EQUILIBRIUM, STABILITY, AND TRANSPORT OF ELECTRON PLASMAS IN THE COLUMBIA NON-NEUTRAL TORUS*

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Abstract

The equilibrium, stability and transport properties of electron plasmas confined on magnetic surfaces in the Columbia Non-neutral Torus are discussed. The equilibrium is characterized by a Poisson-Boltzmann equation. Measured potential and temperature profiles are presented. These plasmas are generally stable but can be destabilized by an ion driven instability that involves the interaction of the ion and electron fluids and has a poloidal mode number of m = 1. The transport of electrons driven by collisions with neutrals is much greater than the neoclassical prediction. A code has been written to follow single particle motion to determine why. Finally, sudden jumps between different equilibria with different transport levels are being investigated.

I. INTRODUCTION

The study of non-neutral plasmas confined on magnetic surfaces has only begun recently. Theoretical predictions show that the equilibrium, stability, and transport of these plasmas are fundamentally different from non-neutral plasmas in Penning-Malmberg traps or pure toroidal traps. The equilibrium is different because the force balance between the electrostatic and pressure terms parallel to the magnetic field lines determines the force balance on an entire toroidal surface rather than just a single isolated field line [1]. These plasmas are stable to many oscillations [2]. The dynamics are also dominated by the large electric field due to the space charge of the plasma. This large electric field causes an ExB drift of particles within surfaces, which counters cross-surface drifts, which may lead to excellent confinement [3].

The Columbia Non-neutral Torus (CNT) is an experiment that is investigating the properties of electron plasmas in a stellarator magnetic surface configuration [4]. The magnetic surfaces are created with just four circular coils (see Fig. 1). Electron plasmas are then created in steady-state by placing an electron emitter, which is mounted on a ceramic rod, on the magnetic axis. They are then diagnosed with similar filaments that are also mounted on ceramic rods that are used as Langmuir and emissive probes [5].

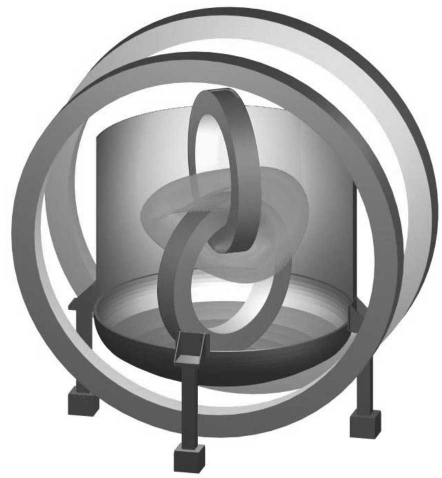

Figure 1. A cutaway CAD drawing of the Columbia Non-neutral Torus. Included are the vacuum vessel (cut in half), the two outer poloidal field coils, the two inner interlocking coils, and the rendering of the last closed magnetic flux surface.

In section II, the equilibrium properties of electron plasmas are discussed. The stability of these plasmas is discussed in section III. Finally, in section IV, the transport properties of these plasmas are summarized.

II. EQUILIBRIUM

It has been established that the confinement time for pure electron plasmas in CNT is much longer than the equilibrium timescale. Therefore a stable equilibrium has been established on each magnetic surface [5]. The character of the equilibria is a subject of ongoing study. In particular the effect of transport parameters (such as magnetic field strength and neutral pressure), electrostatic effects (emitter potential), and geometry (location of emitters) are of interest.

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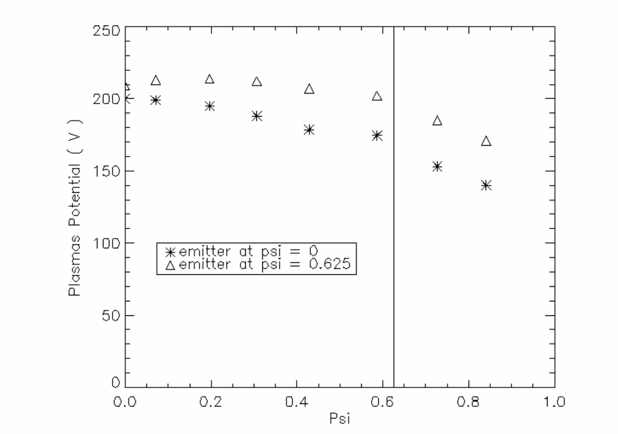

Figure 2. The potential profile for an emitter biased to 200 V on the axis and on the magnetic surface = 0.625.

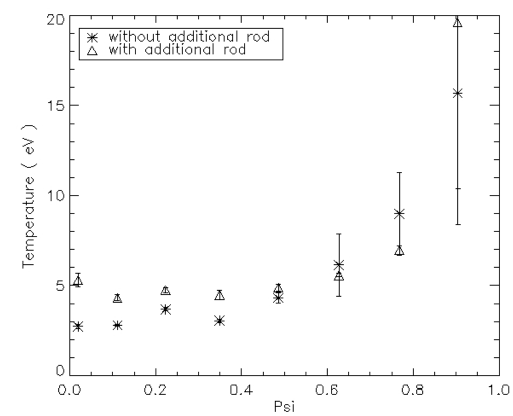

Figure 3. Temperature profiles with and without an additional insulating rod inserted into the plasma.

All of the experiments reported here have been done with the emitter in the thin (= 0°) cross-section of the plasma, where the density and magnetic field are strongest. Future experiments will study emission from the thick cross section where the magnetic field is weakest. Such a study may reveal important effects on the equilibrium from trapped versus passing particles.

The equation governing the equilibrium of a pure electron plasma on magnetic surfaces is a modified version of the Poisson-Boltzmann equation [1],

$$\nabla^2\Phi = \frac{e}{\varepsilon_0} N(\psi)\exp\left(e\Phi \big/ T_e(\psi) \right). \qquad (1)$$

The equilibrium is characterized by the distributions of potential, , density, n_e, and temperature, T_e, of the electrons. In the complex geometry of CNT this equation must be solved numerically.

In general, measurements in CNT when emitting at the magnetic axis have shown that the temperature profile is flat inside but rises sharply at the edge of the plasma [5]. The potential drops across the plasma from a maximum at the axis. The density varies somewhat across the plasma being mostly constant and dropping at the edge.

The density increases with emitter bias, as expected from Poisson's equation. The temperature also increases with emitter bias. So far the effect of magnetic field strength and pressure on the equilibrium profiles is not clear.

Profile measurements have been performed with the emitter off of the magnetic axis, but in the same cross section. As the emitter is moved outward, the potential between the axis and the emitter rises above the emitter potential (see Fig. 2). This behavior may be an indication that the plasma is in a global thermal equilibrium state. To confirm whether this is true numerical solutions to Eq. 1 will be used to reconstruct these equilibria.

A major source of transport in the plasma is the insulating rods. These affect the equilibrium in a complex way. One reason we believe our temperature is low is that the rods tend to remove high energy electrons by ExB transporting electrons that get close enough to the rods out of the plasma. However, the details of the effect of the rods on temperature are more complex than that. When an additional insulating rod is inserted into the plasma at the = 90° cross section so that it crosses the magnetic axis and extends through the plasma on either side, the effect is to raise the temperature on the inner surfaces and perhaps lower it on the outer surfaces (see Fig. 3).

The rods also affect the density and potential profiles. The potential profile is nearly flat until around = 0.5 with the rod and the density less than without the additional rod.

III. STABILITY

In CNT, stable plasmas are created when the neutral pressure is low [5], but when ion content is raised to about $n_i/n_e = 0.1$, an instability is observed [6]. This is similar to the ion-resonance instability observed in Penning and pure-toroidal field traps [7], but the presence of magnetic surfaces in CNT changes the underlying physics governing the instability [1,2].

For the experiments studied so far in CNT, one or more ceramic probe arrays inside the plasma act as a sink for ions, so that the plasma does not become fully neutralized. Thus these experiments involve non-neutral plasmas in a steady state; electron losses are balanced by emission from the axial emitter, and ionization is balanced by ions becoming neutralized when they strike the ceramic rod. When the neutral pressure is high enough for the plasma to go unstable, the plasma is in a steady state with oscillations.

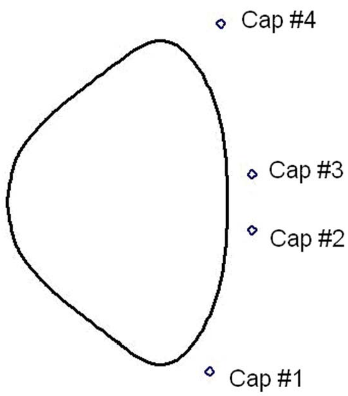

Figure 4. The locations of the four external capacitive probes used to measure the mode number of the instability. All of the probes are in the plane of the thickest cross section of the plasma (= 90°).

The measured frequency of the instability decreases with increasing magnetic field strength and increases with increasing radial electric field; suggesting that the instability is linked to the ExB flow of the plasma. The frequency does not, however, scale exactly as E/B, and it depends on the ion species that is introduced. The measured frequency dependencies suggest that the instability involves an interaction between ions and electrons in the plasma.

When hydrogen has been introduced into the plasma, the observed oscillations from the instability become very small at high magnetic fields. On the other hand, when nitrogen, krypton or argon are introduced into the plasma, the observed oscillations remain large even at the maximum magnetic field of 0.1 Telsa. This suggests that the instability is a two-stream instability, relying on a difference in ion and electron fluid motion.

In order to measure the spatial structure of the instability, a set of 4 capacitive probes were placed outside of the last closed flux surface, on the thick cross section of the plasma (= 90°). Fig. 4 shows the locations of these probes, and Fig. 5 shows the signals on these probes for one specific shot. The delay in phase of the fundamental mode of these signals has an almost 1 to 1 ratio with the change in poloidal angle of the locations of the probes. This strongly suggests that the fundamental frequency of the instability has a poloidal mode number m=1. The oscillations are moving in the same direction as the bulk ExB fluid flow of the plasma.

An instability with m = 1 does not correspond to a rational surface in CNT. The instability may involve an interaction between ions, and electrons that are mirror trapped and therefore do not circulate toroidally. As discussed in the following section, a large fraction of the electrons in CNT are mirror trapped due to the large variation of the magnetic field strength.

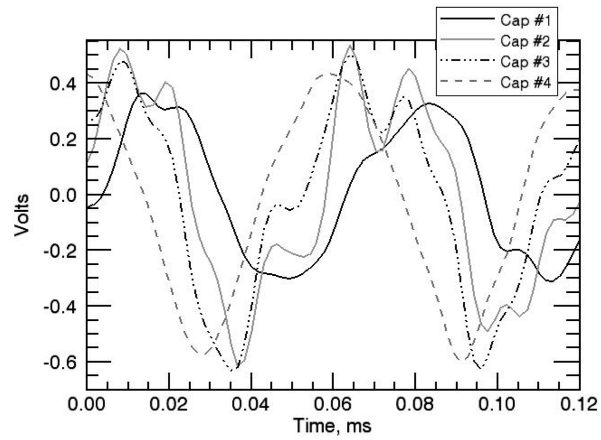

Figure 5. The signals on the 4 external capacitive probes. The phase delay of the fundamental of these signals suggests that the ion driven instability has a poloidal mode number of 1. For this shot, magnetic field is 0.1 Tesla, emitter bias is -300 Volts, and the background neutral pressure has been raised to 2.2E-7 Torr of nitrogen.

IV. TRANSPORT

The transport of electrons confined on magnetic surfaces is characterized by a confinement time. The longest confinement time measured, to date, in CNT is 20 ms [5]. We have found that at low neutral pressures the presence of the insulated rods in the plasma limits the confinement and that at higher neutral pressures transport scales linearly with neutral pressure, indicating electron-neutral collisions are the dominant transport mechanism [3].

The measured neutral-limited confinement times are much greater than drift time scales, but they are much less than the theoretically predicted neoclassical time scales (on the order of seconds) [3]. The neoclassical confinement times are expected to be very large because the space charge of a non-neutral plasma creates a large electric field, which in turn creates a large ExB drift primarily within the magnetic surfaces that tends to counteract cross-field drifts and keep particles confined. The fact that we do not measure these theoretically possible long confinement times points to two possible explanations that are currently under investigation: a poor match between equipotential and magnetic surfaces, and a phase space loss cone, ie. unconfined particle orbits.

The long predicted confinement times are partly due to the prediction that the surfaces of constant electric potential closely follow the magnetic surfaces for a small Debye length plasma. However, the present electrostatic boundary condition in CNT imposes large differences between the electrostatic contours and the magnetic surfaces in the edge region of CNT. Therefore, a set of copper meshes that conforms to the outer surface has been

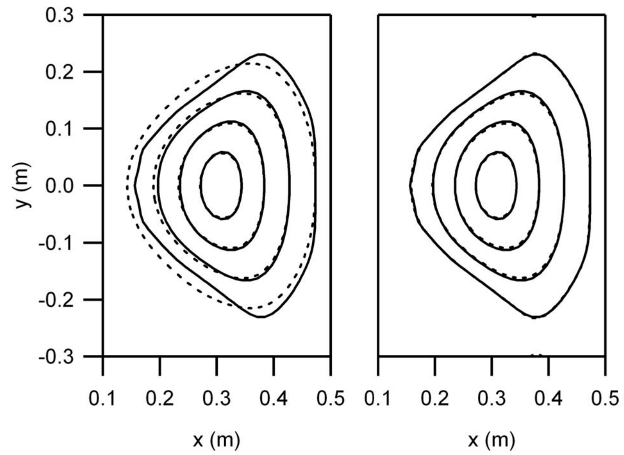

Figure 6. Contours showing the magnetic surfaces (solid) and equipotential surfaces (dashed) for the case of no meshes (left) and equipotential meshes installed on the boundary (right).

constructed to enforce an electrostatic boundary condition that matches the shape of the magnetic surfaces. These meshes will also be used to measure the longer expected confinement times in an unperturbing manner (together with a retractable electron emitter) by measuring the decay time of the image charge on the probe after the plasma has been terminated.

Secondly, a previously unknown loss cone mechanism may be responsible for the low measured confinement times. A code was written that integrates the drift equations:

$$\frac{d\vec{x}}{dt} = \frac{v_{\parallel}}{B}\vec{B} - \frac{\mu B + m v_{\parallel}^2}{eB^3}\vec{B}\times\vec{\nabla}B, \qquad (2)$$

$$\frac{dv_{\parallel}}{dt} = -\frac{\mu}{mB}\vec{B}\cdot\vec{\nabla}B, \qquad (3)$$

for an electron subject to a simple magnetic field. The effect of the strong electric field is currently being added.

For the case of no electric field it was shown that the fraction of trapped particles was about 46%. These trapped particles leave the magnetic surfaces quickly, so a relatively poor confinement is to be expected.

A second version of this code is currently under development. It will be written in magnetic coordinates and will include the effects of the strong electric field. The use of magnetic coordinates should improve the computation speed and will make the code more natural to study transport.

Finally, another transport phenomenon has been studied in CNT: sharp jumps in the electron emission current (see Fig. 7). In a steady state plasma, the confinement time = eN_e/I_e, where N_e is the total number of electrons and the emission current, I_e, is equal to the loss rate of electrons from the plasma [3]. The total number of electrons is related to the total potential drop in the plasma from axis to edge, which does not change much during a jump, so a jump up in current is indicative of a jump to a state of poorer confinement.

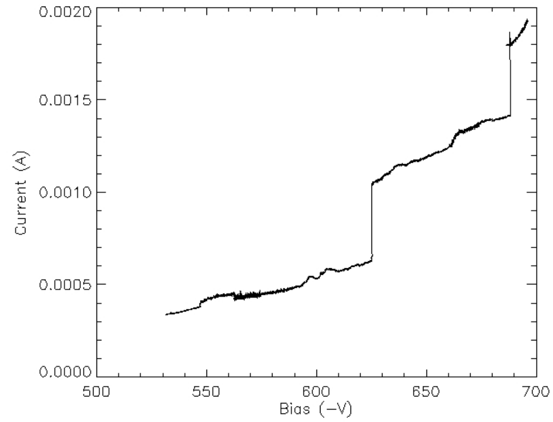

Figure 7. An example of jumps in the emission current.

These jumps are seen to occur at particular critical emission currents. Whenever a parameter affecting transport causes the emission current to cross one of the critical currents there will be a jump. The jumps also exhibit hysteresis, a consequence of a negative differential resistance in the current-voltage characteristic, which we have also observed. Although the two states of the jump have the same emitter potential and total potential drop, they have significantly different potential profiles. Therefore, they represent two different equilibrium states.

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