The Status of the Design and Construction of the Columbia Non-neutral Torus

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Abstract. The Columbia Non-neutral Torus (CNT) is a tabletop (R=0.3 m, a=0.1 m, B=0.2 T) stellarator now being constructed at Columbia University. The goal of CNT is to study the equilibrium, stability, and transport of non-neutral plasmas confined on magnetic surfaces. CNT will use four circular, planar coils: two interlocking coils with a variable tilt angle, plus two additional poloidal field coils. By varying the angle between the interlocking coils, the rotational transform can be varied from 0.2 to 0.6 and the magnetic shear from essentially zero to 20%. The results of a numerical study of how error fields affect the quality of the magnetic surfaces will be presented. The plasma will be diagnosed by numerous Langmuir and sector probes, connected to a computer data acquisition and control system.

INTRODUCTION

Magnetic surface configurations have long been used to confine fusion plasma but have only recently become of interest as confinement devices for non-neutral plasmas [1], [2]. The physics of non-neutral plasmas on magnetic surfaces has been shown to be fundamentally different from previous configurations [3], [4], including the Penning trap. The goal of the Columbia Non-neutral Torus (CNT) is to study the equilibrium, stability, and transport of non-neutral plasmas which are confined on magnetic surfaces.

Our definition of a magnetic surface is a surface where a single field line comes arbitrarily close to every point on that surface. Stellarators and tokamaks are magnetic surface configurations while Penning traps and pure toroidal traps are not. An important parameter when discussing magnetic surfaces is the rotational transform, ι, which is the ratio of the number of times a field line winds around poloidally to the number of times it wind around toroidally. A great deal of care has been taken in choosing parameters such that the bad surfaces, also known as stochastic regions and magnetic islands, exist only outside a large confining region of magnetic surfaces. Error fields can reduce the confining volume by introducing bad surfaces. The effects of a full range of expected error fields were studied computationally and will be discussed.

FIGURE 1. A cutaway drawing of CNT showing the vacuum vessel and the four circular coils.

PHYSICS TO BE STUDIED ON CNT

Fundamental plasma physics: CNT will study the largely unexplored area of confinement of non-neutral plasmas on magnetic surfaces. The physics of such plasmas is fundamentally different from non-neutral plasmas in other devices. Magnetic surface configurations can also explore the whole range of plasma neutrality from single component to quasi-neutral. CNT is a rather unique concept. The device is simple, small, elegant, and, as will be described later, can explore a wide range of rotational transform profiles.

Antimatter physics: Stellarators can confine particles of opposite charge and can confine light, energetic particles. CNT may therefore be an excellent confinement device for exotic antimatter plasmas such as positron/electron or positron/anti-proton plasmas[5].

Physics relevant to fusion and astrophysics: CNT could be used to study the physics of strongly rotating toroidal plasmas which are of great interest to both the fusion and astrophysics communities. Partially neutralized electron rich helium plasmas are of particular interest to fusion science and will be studied in CNT.

THE PRESENT DESIGN SPECIFICATIONS

Basic Parameters

CNT is a small ultrahigh vacuum stellarator now being constructed at Columbia University. CNT consists of only four circular, planar coils. Two of the coils are interlocking, have a radius of 0.405 m, and will be placed inside the vacuum vessel. These two coils will be copper, water cooled, and driven by a 200 kW power supply. The pulse length and repetition rate will be limited by the ability to cool the copper conductors. The other

Parameter	**Value**
n_e	$10^{12} - 10^{14}$ m^{-3}
T_e	1 - 100 eV
B	0.05 - 0.2 T
R	0.3 m
a	0.1 m
p	10^{-10} Torr

two coils are called the poloidal field coils or PF coils. They will have a radius of 1.08 m and will reside outside the vacuum vessel. The angle between the two interlocking coils (the tilt angle) can be varied between 63° and 90°. This allows us to explore rotational transforms of 0.2 to 0.6 and shear from essentially zero to 20%.

Plasma Diagnostics

Methods have been developed to measure plasma temperature and density profiles accurately in Penning traps and other open field line configurations [6]. Toroidal configurations, including those which have magnetic surfaces, do not have open field lines so the same diagnostics cannot be used. Like many other toroidal devices, the temperature and density of plasmas in CNT will therefore be measured using an array of Langmuir-type probes. Current-voltage characteristics of such probes can be determined and used to estimate the density and temperature of plasmas. [7]. Fluctuations in the image charge on a set of capacitive probes surrounding the plasma will be used to measure large scale fluctuations in plasma density and location. We expect to have between 15 and 20 such probes surrounding the plasma so that fluctuations can be localized. These probes can also be biased to alter the plasma equilibrium or excite waves.

COMPUTATIONAL STUDIES

The confinement of plasmas in CNT or any other magnetic surface configuration is limited by stochastic regions and magnetic islands. Parameters are chosen such that these so-called bad surfaces are kept to the outside of a large region of good surfaces. The confining magnetic field of a stellarator is created wholly by the magnetic coils. It is therefore possible to computationally study the magnetic topology. In the case of CNT, which has only planar, circular coils, this requires relatively little computational might. The real magnetic coils have been approximated by sets of 100 circular thin wire coils which occupy a volume similar to the windings of the real coils. In the case of the interlocking coils, the structural mounts that the coils are to be wound on, were approximated as 1 cm thick regions which are void of any windings . Poincare plots of numerous field lines are made at three different toroidal cross sections. Stochastic regions can be seen as thick or undefined surfaces and magnetic islands can be seen as holes either in the surfaces or between them.

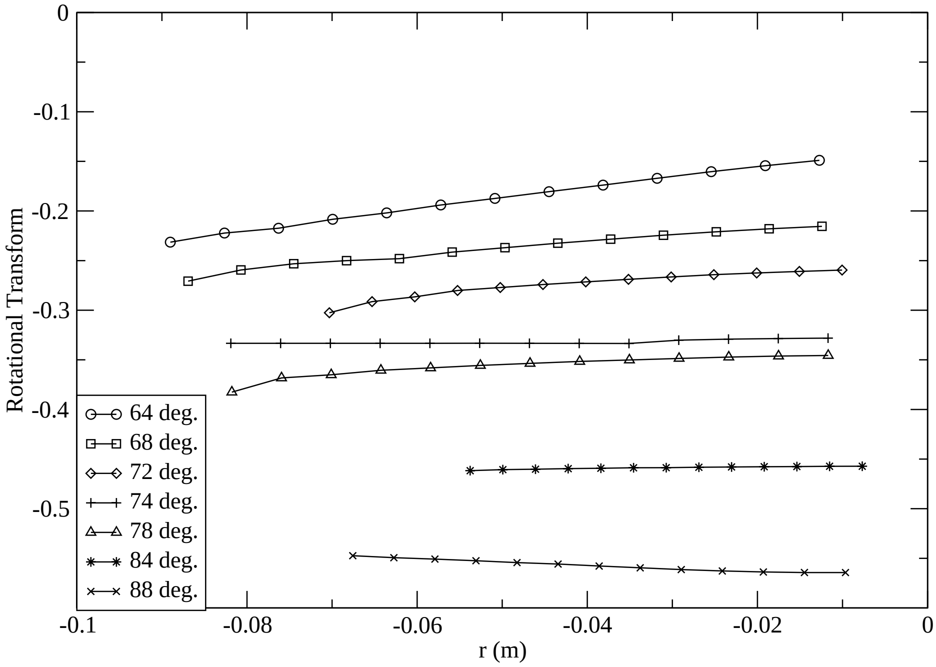

FIGURE 2. The rotational transform profiles for various tilt angles. The bottom axis represents the radial distance away from the magnetic axis.

Parameter Optimization

We have chosen to maximize the size of the confining volume by varying two parameters: the angle between the two interlocking coils (the tilt angle), and the current flowing through the poloidal field (PF) coils. Different rotational transform profiles can be accessed through a change in tilt angle. Engineering constraints dictate that tilt angles must be chosen before the coils are placed in the vacuum vessel and that there can at most be three working tilt angles. The PF current was optimized for a range of tilt angles from 63° to 90°. Tilt angles were chosen such that each had a unique ι profile and had a large volume of good surfaces. The three tilt angles chosen were 64°, 78°, and 88°. Poincare plots of the 64° tilt angle are shown in Fig. 3.

Error Field Analysis

There are numerous sources of error fields in any magnetic configuration. Sources of such error fields are slight errors in coil placement or alignment or imperfections in coil windings. In stellarators, the error fields can introduce bad surfaces to the topology thereby limiting the confinement. An error field analysis was carried out to understand and quantify the effects of error fields on the magnetic topology of CNT. Poincare plots for each chosen tilt angle were made as various sources of field errors were added. The tolerance to error fields was determined by the resulting loss of confining volume.

Error field sources that were primarily investigated were those resulting from slight

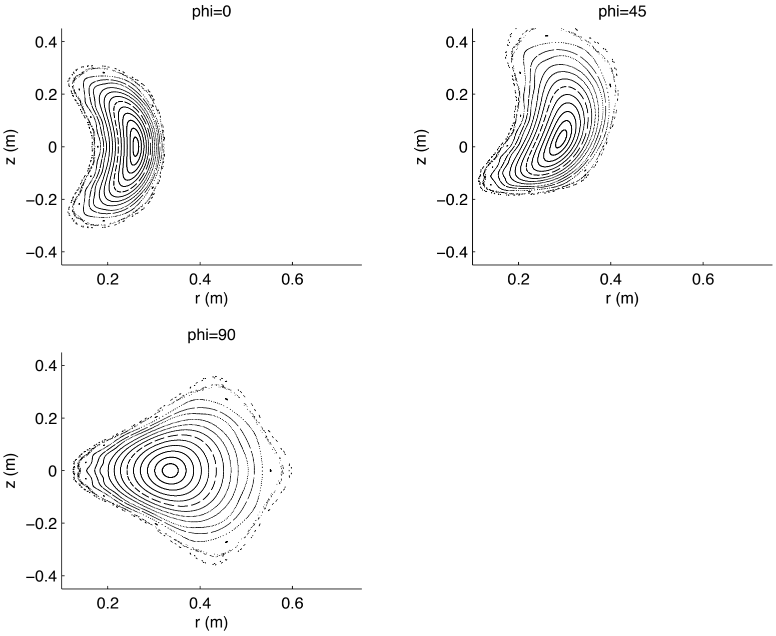

FIGURE 3. Poincare plots for the 64° tilt angle. The plots are toroidal cross-sections at 0°, 45°, and 90°.

perturbations to coil positions and/or alignments. First, the effect of perturbing a single coil 1 cm along all of the axes of symmetry and in numerous random directions, presumably off the axes of symmetry, was studied. Perturbations of 1 cm were made to the alignments by tilting the coil such that the edge of the coil would move 1 cm from its proper location. For all tilt angles, all perturbations of 1 cm to the PF coils were found to be tolerable. Next, the effect of introducing similar sorts of perturbations to the interlocking coils was studied. These perturbations had a much more drastic effect. This is because the interlocking coils are closer to the confining region and play a more significant role in the topology than the PF coils do. The effect was found to be more pronounced in the configurations with larger tilt angles. All of the chosen tilt angles were found to be stable to single 0.5 cm perturbations to the interlocking coils.

To estimate a tolerance in coil placement, the collective effects of random perturbations to all of the coils were studied. Poincare plots were produced after random perturbations limited to a given tolerance were made to all coil locations and alignments. The tolerance was determined as the maximum tolerance which resulted in limited loss of confining volume. Perturbations of this type were found to have the most drastic effect on the 88° tilt angle; the working maximum value for the tolerance was limited to that for the 88° tilt angle. By way of this method, a final value for the tolerance in coil placement was determined to be 0.2 cm.

The effects of field errors from current leads and winding transitions have been approximated and appear not to have a noticeable effect on the magnetic surface quality, if concentrated in the region away from the plasma.

CONCLUSIONS

The goal of CNT is to study the equilibrium, stability, and transport of non-neutral plasmas on magnetic surfaces. CNT will primarily be a basic plasma physics experiment used to confine pure electron and partially neutralized electron-ion plasmas but may also be used to study exotic plasmas such as electron-positron plasmas. Details of the present design of the device were presented. The magnetic topology was studied computationally. Parameters were optimized such that the effects of stochastic regions and magnetic islands were minimized. A thorough error field analysis was conducted. The magnetic surfaces are tolerant to rather large perturbations to single coils. The tolerance decreases as the number of perturbed coils increases. The tolerance was found to be lower for larger tilt angles, and lower for the two interlocking coils. It was found that a general tolerance in coil placement and alignment of 0.2 cm consistently produces a large volume of good magnetic surfaces for all tilt angles.

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