Non Neutral Plasmas in the CNT Stellarator*

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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. These plasmas are stable to many oscillations [2]. The large electric fields cause an ExB drift of particles within surfaces, countering cross-surface drifts. This is predicted to lead to excellent confinement [3]. The Columbia Non-neutral Torus (CNT) is an experiment designed to study non-neutral plasmas confined on magnetic surfaces [4]. This stellarator configuration is created with just four circular coils (see Fig. 1). Electron plasmas are then created in steady-state by emitting from a biased tungsten filament inside the plasma.

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.

I. Equilibrium: At low neutral pressures, stable equilibriums are established on the magnetic surfaces of CNT [5]. The equation governing the equilibrium of a pure electron plasma on magnetic surfaces is a modified version of the Poisson-Boltzmann equation [1],

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

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The equilibrium is characterized by the distributions of potential, Φ, density, n_e, and temperature, T_e, of the electrons. The character of the equilibrium 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.

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.

II. Stability: When ion content is raised to about $n_i/n_e = 0.1$, an instability is observed. 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 instablity[1,2].

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 ($\varphi = 90$). The delay in phase of the signal between the capacitors 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.

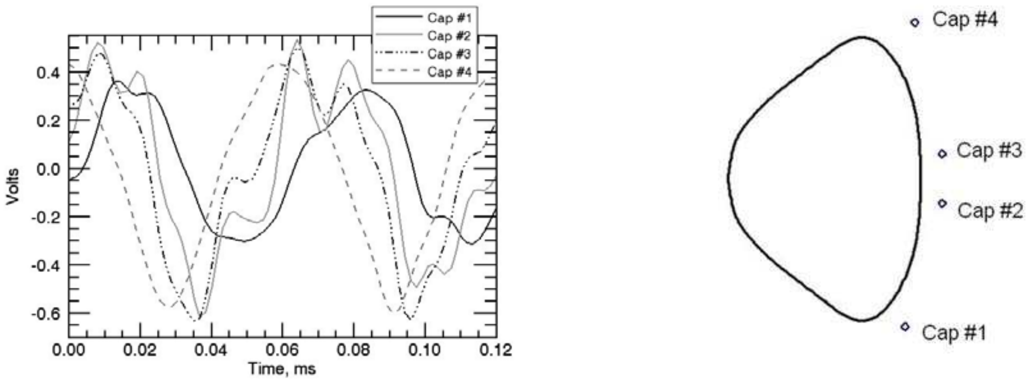

Figure 5. The signals on the 4 external capacitive probes, along with the locations of the probes in the thick cross section of the plasma (φ = 90°). For this shot, magnetic field is 0.1 Tesla, emitter bias is -300 Volts, and the background neutral pressure has been raised to 2.2E-7 Torr of nitrogen.

III. Transport: 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].

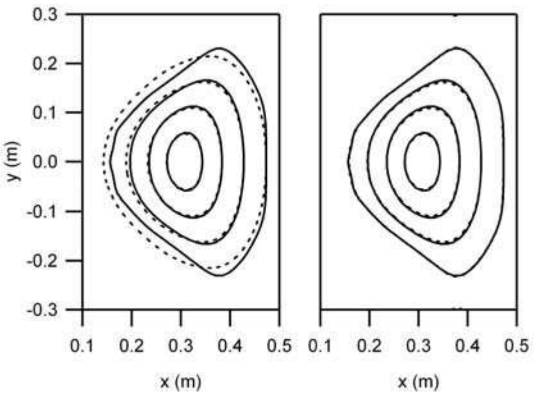

Figure 6. Contours showing the magnetic surfaces (solid) and equipotential surfaces (dashed), without (left) and with (right) a conforming conducting boundary.

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 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 constructed to enforce an electrostatic boundary condition that matches the shape of the magnetic surfaces.

Secondly, a phase space loss cone mechanism may be responsible for the low measured confinement times. A code was written that integrates the drift equations for an electron subjected to a simple magnetic field. For the case of no electric field it was shown that the fraction of trapped particles was about 46%. Consistent with measurements and calculations from other classical stellarators, these trapped particles leave the magnetic surfaces quickly. The effect of the electric field, which should lead to much greater trapped particle confinement times, is currently being added.

References:

[1] T. Sunn Pedersen and A.H. Boozer, “Confinement of nonneutral plasmas on magnetic surfaces,” Physical Review Letters, vol. 88, pp. 205002, May 2002.

[2] A.H. Boozer, “Stability of pure electron plasmas on magnetic surfaces,” Physics of Plasmas, vol. 11, pp. 4709-4712, Oct. 2004.

[3] J.W. Berkery, T. Sunn Pedersen, J.P. Kremer, et al., “Confinement of pure electron plasmas in the Columbia Non-neutral Torus,” Physics of Plasmas, vol. 14, pp. 062503, Jun. 2007.

[4] T. Sunn Pedersen, J.P. Kremer, R.G. Lefrancois et al., “Construction and initial operation of the Columbia Nonneutral Torus,” Fusion Science and Technology, vol. 50, pp. 372-381, Oct. 2006.

[5] J.P. Kremer, T. Sunn Pedersen, R.G. Lefrancois et al, “Experimental confirmation of stable, small-Debye-length, pure-electron-plasma equilibria in a stellarator,” Phys. Rev. Lett., vol. 97, pp. 095003, Sept. 2006.

[7] A.J. Peurrung, J. Notte, and J. Fajans, “Observation of the ion resonance instability,” Phys. Rev. Lett., vol. 70, pp. 295-298, Jan. 1993.