*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-5.079 (2004)*

Confinement of non-neutral plasmas in the CNT stellarator

T. Sunn Pedersen[1], A. H. Boozer[1], J. P. Kremer[1], R. Lefrancois[1],

1. Dept. of Appl. Physics and Appl. Math, Columbia University, NY, NY 10027, USA

Introduction

The confinement of non-neutral plasmas on magnetic surfaces is a relatively unexplored area of plasma physics. The equilibrium of a pure electron plasma on magnetic surfaces is fundamentally different from that of a pure electron plasma confined in a Penning trap, and from that of a quasi-neutral plasma confined on magnetic surfaces [1]. The confinement time is predicted to be very long for such plasmas, as long as the Debye length is small compared to the minor radius.

The Columbia Non-neutral Torus (CNT) is a small, ultralow aspect ratio stellarator being constructed at Columbia University specifically to study non-neutral plasmas on magnetic surfaces. CNT will explore the physics not only of pure electron plasmas, but also partly neutralized plasmas, including helium plasmas with an electron surplus, and electron-positron plasmas. The former are of interest to fusion science, allowing a study of electron-ion plasmas in the extreme ion root. The latter are of importance to basic plasma physics due to the perfect symmetry between the electron and positron.

In this paper we present an overview of the physics issues being addressed in the CNT device. Details on electron injection and diagnosis of pure electron plasmas are given, and the construction status is described.

Physics issues to be addressed in CNT

CNT is the first stellarator specifically designed to confine non-neutral plasmas. It is unique in several ways. It is designed to reach ultrahigh vacuum, where neutral interactions and ion contamination is negligible, allowing studies of pure electron plasmas for long times. It has a unique and simple coil set consisting of four circular coils, and the effective aspect ratio can be as low as 1.54 [2].

The equilibrium of a pure electron plasma confined on magnetic surfaces is fundamentally different from previously studied configurations. At densities well below the Brillouin limit [3], where diamagnetic and centrifugal effects are negligible, the equilibrium is described by a self-consistency equation for the electrostatic potential [1]:

$$\nabla^2 \phi = \frac{e}{\varepsilon_0} N(\psi) \exp\left(\frac{e\phi}{T_e(\psi)} \right)$$

Here, we use ψ as the magnetic surface variable. T(ψ) is the actual electron temperature, which is assumed to be constant on a magnetic surface due to rapid parallel heat conduction, and N(ψ) is a flux function with units of density that partly determines the electron density distribution, according to

$$n_e = N(\psi) \exp\left(\frac{e\phi}{T_e(\psi)} \right)$$

One of the near-term goals of CNT is to create and diagnose pure electron equilibria, and compare them to 3-D numerical solutions of the equilibrium equation.

Charged particles have rapid ExB drifts in magnetically confined non-neutral plasmas, due to the large space charge. This changes the orbits of the particles significantly. In stellarators, this orbit effect is particularly important since even modest electrostatic potentials can significantly reduce the neoclassical transport in the low collisionality regime. Stellarators typically develop negative potentials with magnitudes on the order of kT/e in order to satisfy ambipolarity, and this modest electric field is enough to reduce the neoclassical transport of particles significantly. This solution to the ambipolarity equation is called the 'ion root'. In a pure electron plasma with many Debye lengths, the electrostatic potential will be negative and much larger than –kT/e. Therefore, the plasma will be in the extreme ion root, and confinement is predicted to be excellent. It is a near-term goal of CNT to experimentally explore the confinement of electrons in this regime.

When a reliable experimental procedure for creating pure electron plasmas has been established, ions will be injected by gas puffing and (if needed) modest heating of the electrons, to allow for ionization of the neutrals. This will enable a study of plasmas of arbitrary neutrality from pure electron all the way to quasi-neutral. Confinement of ions will be excellent since the surplus of electrons creates a large potential well for the ions.

The expected accumulation and extremely long confinement time of positive particles in a strongly negative plasma can be used to accumulate positrons in an initially pure electron plasma. The positron sources available today, which are more than 10 orders of magnitude weaker than inexpensive thermionic sources of electrons, appear to be sufficient to accumulate significant amounts of positrons using this scheme. Indeed, if the currently predicted confinement scalings are confirmed experimentally, it will be possible to accumulate enough low energy positrons to create an electron-positron plasma in CNT. Such plasmas are of interest to basic plasma physics due to the perfect symmetry in mass between the positive and negative particles [4].

Creation of pure electron plasmas in CNT

The most important parameter in non-neutral plasmas is the number of Debye lengths. This number is trivially large in quasi-neutral plasma experiments, but in non-neutral plasmas care is required in order to achieve these conditions. An electron emitter must be emitting at a reasonably large rate to ensure sufficient electron density, and at the same time, must emit the electrons with as little kinetic energy as possible, in order to minimize the electron temperature.

Electrons will be injected into the stellarator magnetic surfaces of CNT by direct insertion of a probe consisting of multiple tungsten mesh electron emitters. The tungsten meshes will be in close proximity to an insulating aluminium oxide tube that will charge up negatively due to the electron emission, and will help direct the flow of electrons off the mesh into the plasma. There will be no anode. Although emission currents in such a configuration are relatively small, they should be large enough that plasma parameters of interest can be reached. The meshes will be independently biased to tailor the electrostatic potential profile.

Baseline diagnostics

The baseline diagnostics of CNT will be arrays of two kinds of probes, small internal Langmuir type probes, and large capacitive (sector) probes external to the plasma.

The Langmuir probes can be operated as emissive floating probes, yielding a measurement of the local plasma potential, or the current-voltage characteristic can be mapped out and yield local electron temperature and density information. The current-voltage characteristic has to be properly adjusted for the non-existence of ions, and the existence of potentially large ExB flows [5, 6].

The capacitive probes can be used to diagnose charge distributions in the plasma through measurements of the image currents that flow to and from grounded capacitive probes. These probes can also be used to actively perturb the plasma equilibrium, since it is sensitive to the electrostatic boundary conditions.

Construction progress

The main components of the CNT experiment are the four coils and the vacuum chamber. The vacuum chamber has been received and is installed in the CNT lab. The chamber is made from 316L stainless steel following standard UHV practices and should be capable of reaching a base pressure of $2*10^{-10}$ Torr after a 200ºC bakeout.

Each of the two poloidal field coils consists of 192 turns of watercooled rectangular hollow copper conductor wound as 6 double pancakes. These coils have been received

The two smaller interlocking coils are under construction. Each of these coils will be wound from the same conductor in a five-double pancake, 140 turn configuration, and will be encased in a 316L stainless steel vacuum jacket.

Figure 1. The poloidal field coils and the vacuum chamber in the CNT lab.

References

1. T. Sunn Pedersen and A. H. Boozer, Phys. Rev. Letters **88** p. 205002 (2002)
2. T. Sunn Pedersen et *al*., accepted in Fusion Science and Technology (2004)
3. L. Brillouin, Phys. Rev. **67**, p. 260 (1945)
4. T. Sunn Pedersen et *al*., J. Phys. B, **36**, p. 1029 (2003)
5. T. Sunn Pedersen et *al*., Phys. Plasmas **11**, p. 2377 (2004)
6. H. Himura, C. Nakashima, H. Saito, and Z. Yoshida, Phys. Plasmas **8**, p. 4651 (2001)