THE COLUMBIA NONNEUTRAL TORUS: A NEW EXPERIMENT TO CONFINE NONNEUTRAL AND POSITRON-ELECTRON PLASMAS IN A STELLARATOR

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The Columbia Nonneutral Torus is a new stellarator experiment being built at Columbia University, New York, to study the confinement of nonneutral and electron-positron plasmas. It will be a two-period, ultralow aspect ratio classical stellarator configuration created from four circular coils. The theory of the confinement and transport of pure electron plasmas on magnetic surfaces is reviewed. The guiding principles behind the experimental design are presented, together with the actual experimental design configuration.

KEYWORDS: *fusion, stellarator, nonneutral plasma*

I. INTRODUCTION

Confinement systems that use magnetic field lines alone have several advantages over those that use magnetic and electric fields, such as the Penning trap. Some of these advantages are the ability to confine positive and negative particles simultaneously and the ability to confine light, energetic particles. Closed toroidal field (TF) line systems have been used to confine pure electron plasmas,[1–4] and more recently, magnetic surface configurations have become of interest as confinement devices for nonneutral plasmas.[5,6] The physics of pure electron plasmas confined on magnetic surfaces is fundamentally different from previously studied configurations.[6]

In contrast to other magnetic surface configurations, a stellarator has the advantage that it can be steady state and does not require internal currents. This means that it can be operated at arbitrarily low density, which is an important advantage for making nonneutral and electron-positron plasmas since these will be very low density compared to quasi-neutral fusion plasmas. A stellarator, the Columbia Nonneutral Torus (CNT), is currently being constructed specifically to investigate the physics of nonneutral plasmas confined on magnetic surfaces. This paper reviews the theory of nonneutral plasmas confined on magnetic surfaces and discusses some of the experimental parameters that are of importance to a nonneutral stellarator experiment. We also present the design of the CNT stellarator, which is unique in that it will be ultrahigh vacuum; will be very low aspect ratio; and will require only four simple, circular planar coils.

II. CONFINEMENT OF PURE ELECTRON PLASMAS

The equilibrium of a pure electron plasma in a magnetic surface configuration is described by a self-consistent equation for the electrostatic potential[6]:

$$\nabla^2\phi = \frac{e}{\varepsilon_0} N(\psi)\exp\left(\frac{e\phi}{T_e(\psi)}\right) , \tag{1}$$

where ψ is the magnetic surface coordinate; that is, each magnetic surface is described by $\psi = constant$. The

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temperature is taken to be constant on a magnetic surface due to rapid thermalization along field lines $T_e = T_e(\psi)$. The function $N(\psi)$ indirectly specifies the density profile. The equilibrium plasma flow is

$$\vec{v}_e = \left(\frac{\vec{\nabla} p}{e n_e} - \vec{\nabla}\phi \right) \times \vec{B} \Big/ B^2 + \frac{v_{e\parallel}}{B} \vec{B} \ . \tag{2}$$

It can be shown that this flow cannot cross the magnetic surfaces.[6] The parallel flow adjusts itself to make the total particle flux divergence free, even if the perpendicular particle flux is not. With closed TF lines, or in a Penning trap, the parallel flow cannot do this, and hence, contours of constant density and electrostatic potential must coincide to keep the perpendicular particle flux divergence free.

The equilibrium electrostatic potential given by Eq. (1) minimizes an energy-like quantity[7]:

$$\begin{aligned} U &= \int \left(\frac{1}{2}\, \varepsilon_0 (\nabla\phi)^2 + N(\psi) T(\psi) \exp(e\phi/T(\psi)) \right) dV \\ &= \int \left(\frac{1}{2}\, \varepsilon_0 E^2 + p \right) dV \ . \end{aligned} \tag{3}$$

The equilibrium electron density increases near positive image charges. Although this is what would be naively expected, it is in contrast to what happens in the Penning trap[8] and the pure TF trap,[9] which have electrostatic potentials that maximize the potential energy, and the electron plasma tends to move away from positive image charges. However, the energy-like quantity that is minimized in equilibrium in a magnetic surface configuration is not the free energy, so this does not guarantee stability of all possible configurations. Further work is needed to develop proper stability criteria of pure electron plasmas confined on magnetic surfaces.

II.A. Confinement

Confinement in a nonneutral stellarator is limited by neoclassical diffusion, and possibly direct orbit losses, if the nonneutral stellarator does not possess quasi symmetry. In addition to the curvature and ∇B drifts, the E × B drift also causes particles to drift away from the magnetic surfaces, to the extent that the electrostatic potential is not constant on a magnetic surface. The electrostatic potential contours do match very closely to the magnetic surfaces in any region with appreciable plasma density, unless the Debye length is large.

In addition to the rotational transform, the E × B drift can be sufficiently strong to cause particles to move poloidally on magnetic surfaces, squeezing in their drift orbits. In the limit where this effect is dominant, a simple scaling estimate yields the following particle confinement time[6]:

$$\tau_p > \tau_e \frac{a^4}{\lambda_D^4} \ , \tag{4}$$

where τ_e is the electron collision time, and the estimate above is valid for small Debye lengths, and direct orbit losses (bad orbits) are neglected since the large electric field should prevent significant orbit losses.

During the initial formation phase of a pure electron stellarator plasma, the electric field will be weak, and the scaling law above will not hold. The magnetic surface configuration itself will provide excellent confinement of passing particles, but there will be some direct orbit losses until the space charge electric field becomes sufficient to significantly alter the particle orbits.

III. CONFINEMENT OF PARTLY NEUTRALIZED AND ELECTRON-POSITRON PLASMAS

A stellarator confines both positive and negative particles simultaneously whether space charge and internal currents are present or not. This allows the study of plasmas of arbitrary neutralization, a field of plasma physics that is currently largely unexplored. Positive particles, ions or positrons, will be very well confined in an electron-rich plasma by the overall negative space charge as well as by the magnetic surfaces. As one slowly neutralizes the plasma, the electric field weakens as the density rises. The electron confinement time will then be[10]

$$\tau_p \approx \tau_e \frac{a^4}{\lambda_C^4} \ . \tag{5}$$

This is a similar scaling to that of a pure electron plasma; however, the Debye length λ_D is replaced by the Coulomb length

$$\lambda_C^4 \equiv \frac{(n_e + n_p)^2}{(n_e - n_p)^2}\, \lambda_D^4 \ , \tag{6}$$

where n_e is the electron density and n_p is the density of the positive species, assumed to be a proton or a positron. In a quasi-neutral plasma a/λ_C is on the order of ≤ 1, whereas in a pure electron plasma $a/\lambda_C = a/\lambda_D \gg 1$.

A partly neutralized plasma may be characterized by $a/\lambda_D > a/\lambda_C \gg 1$. The confinement time given by Eq. (5) is long in this limit, and that may allow significant accumulation of positrons injected into a stellarator containing an initially pure electron plasma, even with the relatively weak positron sources available today.[10] Hence, this may be an attractive way to create the first laboratory electron-positron plasma.

As predicted by this scaling, confinement can become very poor as the plasma becomes quasi neutral unless the stellarator has quasi symmetry.

IV. IMPORTANT PARAMETERS FOR A NONNEUTRAL STELLARATOR EXPERIMENT

To guide the design of the CNT, we have identified important physics parameters for a nonneutral stellarator. Specifically, we have focused on parameters of importance to confining pure electron plasmas. The most fundamental physics parameter of any plasma physics experiment is a/λ_D, where a is the smallest characteristic size of the plasma—in the case of a stellarator, the minor radius. For the electron cloud to be a plasma, $a/\lambda_D \gg 1$ should be satisfied. In a nonneutral plasma experiment, including the CNT, this is a nontrivial constraint that requires careful matching of the injected electron energy to the plasma potential or some method of cooling the plasma after it has been injected. Particularly important in a nonneutral stellarator is $a/\lambda_D \gg 1$, given the predicted strong scaling of the confinement time with a/λ_D, Eq. (4). Another important parameter is the timescale for ion accumulation due to ionization of background neutrals τ_I. When $\tau_I \gg \tau_p$, electron plasmas will decay before being significantly contaminated. When $\tau_I \ll \tau_e$, ions will significantly neutralize an initially pure electron plasma before it decays away. It is desirable to maximize both timescales since either one can trivially be decreased. A large τ_I will be achieved through the ultrahigh vacuum design and operation at low plasma temperature. A large τ_p can be achieved by making the Debye length short compared to the system size, although there is a trade-off involved, which will be addressed in the following.

A key issue for a nonneutral plasma on magnetic surfaces is whether the plasma truly equilibrates on a magnetic surface through parallel dynamics faster than the E × B drift can take the plasma away from the magnetic surfaces. In a quasi-neutral plasma, this is basically always true, but the E × B drift can be very large in nonneutral plasmas. The timescale for perpendicular distortions is the E × B rotation time $\tau_\perp = 2\pi a/(\mathrm{E/B})$. The parallel thermal equilibration time $\tau_\parallel$ can be approximated by the time it takes a thermal particle to move along the magnetic field to fully explore the magnetic surface. The ratio of the two timescales can then be expressed as

$$\frac{\tau_{\mathrm{E\times B}}}{\tau_\parallel} = \frac{\pi a/v_{\mathrm{E\times B}}}{\pi R/\iota v_{th}} \approx 2\sqrt{2}\varepsilon\iota\,\frac{\lambda_D}{a}\sqrt{\frac{n_B}{n}}$$

$$= \varepsilon\iota B\left(2\sqrt{2}\,\frac{\lambda_D}{a}\sqrt{\frac{\varepsilon_0}{2mn}}\right) , \qquad (7)$$

where $n_B = \varepsilon_0 B^2/2m_e$ is the Brillouin density. Since $\iota < 1$, $\varepsilon < 1$, the conditions that $a/\lambda_D \gg 1$ and $\tau_\perp/\tau_\parallel \gg 1$ can only be satisfied simultaneously if $\sqrt{(n_B/n)} \gg 1$, which is well-satisfied in most nonneutral plasma experiments. The CNT is designed to operate in the $\sqrt{(n_B/n)} \gg 1$ regime as well.

V. DESIGN OF THE CNT

V.A. Design Criteria

The CNT is the first experiment specifically designed to study the physics of nonneutral and electron-positron plasmas confined in a stellarator. Based on the physics analysis just presented and the mission of the CNT as a university-based, inexpensive basic plasma physics experiment, the CNT was designed according to the following criteria, roughly in order of importance:

1. good magnetic surface quality without large islands and ergodic regions and resilience against magnetic field errors
2. ultrahigh vacuum level, $<3 \times 10^{-10}$ torr, to prevent ion contamination and to make neutral interactions (such as neutral drag) negligible
3. a value of $\varepsilon\iota B$ large enough to allow the ratio of perpendicular-to-parallel-dynamical timescales to be large
4. a simple coil system that could be constructed quickly and inexpensively
5. maximum physics flexibility, including the ability to change iota and shear profiles
6. a simple and inexpensive vacuum chamber, but with good port access for vacuum pumps, diagnostics, etc.
7. the ability to access configurations with some magnetic shear.

In contrast to fusion stellarator designs, we did not consider magnetohydrodynamic (MHD) stability nor optimization for neoclassical confinement, such as incorporation of quasi symmetry. MHD stability is likely irrelevant to the extremely tenuous plasmas studied in nonneutral plasma physics. Although an optimization of the magnetic configuration for neoclassical confinement would likely also be beneficial for nonneutral plasma confinement, it was decided that incorporation of quasi symmetry would make the coil design and fabrication too difficult to achieve with the relatively modest resources available for the CNT. Also, the E × B drift will significantly alter the particle orbits. If the number of Coulomb lengths can be made large enough, the mirror force responsible for the magnetic drifts and trapped particles will be small compare to the force from the electric field, and the particle orbits will be determined primarily by the E × B drift and parallel electric fields. This should drastically reduce prompt orbit losses, even for a classical stellarator.

V.B. Overview of Design Parameters

The CNT will be an ultralow aspect ratio, two-period classical stellarator capable of operating in three significantly different configurations. The three configurations correspond to three different angles between the two interlocking (IL) coils (see Figs. 1 and 2). In addition to the IL coils, only two other coils are needed: the poloidal field (PF) coils (see Sec. V.C for details on those). The main parameters of the experiment are listed in Table I.

The aspect ratio is ultralow, especially for the 64-deg configuration $A = 1.5$. This is evident from the three-dimensional renderings of the last magnetic surface, shown in Fig. 3. The average minor and major radii (a and R) and the aspect ratio A are defined as in the VMEC code, which equates πa^2 with the toroidally averaged cross-sectional area of the largest flux surface and then defines $2\pi R = V/\pi a^2$, where V is the volume of the largest flux surface. For such an ultralow aspect ratio and a shape that does not resemble an axisymmetric tokamak shape, other definitions of a and R give somewhat different results for A.

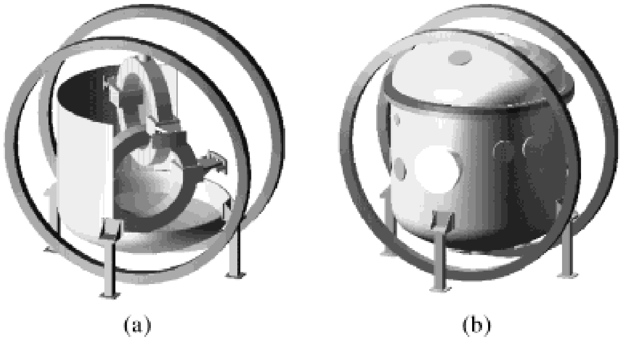


Fig. 1. Computer-aided design drawings of the CNT experiment: (a) is a cutaway view of the experiment, showing the PF coils and the IL coils inside the vacuum chamber, suspended from brackets welded to the inner diameter of the vacuum chamber.

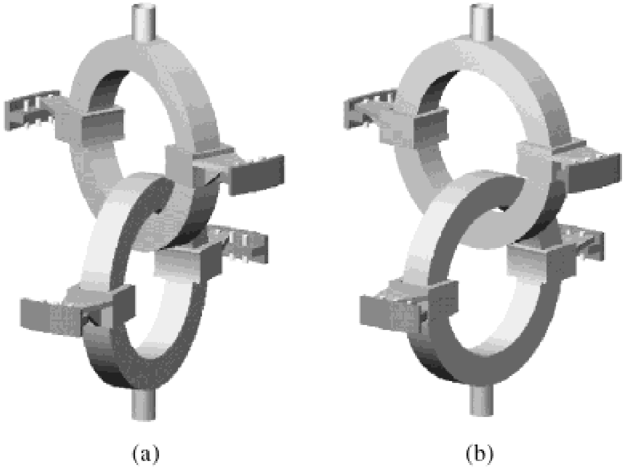


Fig. 2. The IL coils mounted on their brackets: (a) shows the two coils at an angle of 64 deg, and (b) shows them at an angle of 88 deg.

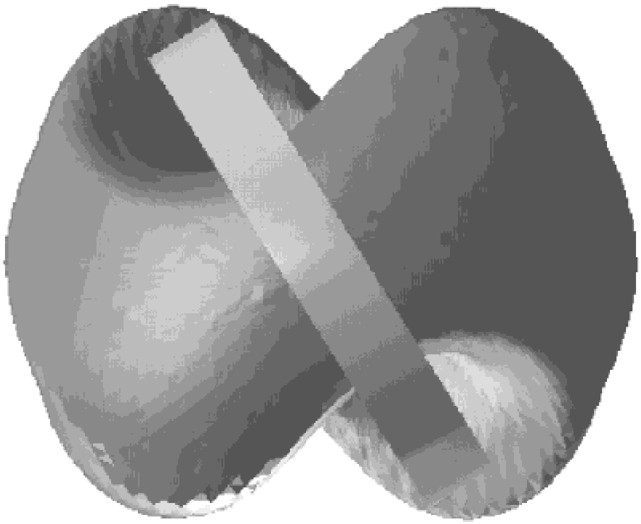


Fig. 3. Looking from above, a rendering of the outermost magnetic surface for the 64-deg configuration, with the top IL coil shown. The low aspect ratio is particularly striking in this view.

V.C. Coil Design

The coil configuration is perhaps the simplest of any stellarator constructed, consisting only of four circular, planar coils in two identical pairs: two IL coils and two PF coils, creating a two-period, low aspect ratio, classical stellarator configuration.

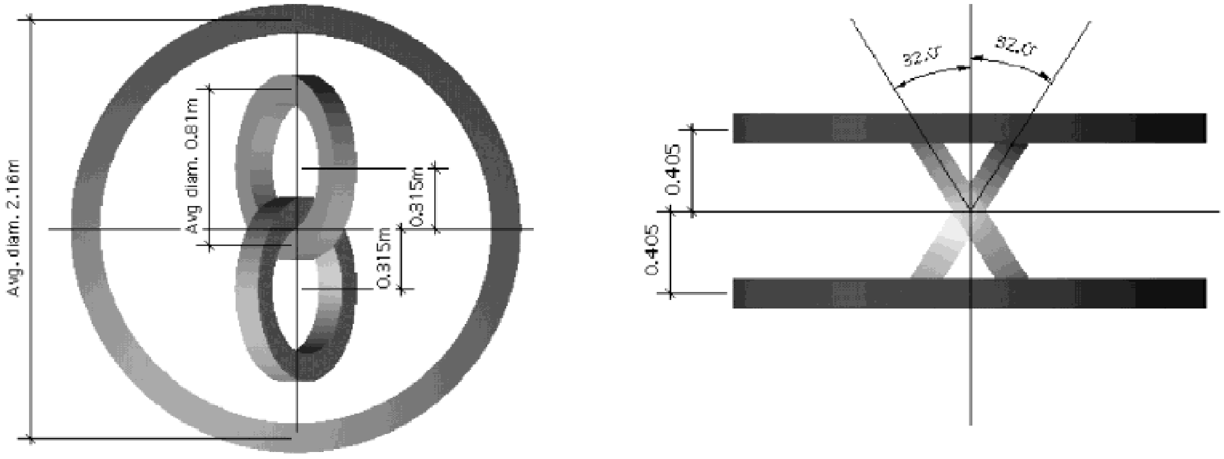
The PF coils will be placed outside the vacuum chamber, will have an average radius of 108 cm, and will carry 30 to 50 kA-turns when the IL coils are at full current. They will be wound from rectangular copper conductor with a central water cooling channel. The two IL coils will be wound from rectangular hollow copper conductor, with an average coil radius of 40.5 cm encased in a Type 316L stainless steel vacuum jacket. The two coils (see Fig. 2) are placed vertically inside the vacuum chamber, each coil suspended on brackets welded to the vessel inner diameter, with the leads coming out through the top and bottom vacuum vessel flanges, respectively. The vertical distance between the centers of the two IL coils will be 63 cm, and the angle between the two coils (the tilt angle) can be changed from 64 to 88 deg with an intermediate angle at 78 deg. The coil dimensions and placements are shown in Fig. 4. The design current is 170 kA-turns limited by a 200-kW

TABLE I

Overview of Parameters for the Three Different Magnetic Configurations in the CNT Stellarator

Tilt Angle	IL Coil Current (kA-turns)	PF Coil Current (kA-turns)	Magnetic Field on Axis (T)	Plasma Volume (m^3)	Average Major Radius, R (m)[a]	Average Minor Radius, a (m)[a]	Aspect Ratio, $A = R/a = 1/\varepsilon$[a]
64	170	40.3	0.31	0.230	0.303	0.196	1.5
78	170	43.9	0.28	0.128	0.319	0.143	2.3
88	170	46.8	0.26	0.131	0.325	0.143	2.4

[a] Following the definition used in the VMEC code; see discussion in text.



(a) (b)

Fig. 4. The coil configuration for the 64-deg tilt angle is shown in (a) a side view and (b) a top view.

direct-current (dc) power supply that will be used for the experiment. The added complexity of having the coils inside the vacuum chamber, especially with the strict requirements on the vacuum, was determined to be acceptable given the tremendous physics flexibility that comes from the ability to change the tilt angle. Equally important, it allowed an eightfold increase in $\varepsilon\iota B$ by allowing more copper in the coils (increasing B for the same power supply), a larger IL coil tilt angle (which increases iota), and larger plasma minor radius (since the toroidal vacuum chamber was actually cutting off good magnetic surfaces). The cylindrical vacuum chamber, described in Sec. V.E, was also more easily designed and manufactured than a toroidally shaped chamber would have been.

V.D. Magnetic Field

Given the tenuous plasmas to be studied in the CNT, only the vacuum magnetic fields were considered in the optimization of the magnetic fields for the CNT. The basic configuration, consisting of two interlocking circular coils with two large PF coils, was developed by Rudakov et al.,[11] who based their configurations on earlier work by Gourdon et al.[12] For the CNT design, a Fortran code was developed that takes advantage of the simple analytic formulas for the magnetic field of a current ring in terms of elliptic functions, eliminating the need to integrate the Biot-Savart formula along the current paths in the coils. This code was used to further optimize the design, to determine the optimum tilt angles and the optimum ratio of IL to PF coil currents, and to determine the susceptibility of the coil configurations to field errors caused by coil misalignments, winding transitions and current leads, and magnetic materials. Because of the analytic formulas, the code runs very fast, and these studies were performed on a standard Pentium-based workstation.

Iota profiles as a function of radius are shown for different tilt angles in Fig. 5. It is clear that both iota and the magnetic shear vary significantly as functions of the tilt angle. For example, at an angle of 64 deg, the central iota is ~0.15, with iota increasing to 0.24 at the plasma edge, whereas iota is nearly 0.6 on axis and slightly lower at the plasma edge at an IL coil angle of 88 deg. At

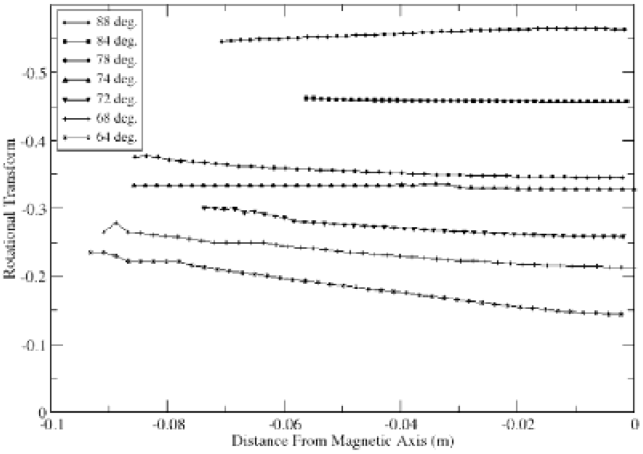


Fig. 5. Iota profiles for different angles between the IL coils.

intermediate angles, iota is at an intermediate value, and the configuration is nearly shear free. The field error analysis shows, not surprisingly, that configurations with iota going through low-order rational values are much more sensitive to field errors.[13] These tend to have smaller volumes, too, as outer surfaces break up due to these resonances. Three working tilt angles were chosen: 64, 78, and 88 deg. These tilt angles yield large magnetic surface volumes and relative resilience against field errors, and they scan the range of iotas from 0.15 to 0.56 and represent three generic shear configurations: positive (stellarator-like), near zero, and weak negative (tokamak-like) shear. Shear is predicted to be important in suppressing diocotron instabilities.[14] The three tilt angles also represent three rather different shapes, as shown in Fig. 6.

V.E. Vacuum Chamber

The vacuum chamber, shown in Fig. 7, is constructed from Type 316L stainless steel. It consists of an upright cylinder and two domed ends, with various ports. The top dome is removable for installation and repositioning of the IL coils. The inside of the vacuum chamber is electropolished, and only metal seals are used. It is bakeable to >200°C and should reach a vacuum of $<2 \times 10^{-10}$ Torr. The vessel has been leak checked and is awaiting final pumpdown to its base pressure after installation of the IL coil suspension brackets.

V.F. Expected Plasma Parameters and Discharge Scenarios

A desirable operational point for initial pure electron plasma studies could be $n_e = 10^{12}$ m^{-3} and $T_e =$ 1 eV. At this point, and at the 88-deg tilt angle, $a/\lambda_D \approx 25$, $\tau_\perp/\tau_\parallel \approx 15$, and $\tau_I \approx 2.7 \times 10^5$ s. The calculations here assume for simplicity that the neutrals are hydrogen atoms, which is not an unreasonable assumption as hydrogen often dominates in the ultrahigh vacuum range. The electron confinement time is >1 h as predicted by Eq. (4), dominated by electron-electron collisional transport. The ion contamination time is a very strong function of temperature though. At $T_e =$ 5 eV, $\tau_I = 2.4$ s, which is still rather long but now significantly shorter than the electron confinement time as well as the experimentally achievable pulse length. The magnets are powered by a 200-kW dc continuous wave power supply. This limits the maximum B-field on the magnetic axis to 0.3 T but allows plasma experiments with coil flattop currents lasting >15 s at full current and >60 s at half the design current. Although the coils are continuously water cooled, the coil conductors will heat up more or less adiabatically during a full-current pulse, and the allowable temperature rise of the copper determines the maximum pulse length.

VI. RELEVANCE TO FUSION STELLARATOR RESEARCH

The CNT research program can contribute to stellarator fusion research in several ways. The role of the electric field in confining plasma in stellarators is a very active area of research, and the CNT will explore the extreme case where the electrostatic potential energy of the particles completely dominates their kinetic energy. The ultrahigh vacuum and very low plasma densities will make the mean free path of particles (ions or electrons) extremely long, allowing detailed studies of collisionless orbit confinement. The simplicity of the CNT coils; the extremely low aspect ratio; the large, high-quality magnetic surfaces; and the relative resilience to magnetic field errors are all attractive features for a future fusion device, but the configuration will need to be optimized for high-beta stability and neoclassical confinement before it could become a serious candidate for a fusion reactor. Such an optimization, based on a parameterization of relatively simple coils rather than a parameterization of the plasma surface shape, and with a starting point in the CNT configuration, might lead to a fusion optimized stellarator with significantly simpler coils than the designs presently being considered.

VII. CONCLUSION

The CNT is being constructed specifically to study nonneutral and electron-positron plasmas confined in a stellarator. The design is a compromise between the need to build the device as easily and economically as possible and the desire to access the most interesting parameter regimes of such a device. We arrived at a design with a simple coil configuration: two adjustable IL in-vessel coils; a significant magnetic field strength; large,

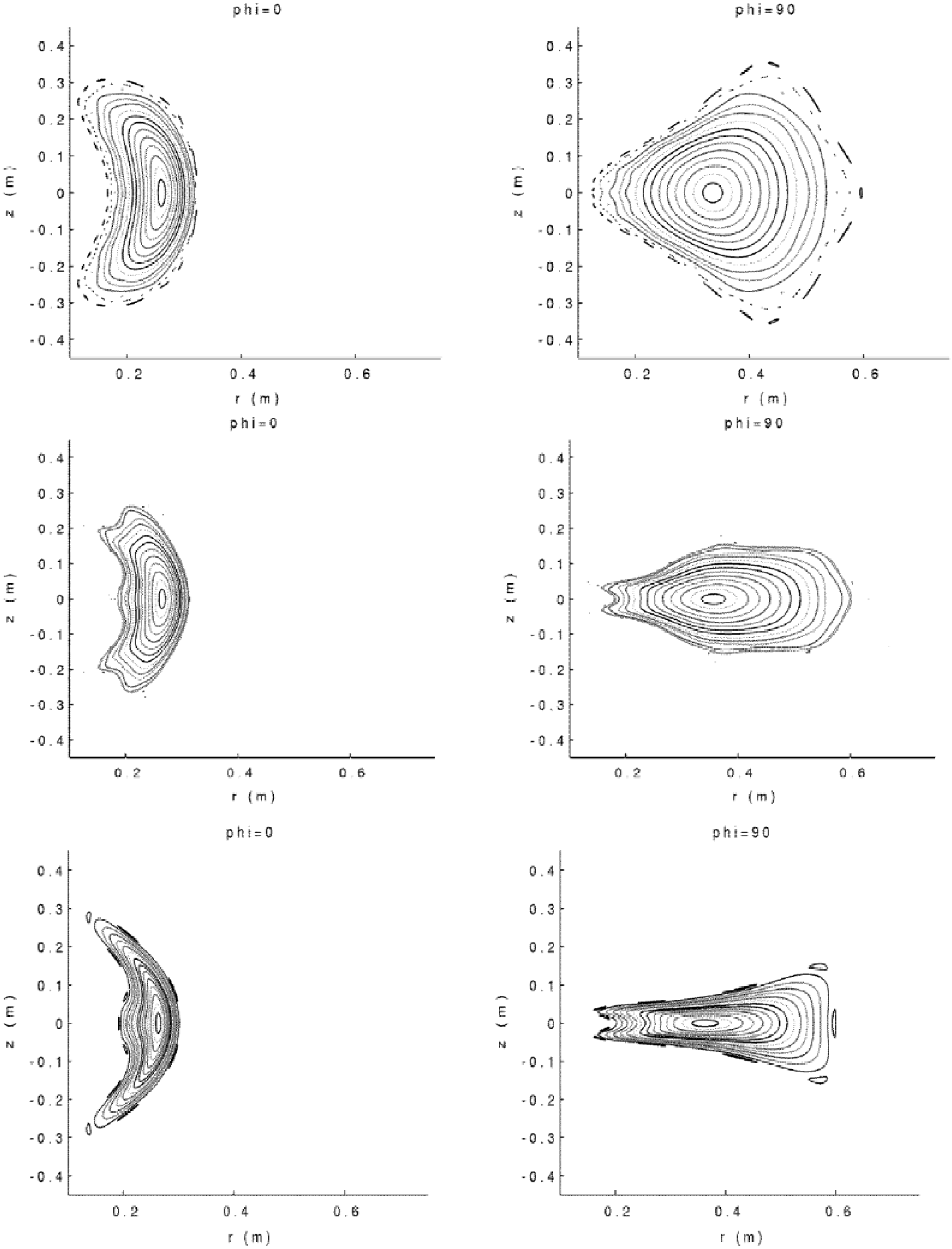


Fig. 6. Poincare plots of the magnetic surfaces at the two principal toroidal planes (left and right) for the three chosen tilt angles: 64 (top), 78 (middle), and 88 deg (bottom).

Fig. 7. The CNT vacuum chamber complete after leak tests at Ability Engineering in South Holland, Illinois.

ultralow aspect ratio magnetic surfaces; and an ultrahigh vacuum. The experiment is currently under construction.

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