Non-neutral Plasma Confinement in Toroidal Geometry

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Abstract. Studying non-neutral plasma is a long and established field however the majority of these studies utilized cylindrical traps. The newly constructed Lawrence Non-Neutral Torus (LNT) II apparatus will study non-neutral plasmas in toroidal geometry. The LNT II features an improved toroidal magnetic field magnitude (∼1 kG) and base vacuum pressure (<10⁻⁹ Torr) from the previous apparatus. A segmented Au-plated Al electrode shell contributes to the reduction in field asymmetries and enables enhanced diagnostics. Additionally, the electron source is located on a retractable bellows for study of confinement dynamics in a complete torus. Confinement times on the order of 1 second would represent more than an order of magnitude improvement over measurements made with the previous apparatus.

1. Introduction
The study of non-neutral plasmas has led to insights in the fields of atomic physics, condensed matter physics, fluid dynamics, and astrophysics. In general, non-neutral plasmas, plasmas with a single sign of charge, can be contained relatively easily and for long periods of time. As such they could be a useful test bed for neutral plasmas experiments. Additionally new applications based on the results of non-neutral experiments are common (e.g. accelerators and beams, formation of antihydrogen, atomic clocks, centrifugal separation of multi-species plasmas). The vast majority of these experiments were conducted in a cylindrical geometry. Malmberg, Driscoll, and others demonstrated over the years that electron plasmas confined in cylindrical traps provide a well-controlled and diagnosed system that is rich in physics phenomena [1]. O’Neil, Dubin, and others have demonstrated that elegant theory can be applied to such systems [2]. Remarkable agreement between theory and experiment has been achieved in these systems.

One way to uncover new physics and stretch theoretical understanding in new directions is to modify the magnetic topology and the spatial geometry. We choose to study electron plasmas in toroidal geometry and have identified a number of interesting physics phenomena that can be studied in such systems. One reason the study of electron plasmas in toroidal geometry is interesting arises because the plasma experiences a magnetic field gradient and magnetic curvature. The $\nabla B$ and curvature drifts cause vertical drifts in the same direction that would suggest confinement is not possible. Indeed this is the case for neutral toroidal plasmas in the absence of a rotational transform. However, for non-neutral plasmas with a sufficient density, the rotation associated with the space charge electric field is predicted to provide an equilibrium[3]. Observation of this equilibrium was seen as early as 1969 [4]. However, several early experiments...
focused on charge injection techniques but were unsuccessful in generating confinement times longer than $\sim 100 \mu$sec.

A serious experimental challenge is posed by the need to rapidly inject sufficient charge across the magnetic field to establish equilibrium. The experiment described here is designed to overcome that obstacle by (initially) confining the plasma in a partial torus. The electron source is located in the portion of the torus that is excluded from the C-shaped confinement region and electrons are thereby injected directly on to magnetic field lines that connect to the trapping region. This procedure borrows from the well established techniques of plasma formation in cylindrical traps \[5\]. This technique was used successfully to trap electron plasmas for 18 ms in a previous experiment at Lawrence University \[6\] and has been used more recently in the SMARTEX-C device \[7\]. Both of these previous experiments operated at about 200 G. Confinement in the former experiment was limited by collisions with neutrals (base pressure $\sim 10^{-7}$ Torr). Plasma lifetime in the latter experiment was limited by the 1 msec flattop on the magnetic field. Another recent experiment is the Proto-RT \[8\], which uses an internal conductor to create a dipole magnetic field. Closed magnetic surfaces are established by superimposing a toroidal magnetic field. The trap is then filled by biased injection from one point at the edge of the device. The Columbia Non-neutral Torus \[9\] and the Compact Helical System \[10\] also rely on closed magnetic surface configurations (i.e. stellerator fields) to achieve long confinement for a toroidal electron plasma.

The original Lawrence Non-neutral Torus (LNT) experiment (described in Ref. \[11\]) successfully demonstrated the existence of an equilibrium state for toroidal electron plasmas. Confinement times much longer than the characteristic single-particle drift times were observed. When active feedback was employed to suppress growth of the m=1 diocotron mode, confinement times on the order of 10’s of msec were observed \[6\]. However this apparatus was limited by poor vacuum pressure, low magnetic field strength and asymmetries in the fields. Another significant limitation was the inability to confine the plasma in a completely toroidal trap. These observations guided the concept and design of the LNT II experiment described in this paper.

2. Theoretical Considerations

The existence of an equilibrium state for pure electron plasmas in a toroidal magnetic field is not a trivial issue. The hope for establishing toroidal equilibrium for non-neutral plasmas rests on the (poloidal) rotation of the plasma due to its space charge electric field. Poloidal rotation can produce closed particle orbits despite the presence of vertical drifts. A number of theoretical papers predict the existence of toroidal equilibria (see for example \[12\]). To generate closed drift orbits, the electrostatic potential energy hill generated by the plasma must be greater than the thermal energy, $e\phi_s \gg kT$, (where $\phi_s$ is the space charge potential at the center of the plasma, $T$ is the temperature, $e$ is the electronic charge and $k$ is Boltzmann’s constant) or equivalently, that the Debye length be much smaller than the plasma size. This requirement poses difficulties for the experimentalist. Equilibrium requires the presence of substantial space charge, whereas the initial conditions for a real experiment are an empty trap. Charge injection must proceed rapidly enough for equilibrium to be established before cross-field drifts take the injected charge out of the confinement region. The LNT device and its successor (described here) solve this problem by making the confinement region “partially toroidal.” By limiting the confinement region to a toroidal sector, charge can be injected onto (and dumped for diagnosis along) field lines tied to the trapping region.

Macroscopic force balance considerations show that toroidal equilibrium for non-neutral plasmas requires an auxiliary electric field directed along the major radius \[13\]. The auxiliary electric field balances the outward electrostatic hoop force. For plasmas surrounded by a conducting shell, the auxiliary field may be spontaneously generated by image charges.
Alternatively, biased electrodes can provide the necessary electric field.

The question of whether toroidal equilibria, assuming they exist, are stable is likewise not a trivial one. Mutual self-repulsion of electrons (together with Earnshaw’s theorem) requires that the equilibria for pure electron plasmas be states of maximum potential energy. The plasmas must sit on top of their own potential energy hill. Ordinarily, states of maximum potential energy are unstable. Stable toroidal equilibria are predicted to exist subject to certain criteria (see [3, 13]). O’Neil’s paper [3] is particularly illuminating because in it he demonstrates that under a rather broad set of experimental conditions one can expect toroidal equilibria for non-neutral plasmas to be stable. His argument is that the plasma kinetic energy is constrained by the existence of adiabatic invariants and therefore cannot accept energy liberated by the growth of an instability. Bhattacharyya and Avinash [13] find stability to rigid, axisymmetric displacements depends on the spatial variation in the auxiliary electric field. Although their model is quite restricted, it does suggest that experimental designs should incorporate auxiliary electric field electrodes with sufficient flexibility to produce a wide range of field variation indices. Such is the case for the design described below.

In a symmetric straight cylinder with an axial magnetic field non-neutral plasmas are, in theory, perfectly confined [14]. O’Neil’s confinement theorem follows from conservation of energy and canonical angular momentum about the symmetry axis. In real experiments, finite confinement times result from small asymmetries in the trap and the presence of neutral background gas atoms. Crooks and O’Neil [15] point out an interesting new transport mechanism for toroidal non-neutral plasmas that exists even in perfectly symmetric toroidal traps. The poloidal E×B rotation in the non-uniform toroidal field leads to magnetic pumping whereby electrostatic potential energy is alternately transferred (pumped) to and from kinetic energy to conserve singular particle angular momentum about the symmetry axis and to maintain the adiabatic invariance of the single particle magnetic moment. Kinetic energies associated with parallel and perpendicular motion are pumped to different degrees. Electron-electron collisions, acting to equilibrate the parallel and perpendicular temperatures, then lead to plasma heating and hence transport. A goal of the work proposed here is to reduce asymmetry-induced transport and transport due to collisions with neutrals enough to observe the magnetic pumping transport mechanism.

3. Lawrence Non-Neutral Torus II

|                      | LNT II | LNT       |
|----------------------|--------|-----------|
| Major Radius         | 17.4 cm| 43 cm     |
| Minor Radius         | 1.27 cm| 4.5 cm    |
| Magnetic Field       | 1000 G | 200 G     |
| Base Vacuum Pressure | $\sim 10^{-9}$ Torr | $>10^{-7}$ Torr |
| Density              | $\sim 10^7$ cm$^{-3}$ | $5 \times 10^6$ cm$^{-3}$ |
| Temperature          | 5 eV?  | 10 eV?    |
| Confinement Time     | 1 sec? | 40 msec   |

The original experiment, the LNT, is described in more detail in Ref. [11]. Briefly, the LNT featured a spiral tungsten filament which was permanently located between two mesh grids. These grids set up the electrostatic boundaries of the trap. The electrostatic boundary
Figure 1. Comparison of the previous experiment, LNT, to the new apparatus, LNT II. Note the decreased evacuated volume and the increased distance from the center of the plasma to the magnetic field coils.

conditions in the poloidal plane were provided by the grounded rectangular Al vacuum chamber walls located far from the plasma and a set of toroidal continuous stainless steel hoops. The hoops were also used to apply an auxiliary radial electric field. The plasma was trapped in a 300° toroidal arc between the grids. Four wall probes were used for non-destructive detection of the plasma and a phosphor screen and CCD camera were available to image the dumped plasma.

There are several significant advantages to the new apparatus. The LNT II features an improved toroidal magnetic field magnitude (up to 1 kG) and base vacuum pressure ($<10^{-9}$ Torr). A segmented Au-plated Al electrode shell contributes to the reduction in field asymmetries and enables enhanced diagnostics. Additionally, the electron source is located on a retractable bellows for study of confinement dynamics in a complete torus. A comparison of the design characteristics are listed in Table 1 and a comparison of their relative sizes is shown in Fig. 1.

3.1. Vacuum System

The vacuum chamber of the LNT II is 316 stainless steel and is sealed with copper gaskets as opposed to the viton rubber seal used in the LNT. This change permits for the system to be baked. The chamber (see Fig. 2) has a unique formed bellows section on the inner column, which ensures independent compression of the two lid gaskets. The pumps from the previous experiment, a 700 l/s (8") turbomolecular pump and an 8" cryogenic pump are used. After baking we obtained a base pressure of $3.5 \times 10^{-10}$ Torr, an improvement over the base pressure in LNT of three orders of magnitude.

3.2. Toroidal Magnetic Field System

Sixty turns of water-cooled copper constitute the toroidal field coil. The coil design was tailored to match the expected load for a 20V/1500A DC power supply, and when energized will provide a magnetic field of up to 1 kG at the location of the plasma. Each turn consists of a thick-walled (5/8” O.D.) copper tube, a 2.5” x 3/8” copper return bar (see Fig. 1 and water-cooled on the vertical span), and flexible 4/0 cable linking the center tube to the return leg. To minimize
**Figure 2.** Schematic diagram of the vacuum chamber featuring an internal bellows section for independent compression of both lid gaskets. Inside the chamber is shown the location of the segmented electrode shell and plasma. Not shown is the support for the electrodes.

**Figure 3.** Top view of the LNT II.

toroidal field ripple, the tubes are arranged with circular symmetry (see Fig. 3), and the return legs are placed as far from the plasma as is practical. The return legs are grouped into twelve 5-turn bundles (see Fig. 3). The arrangement of return legs dominates the expected toroidal field ripple, but should be less than one part in 100,000. In order to minimize vertical field errors, the coil is “backwound” by connecting half the 5-turn bundles (every other bundle) in series going around in the positive toroidal sense and the remaining half are connected in the negative toroidal sense.
3.3. *Internal Segmented Shell*

A gold-plated aluminium shell surrounds the plasma and is segmented in both the poloidal and toroidal directions. The shell is composed of twelve 30° toroidal modules (see Fig. 4). One of the modules (the injection module) has a slot in the outer wall into which the filament can be inserted. The two modules on either side of the injection module will be used as trapping electrodes (similar to the function of the grids in the LNT). The remaining nine modules comprise the trapping region sectors (270°). These precisely machined electrodes provide a symmetric boundary with controlled potentials.

There are two module configurations. Eleven modules are divided into four segments (i.e. top, bottom, inboard and outboard, see Fig. 4). These can be used to apply a (major) radial electric field to balance the outward hoop force and control the major radial position of the plasma. The segments also function as wall probes monitoring the induced image charge on the wall segments for diagnosis of the \( m=1,2 \) diocotron modes. The second type of module is divided into eight segments. This module (on the left in Fig. 4) will allow us to observe higher order modes (i.e. \( m>2 \)). It will also be used to study the effect of a ‘rotating wall’ [16, 17].

3.4. *Electron Injection System*

The filament and collector plate are mounted on a translatable stalk to permit withdrawal of the assembly and transition to fully toroidal trapping. The filament is a 2.5 cm diameter flat spiral of 0.5 mm tungsten wire. Preliminary experiments yielded an emission current of \( \sim 1 \) mA at 11 V, 11 A DC (121 W). The radial potential variation across the spiral matches the target space charge potential in a plasma with a density of \( 10^7 \) cm\(^{-3} \). Ultimately we hope to trap electron plasmas in a complete torus by injecting and trapping in the 270° trapping region, then withdrawing the filament, and finally, relaxing the trapping potentials on the modules adjacent to the injection module. Success in this endeavor will depend on our ability to achieve confinement times approaching 1 second.

On the other side of the stalk containing the filament is a collector plate. This plate can be used to detect total charge trapped in the partial-torus plasma but will not be available if the filament is retracted for total toroidal confinement.
4. Conclusions

Theory predicts that poloidal E×B rotation due to the space charge electric field can provide equilibrium for a toroidal non-neutral plasma. Experiments in the LNT verified this prediction but confinement was limited to ~40 ms due to poor vacuum, low magnetic field strength and trap asymmetries. This paper describes the LNT II which features a higher magnetic field, improved vacuum conditions and contains a complete segmented electrode shell. Progress towards the containment of long-lived (~1 s) non-neutral plasmas in toroidal geometry will ultimately allow study of long time scale dynamics and transport in these novel plasmas.

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