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Pure electron plasmas in the CNT stellarator

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Abstract: Recent experimental, numerical, and theoretical results for non-neutral plasmas confined in the Columbia Non-neutral Torus stellarator are presented. Numerical equilibrium studies show that the electric potential is very sensitive to electrostatic boundary conditions. A numerical investigation of electron orbits indicates that variations in the electrostatic potential on magnetic surfaces cause unconfined orbits, despite a very strong radial electric field due to the non-neutrality. These findings are consistent with experimental results showing very rapid collisional transport. The installation of a conforming conducting boundary has reduced electrostatic potential variations and allowed to increase the confinement time by almost an order of magnitude, reaching 190ms. Observed transport jumps as well as ion driven instabilities are also discussed.

1 Introduction

The Columbia Non-neutral Torus is a simple stellarator using four planar circular coils [1, 2], see FIG. 1. It is the first stellarator specifically designed to study non-neutral plasmas confined on magnetic surfaces. Unlike Penning traps which are limited to the confinement of like-charged particles, the magnetic surface configuration of CNT allows one to confine plasmas of arbitrary degree of neutrality.

The current focus of CNT is on understanding the equilibrium, stability and transport of pure electron plasmas on magnetic surfaces. Because of the electron space charge, such plasmas have very strong, negative electric fields ($e|\Delta\phi|/T_e \gg 1$). Thus CNT explores the extreme ion root of stellarator neoclassical transport, which should lead to excellent confinement [3, 4].

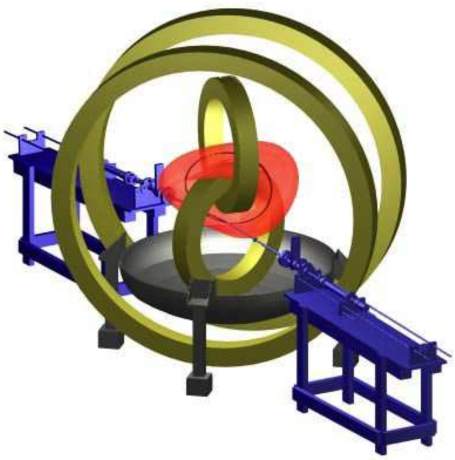

Figure 1: *Cutaway view of the CNT device with the four coils, the plasma volume and the probes.*

Figure 2: *Copper mesh conforming to the magnetic surfaces installed in CNT.*

2 Experimental setup

Pure electron plasmas are created in steady state in CNT by a heated filament mounted on a ceramic rod, biased negative relative to the vacuum chamber and placed on the magnetic axis. Parallel and cross surface transport then fills the magnetic surfaces. Other filaments are used as probes to measure the plasma potential, density, and temperature [5]. The plasma central potential ϕ_{axis} is used to estimate N_e, the total electron inventory. In steady state the emission current from the heated filament, I_e, gives the confinement time: $\tau = eN_e/I_e$.

Typical operating values for CNT are magnetic field $B = 0.02$ T and $\phi_{axis} = -200$ V yielding an electron density $n_e = 10^{12}\ m^{-3}$, electron temperature $T_e = 4$ eV in the bulk of the plasma and Debye length $\lambda_D = 1.5$ cm. Until recently the operating neutral pressure was around $p_n = 10^{-8}$ Torr and was lately brought down in the 10^{-9} Torr range, aiming at 10^{-10} Torr.

3 Equilibrium

The equilibrium equation for a pure electron plasma confined on magnetic surfaces is obtained by combining Poisson's equation with a Boltzmann distribution of electrons on each magnetic surface [3] :

$$\nabla^2\phi = \frac{e}{\epsilon_0} N(\psi) \exp\left(\frac{e\phi}{T_e(\psi)}\right)$$

where ψ is a magnetic surface coordinate. When reconstructing an equilibrium density and temperature profiles are used to prescribe $N(\psi)$ and $T(\psi)$ respectively.

A 3-D code was developed which solves this equation in the non-trivial geometry of CNT [6]. This code confirmed that pure electron plasmas confined on magnetic surfaces are a minimum energy state [7], which is the opposite of what occurs in pure toroidal field traps [8]. It also showed that the potential varies significantly on magnetic surfaces when there are few Debye lengths in the plasma ($a \lesssim \lambda_D$) but tends to be constant on surfaces when many Debye lengths are present ($a \gtrsim 10\lambda_D$). However the equilibria are sensitive to electrostatic boundary conditions and even in CNT for which $\lambda_D = 1.5$ cm $\ll a \simeq 15$ cm, potential variations on the outer surfaces are significant and affect the transport (see Section 4).

4 Confinement

Two distinct transport mechanisms have been identified in CNT [9]. At low neutral pressures insulated rods in the plasma limit the confinement by developing a perturbative electric field which allows electrons to $E \times B$ drift out of the plasma.

At higher neutral pressure transport is dominated by electron-neutral collisions. However this neutral-driven transport is much higher than expected. In particular electrons are shown to be lost in about one collision time whereas neoclassical theory [4] indicates that they should be confined for much longer. This inconsistency was resolved by investigating particle orbits.

Because CNT is a classical stellarator there is a very large fraction of mirror-trapped particles and the scaling in [4] assumes that the large electric field across the plasma is enough to close their orbits. This is indeed the case if the electric potential is constant on magnetic surfaces. Then the radial drift is only due to magnetic drifts, which are proportional to the kinetic energy. The poloidal drift is dominated by the $E \times B$ drift and as $e\Delta\phi/T_e \gg 1$, poloidal rotation dominates over the radial drift. Electrons cannot escape the plasma apart from a small region close to the plasma edge, see FIG. 3. However, as explained in Section 3, electrostatic equipotentials can differ notably from magnetic surfaces. This mismatch allows radial $E \times B$ drifts which can bring electrons out of the plasma quite rapidly. Intuitively this is understood as follows. Without electric field and neglecting magnetic drifts, electrons circulate all around magnetic surfaces following field lines. Now if there is an electric field, electrons also drift on equipotential surfaces. And if the equipotential surfaces do not match magnetic surfaces, electrons can jump from one magnetic surface to the other. After a few steps of jumping from one surface to the other an electron can find its way out of the plasma. Simulations show that this process is quite effective and can remove electrons from the plasma in a few microseconds, see FIG. 3. For the first several years of operation in CNT, the electrostatic boundary conditions were imposed by the interlocking coils and the vacuum chamber implying large variations of potential on magnetic surfaces. Recently a conducting boundary conforming to the plasma shape was installed (see FIG. 2). In addition to its use as an external capacitive probe, it reduces the mismatch between electrostatic equipotentials and magnetic surfaces. This resulted in a new record confinement time of 190 ms, roughly 10 times the previous one.

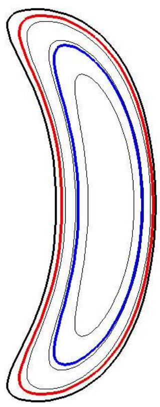

Figure 3: *Plasma cross section at $\varphi = 0°$ and surfaces outside which there are unconfined orbits in the case of: **Blue** potential with no conforming boundary, **Red**: potential constant on surfaces. Also plotted are the magnetic surfaces ψ=0.25,0.5,0.75 and 1.*

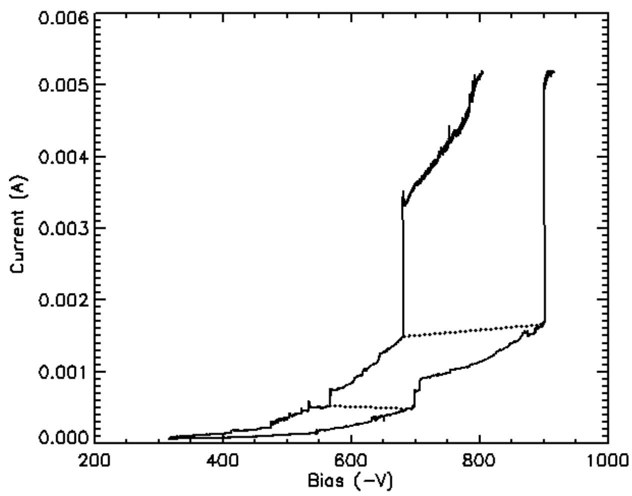

Figure 4: *Jumps in the emission current as the emitter bias is increased. Left curve is at B = 0.01T, right curve at B=0.014T.*

5 Confinement jumps

Another transport phenomenon studied in CNT is sudden jumps in the emission current while parameters controlling this current are varied, see FIG. 4. In steady state the emission current is also the loss rate of electrons, so these jumps are jumps in transport. These jumps have been shown to occur at particular values of the emission current which do not depend on the magnetic field strength (see FIG. 4), the emitter bias voltage, or the ion fraction.

During a jump ϕ_{axis} does not change much so neither does N_e. Because $\tau = eN_e/I_e$ this means that during a positive jump one goes from a good confinement state to a poor confinement state. Measurement of the equilibrium before and after a jump show that the plasma is in two different equilibrium states.

6 Ion instabilities

As noted in Section 3 pure electron plasma confined on magnetic surfaces are in a minimum energy state. Thus theory predicts them to be stable to low frequency oscillations [7]. However it has been observed that if the ion fraction exceeds $\simeq 10\%$ an oscillation appears [10].

This unstable mode has a poloidal mode number m=1 which does not correspond to a rational surface in CNT. This implies that the parallel force balance of the electron fluid is violated. The large fraction of mirror-trapped electrons (see Section 4) could be the cause of this. The frequency of the instability scales linearly with ϕ_{axis}, and decreases with increasing B field which suggests a link to the $E \times B$ flow of electrons. However the instability depends on the ion species studied and the frequency differs significantly from the $1/B$ scaling at low B-field. On the other hand the instability frequency is higher than the orbital ion frequency. This scaling of the frequency suggests a resonant interaction between the ions and electrons.

7 Acknowledgments

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