown in Fig. 3. The ion saturation current is seen to increase with neutral pressure, as expected. There is a slope to this current which is attributed to a dependence of sheath size on the probe potential; as the probe potential increases, the sheath size increases thereby increasing the effective collection area of the probe. This, in turn, results in an increase of the current collected to the probe.[24] The ion saturation current for each of these characteristics was determined as the y-intercept from a fit of the linear region. This is the current at which $A \approx A_p$, a known quantity. The density for a particular n_i is then determined from I_{is} using Eq. (2) with $A_r = A_p$.

The measured values of n_i, determined using the methods described above, are shown for a number of values of p_n in Fig. 4. As expected, n_i is linearly dependent on p_n. A linear fit was applied and produced the following relation: $n_i = 2.2 \times 10^{10}\ \text{m}^{-3} + 3.0 \times 10^{17}\ \text{m}^{-3}\ \text{Torr}^{-1}\ p_n$. Because at zero neutral pressure no ions would be expected, the linear offset is attributed to a systematic error in the measurements. From the fit we can see that for a plasma with neutral pressure 2×10^{-8} Torr, the measured ion density is $n_i = 6.0 \times 10^9\ \text{m}^{-3}$. This is very close to the calculated value of $n_i = 6.2 \times 10^9\ \text{m}^{-3}$.

Note that the close match between the predicted and measured n_i does not necessarily prove that the value of n_i is correct, since both methods assume the scaling of Eq. (2). However, the close match does prove that $R_l/A_r \approx (I_{\text{is}}/e)/A_p$, the loss of ions per m^2 s is equal for the rods and the probe. Since our calculation of predicted n_i assumed that $R_c = R_l$, this provides a check on the calculation of R_c performed earlier. Also, since $A_p \ll A_r$, the probe is not a large perturbation on the steady state balance between ion creation and loss on the rods.

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