Confinement of plasmas of arbitrary neutrality in a stellarator[a)]

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The equilibrium, stability, and transport of pure electron plasmas confined on magnetic surfaces is reviewed. The prospects for creation of partly neutralized plasmas and electron–positron plasmas confined in a stellarator are discussed. The Columbia Non-neutral Torus, a small ultrahigh vacuum stellarator being constructed at Columbia University, is being built to systematically study non-neutral plasmas confined on magnetic surfaces. The experimental design is discussed in the context of relevant physics parameters, and the initial experimental plans for creation and diagnosis of pure electron plasmas are discussed.
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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, including the ability to confine positive and negative particles simultaneously, and the ability to confine light, energetic particles. Closed toroidal field 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 non-neutral plasmas.[5,6] The physics of pure electron plasmas confined on magnetic surfaces is fundamentally different from previously studied configurations. A magnetic surface configuration is characterized by magnetic field lines that lie on toroidal surfaces (the magnetic surfaces), with each field line coming arbitrarily close to any point on the surface that it lies on. The parallel dynamics of the plasma then determines not just what happens on an isolated field line, but an entire surface. Magnetic surface configurations are well-known in fusion science, in particular the tokamak and the stellarator.[7] A stellarator is a magnetic surface configuration created entirely from magnets external to the plasma, so it has the advantage that it does not require any plasma currents, allowing steady state operation at arbitrarily low density. The Columbia Non-neutral Torus (CNT) is a stellarator currently being constructed specifically to investigate the physics of non-neutral plasmas confined on magnetic surfaces.[8] This paper reviews the theory of non-neutral plasmas confined on magnetic surfaces, the design of the CNT stellarator, and the near-term plans for the creation and diagnosis of pure electron plasmas in CNT.

II. CONFINEMENT OF PURE ELECTRON PLASMAS

A. Equilibrium

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

$$\epsilon_0 \nabla^2 \phi = eN(\psi)\exp(e\phi/T_e(\psi)). \tag{1}$$

Here ψ is the magnetic surface coordinate, that is, each magnetic surface is described by ψ=constant. The 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:

$$n_e = N(\psi)\exp(e\phi/T_e(\psi)). \tag{2}$$

The equilibrium plasma flow is

$$\mathbf{v}_e = \frac{(\nabla p/en_e - \nabla\phi)\times\mathbf{B}}{B^2} + v_\parallel \frac{\mathbf{B}}{B}. \tag{3}$$

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 toroidal field lines, or in a Penning trap, the parallel flow cannot do this, and hence, contours of constant density and electrostatic potential must coincide in order to keep the perpendicular particle flux divergence free.

Densities of pure electron plasmas confined in magnetic fields are so low that the currents they carry create negligible magnetic fields. Hence, the magnetic field is rigid.

Two-dimensional equilibria have been investigated numerically in the short Debye length limit ($a/\lambda_D \gg 1$) and the long Debye length limit ($a/\lambda_D \ll 1$).[9] In the long Debye length limit, electrostatic effects are small compared to thermal effects, and n_e is nearly constant on a magnetic surface, whereas ϕ is not, except in cases of high symmetry. In the short Debye length limit, ϕ becomes nearly constant on magnetic surfaces in the plasma interior. The plasma density varies considerably on a magnetic surface, especially near the plasma edge, where parts of a magnetic surface can be almost completely depleted of plasma even though other parts of the surface have an appreciable plasma density. In any region with appreciable density, the electrostatic potential is nearly constant. The zero temperature equilibrium equation, $\mathbf{v}_e \times \mathbf{B} = \nabla\phi$, implies that in the presence of plasma, the electrostatic potential is constant on a magnetic surface.

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B. Stability

The existence of the magnetic surfaces allows the electrons to move along the magnetic field from one part of the magnetic surface to any other part. As a consequence, the equilibrium electron density increases near positive image charges.[9] This is in contrast to the Penning trap[10] and the pure toroidal field trap,[11] which have electrostatic potentials that maximize the potential energy, and the electron plasma tends to move away from positive image charges. Such maximum energy states become unstable if the electrostatic energy of the electron plasma can be coupled to the outside world, for example to resistive conductors,[12] or to a resonant ion population. By contrast, the magnetic surface equilibrium is a minimum energy state, and therefore stable, with respect to low-frequency perturbations, that satisfy the following constraints:[13]

(1) Particles and entropy are conserved;
(2) force balance is maintained;
(3) the temperature is constant along B.

Magnetohydrodynamic instabilities that can be viewed as perturbed equilibria, interchange modes, resistive wall modes, and ballooning modes, all belong to this class of perturbations. The robust stability of a pure electron plasma to this class of perturbations is due to the fact that plasma on a given magnetic surface cannot escape it. The electrons cannot find a lower energy state by redistributing themselves on a magnetic surface, because of the constraint of local thermodynamic equilibrium on the surface, Eq. (2). Therefore, the plasma cannot tap into the energy stored in the repulsive potential created by the electron cloud.

Other types of instabilities may still exist, however. For example, parallel plasma oscillations could couple to perpendicular oscillations, such as diocotron modes. It has been shown that magnetic shear has a stabilizing effect on such perturbations.[14] Such perturbations are likely to be stable as long as the parallel equilibration time is much shorter than the $E\times B$ rotation time, effectively damping the parallel plasma oscillations before the $E\times B$ drift can dissipate the electrostatic energy. CNT has specifically been designed to allow access to this regime, see Sec. IV.

One may encounter other types of instabilities as the density is increased. Our treatment assumes $n_e \ll n_B$, where

$$n_B = \frac{\epsilon_0 B^2}{2 m_e} \tag{4}$$

is the Brillouin density,[15] or equivalently that $|m_e n_e \mathbf{v}_e \cdot \nabla \mathbf{v}_e| \ll |e n_e \nabla \phi|$. If n_e is on the order of n_B or larger, the convective term $m_e n_e \mathbf{v}_e \cdot \nabla \mathbf{v}_e$ can no longer be balanced by the $\mathbf{j}\times\mathbf{B}$ term, and an equilibrium no longer exists. One might therefore reasonably expect instabilities for stellarator pure electron plasmas where n_e/n_B is not small.

C. Confinement

Confinement in a non-neutral stellarator is limited by neoclassical diffusion. The guiding center drifts that cause the particles to drift away from the magnetic surfaces are the $E\times B$ drift as well as curvature and ∇B drifts:

$$\mathbf{v}_D = \frac{\mathbf{E}\times\mathbf{B}}{B^2} + \left(\frac{1}{2} m v_\perp^2 + m v_\parallel^2\right) \frac{\nabla B \times \mathbf{B}}{e B^3}. \tag{5}$$

The $E\times B$ drift causes drift excursions away from the magnetic surfaces because the electrostatic potential contours do not coincide exactly with the magnetic surfaces. 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. A simple scaling estimate yields the following particle confinement time:

$$\tau_p \approx \tau_e \frac{a^4}{\lambda_D^4}. \tag{6}$$

Here τ_e is the electron collision time, and the estimate above is valid for small Debye lengths. This estimate ignores the confinement due to the rotational transform, that is, it assumes that the guiding center drift orbit of the particle winds around on the magnetic surface primarily due to $E\times B$ drift. Hence, the deviations of a particle orbit away from a magnetic surface scale as

$$\frac{\delta}{a} \approx \frac{v_{\nabla B}}{v_{E\times B}} \approx \frac{T_e \nabla B}{e B^2} \frac{B}{\nabla \phi} \approx \frac{T_e}{e\phi} \approx \frac{\lambda_D^2}{a^2}. \tag{7}$$

Neoclassical confinement improvements due to the $E\times B$ drift are seen in quasineutral plasmas as well. In stellarators, one finds two self-consistent solutions to the ambipolar transport of electrons and ions. These are referred to as the electron root and the ion root, depending on the sign of the radial electric field. A pure electron plasma in a stellarator is exploring the physics of the ion root (negative radial electric field) in the extreme regime of $|e\phi| \gg T_e$, rather than $|e\phi| \approx T$ typical of quasineutral plasmas.

In the long Debye length limit, the confinement coming from the magnetic field will dominate and allow for a finite confinement time of the first injected electrons. In a classical stellarator, such as CNT, there will be two kinds of particles, well-confined and poorly confined particles (particles on bad orbits). Passing particles are well-confined with very long confinement times. The mirror-trapped poorly confined particles will be confined for at least $\tau \approx a/v_D$, where a is the minor radius and v_D is the guiding center drift velocity, Eq. (5). Even though this confinement time is low, on the order of 10^{-3} s in CNT, it is sufficient to start the accumulation of electrons and establish a finite Debye length. The passing particles will be confined for at least one collision time, which is much longer, at least initially. Thus, the passing particles will help establish the initial density. Hence, the confinement of the magnetic surfaces will allow initial accumulation of electrons even in the zero density limit, and confinement will improve as the number of Debye lengths increases. In fusion science, stellarators are optimized for neoclassical transport. These so-called advanced stellarators nearly eliminate the fraction of poorly confined particles, for example through the incorporation of a magnetic quasisymmetry.

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 will be very well confined in an electron-rich plasma, by the overall negative space charge as well as by the magnetic surfaces. This means that ions will accumulate at the rate given by ionization of background neutrals. Therefore, partially neutralized plasmas can be trivially obtained from pure electron plasmas by gas puffing and/or electron heating.

The excellent confinement of the positive species in an electron-rich plasma 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.[16] Hence, this may be an attractive way to create the first laboratory electron–positron plasma. The perfect mass symmetry and charge antisymmetry makes theoretical and numerical studies of these plasmas particularly simple, and they are therefore of intrinsic interest to basic plasma physics.[17] They may also be of interest to fusion science, as a way to benchmark codes that treat ions and electrons on an equal footing, such as the GS2 code, which treats both species fully kinetically.[18]

IV. DESIGN OF THE COLUMBIA NON-NEUTRAL TORUS

The Columbia Non-neutral Torus (CNT), a small stellarator currently being constructed at Columbia University, is the first experiment specifically designed to study the physics of non-neutral and electron–positron plasmas confined in a stellarator. The coil configuration is very simple, consisting only of four circular, planar coils. Two of these coils are interlocked and will be inside the cylindrical vacuum chamber. The stellarator magnetic field is characterized by $B \approx 0.3\,\mathrm{T}$ on the magnetic axis, (average) minor radius $a = 0.15–0.2\,\mathrm{m}$, (average) major radius $R = 0.3\,\mathrm{m}$, rotational transform $\iota = 0.15–0.56$, flattop pulse length 15 s, and a base pressure of $< 3\times10^{-10}$ Torr.

A. Important physics parameters

In order to guide the design of CNT, we have identified physics parameters of importance in a non-neutral stellarator, focusing on the physics of 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. In order for the electron cloud to be a plasma, $a/\lambda_D \gg 1$. In a non-neutral plasma experiment, including CNT, this is a nontrivial constraint that requires careful matching of the injected electron energy to the plasma potential, see Sec. V A. $a/\lambda_D \gg 1$ is particularly important in a non-neutral stellarator, given the predicted strong scaling of the confinement time with a/λ_D, Eq. (6). The single particle orbits will be significantly affected by the space charge if $e\phi/T_e \gg 1$. This criterion is automatically satisfied in a small Debye length pure electron plasma, since $|e\phi|/T_e \approx a^2/\lambda_D^2$.

Another important parameter is the time scale for ion accumulation due to ionization of background neutrals, τ_i. When $\tau_i \gg \tau_p$, the electron confinement time, electron plasmas will decay before being significantly contaminated. When $\tau_i \ll \tau_p$, ions will significantly neutralize an initially pure electron plasma before it decays away. It is desirable to maximize both time scales, since either one can trivially be decreased. A large τ_i will be achieved through the ultrahigh vacuum design and operation at low plasma temperatures. A large τ_p can be achieved by making the Debye length short compared to the system size, Eq. (6), although there is a tradeoff which is addressed below.

A key issue for a non-neutral plasma on magnetic surfaces is whether the plasma truly equilibrates on a magnetic surface through parallel dynamics faster than the $E\times B$ drift can take the plasma away from the magnetic surfaces. In a quasineutral plasma, this is generally true, but the $E\times B$ drift can be very large in non-neutral plasmas. The time scale for perpendicular distortions is the $E\times B$ rotation time $\tau_\perp = 2\pi a/(E/B)$. Any breaking of the parallel force balance will lead to plasma oscillations which are subsequently Landau damped in a finite temperature plasma. We approximate the parallel relaxation time by the time it takes a thermal particle to move along the magnetic field to fully explore the magnetic surface,

$$\tau_\parallel = 2\pi R/(\iota\sqrt{T_e/m_e}). \tag{8}$$

Then in order to ensure that the parallel force balance dominates over diocotron-type perpendicular dynamics, we must have $\tau_\perp/\tau_\parallel \gg 1$. The ratio of the two can be expressed as

$$\frac{\tau_\perp}{\tau_\parallel} \approx 2\sqrt{2}\epsilon\iota\sqrt{\frac{n_B}{n_e}}\frac{\lambda_D}{a}. \tag{9}$$

Here, $\epsilon = a/R$ is the volume averaged inverse aspect ratio. Since $\iota \sim 1$ and $a/R < 1$, the conditions that $a/\lambda_D \gg 1$ and $\tau_\perp/\tau_\parallel \gg 1$ can only be satisfied simultaneously if $\sqrt{n_B/n_e} \gg 1$, which is well satisfied in most non-neutral plasma experiments, where typical values are $10^{-2}–10^{-1}$. Equation (9) can be separated into two parts, describing the stellarator magnetic configuration and the plasma parameters, respectively,

$$\frac{\tau_\perp}{\tau_\parallel} \approx (2\sqrt{2}\epsilon\iota B)\left(\frac{\lambda_D}{a}\sqrt{\frac{\epsilon_0}{2m_e n_e}}\right). \tag{10}$$

Based on this expression, the CNT stellarator was designed to optimize $\epsilon\iota B$. Furthermore, the ability to access different values of ι, the magnetic surface shape, and the magnetic shear (the variation of ι from magnetic surface to magnetic surface) are desirable in order to sort out the relevant physics of these plasmas.

B. The choice of internal coils

The considerations above led to a design in which the interlocking coils were placed in the vacuum, replacing a tight-fitting toroidal vacuum chamber with an oversize cylindrical chamber. This allowed for a larger copper cross section in the coils (increasing B), a larger angle between the two coils (increasing ι) and a larger minor radius (increasing ϵ). As importantly, it enabled a design in which the angle between the interlocking coils can be varied, allowing significant physics flexibility. For example, at a 64° tilt angle, an ultralow aspect ratio $\epsilon = 1/A = 0.65$, low rotational transform $\iota \approx 0.2$, reversed shear (that is, ι increasing from the axis to the edge) configuration is achieved, whereas at 88°, a low aspect ratio $\epsilon = 0.4$, high rotational transform $\iota = 0.56$, normal shear configuration is achieved.

In order to reach ultrahigh vacuum, $p_n < 3 \times 10^{-10}$ Torr, each of the internal coils will be encased in its own stainless steel case which will act as a coil form as well as a vacuum chamber, with atmospheric pressure on the inside and ultrahigh vacuum on the outside. Further details of the CNT design can be found in Ref. 8.

V. PLANS FOR INITIAL PHYSICS RESEARCH IN CNT

The first phase of the CNT physics program will focus on the creation of small-Debye length pure electron plasmas, and a characterization of their equilibrium and stability properties at a wide variety of electron densities and temperatures. The methods for injection and diagnosis of these initial plasmas will be discussed in the following.

A. Electron injection

1. Initial operation with stationary injector

Initial electron plasmas in CNT will be created by thermionic emission from a radial array of heated tungsten meshes placed directly on the magnetic surfaces. There will be no anodes, instead each mesh will be backed by an insulator plate that will charge up negative and act to push the electrons off the filament. Parallel transport and the finite size of these meshes will ensure that the magnetic surfaces are filled within tens of microseconds. The primary challenge for the electron injection is to ensure that the electrons are injected at a large enough rate that the desired densities can be reached, and at a low enough kinetic energy that the electron temperature stays low (a few eV or less). A low electron temperature will ensure a small Debye length and a negligible ionization rate of the background neutrals. This requires an accurate match (within a few volts) between the electrostatic potential of the emitter and the plasma potential. Since perpendicular electron transport is slow compared to the time scale to fill up a magnetic surface, most electrons will come back to the emitter because of their in-surface motion ($E \times B$ and parallel transport). Some of the returning electrons will be electrostatically reflected by the emitter whereas others will hit the emitter. In steady state, the potential on the emitter will only be slightly lower than the plasma potential, because otherwise, there would be a large net flux of electrons going from the probe to the plasma.

The emission current necessary to reach a volume averaged density $\langle n_e \rangle$ is simply $I_{\mathrm{injection}} = e \langle n_e \rangle V / \tau_p$, where $N = \langle n_e \rangle V$ is the total number of electrons in the trap, and τ_p is the electron confinement time. As discussed earlier, mirror trapped particles will not be confined initially, when no space charge is present, but will leave the trap in a few milliseconds, whereas the trapped particles will be confined for at least one collision time, which is very long initially. If one conservatively ignores the excellent confinement of the passing particles, and estimates the initial confinement time as 2 ms, and the initial temperature at 5 eV, an initial density of $\langle n_e \rangle = 10^{11}\,\mathrm{m}^{-3}$, which yields $a/\lambda_D \approx 3$, will require an injection current of approximately 1 μA. Prototype injectors capable of injecting 10–100 μA with bias voltages of a few volts are currently being tested.

Plasma density profile control will be achieved by control of the plasma potential profile, through independent control of the voltages applied to the individual tungsten meshes. Due to the rapid parallel transport and the good confinement across magnetic surfaces, each surface will fill up with electrons such that the plasma potential of the magnetic surface will closely matches the voltage of the tungsten mesh.

2. Future injection mechanisms

The existence of a relatively large electron emitter internally in the plasma will be a local perturbation to the plasma and this will not prevent a self-consistent equilibrium from establishing itself. However, in addition to being the source of electrons, it will also be a major sink of electrons. With such an emitter, it may be difficult to measure the electron confinement time in the magnetic surface configuration. Therefore, it will be desirable to either move the magnetic surfaces away from the injector, or to retract the injector, once a plasma has been created. A smaller emitter would be less of a perturbation but would also potentially be less able to establish the desired electrostatic potential profile. Such scenarios are currently under investigation.

B. Baseline diagnostics

The initial diagnostics in CNT will be relatively simple. They will consist of two types of probes, external capacitive probes, and internal Langmuir-type probes.

1. External capacitive probes

The external capacitive probes, or sector probes, will be large copper meshes shaped to conform to external magnetic surfaces. The meshes will surround the plasma, and will be electrically isolated from each other and the vacuum chamber. The purpose of these meshes is twofold. When the meshes are all kept at the same potential, they will provide a boundary condition which makes the electrostatic potential conform to the magnetic surfaces, which will increase the confinement time. The total charge on the meshes will be equal to and opposite of the total charge in the electron plasmas, and the charge distribution on the meshes will provide information about the equilibrium. Meshes can also be biased at different potentials, perturbing the plasma equilibrium. For example, one can apply a low-frequency sinusoidal voltage to one mesh segment, and record the induced voltages or currents on the other meshes. The mutual capacitances that can be derived from such a measurement provide further information about the equilibrium, because they will depend on exactly how the plasma equilibrium responds to the sinusoidal perturbation.

2. Internal Langmuir probes

In addition to the capacitive probes discussed previously, internal probes will be used in CNT. Compared to standard Langmuir probe theory in a quasineutral plasma, the current–voltage characteristic in a pure electron plasma differs because of the absence of ions, and because of the presence of a strong $E\times B$ flow velocity.[19] The ratio of $v_{E\times B}$ to $v_{\mathrm{th}}=\sqrt{T_e/m_e}$ in a pure electron plasma is approximately

$$\frac{v_{E\times B}}{v_{\mathrm{th}}}\approx\sqrt{\frac{n_e}{n_B}}\frac{a}{\lambda_D}. \tag{11}$$

When this ratio is not small, there are significant corrections to the standard exponential form of the electron current. It should be noted that the optimization of $\epsilon\iota B$ ensures that there will be plasma parameter regimes in CNT in which this ratio will be small. Local values of the electron temperature and density and the electron fluid velocity can be obtained by comparison between the theoretically expected current–voltage characteristics (properly corrected for the $E\times B$ flow if necessary) and those obtained experimentally. In addition, emissive high impedance (floating potential) probes will be used to obtain local measurements of the electrostatic potential, including fluctuations. High impedance probes in a pure electron plasma should be emissive since the floating potential of a nonemissive probe in a pure electron plasma is ill-defined, due to the absence of an ion current. If any significant ion accumulation occurs, this can be diagnosed as a finite ion saturation current on the current–voltage characteristic of the nonemitting probes.

C. Expected initial plasma parameters

Plasma densities in CNT are expected to be in the range of 10^{11}–$10^{14}\,\mathrm{m}^{-3}$, depending on the negative bias voltages applied to the tungsten meshes and the size of the plasma. Expected plasma temperature will be in the range from 0.5 to 20 eV, depending on the injection energy (primarily the matching between the plasma and the mesh potentials). For the 64° tilt angle configuration, which has $R=0.3\,\mathrm{m}$, $a=0.2\,\mathrm{m}$, $\iota\approx 0.2$, and $B=0.3\,\mathrm{T}$, one might operate at $T_e=3$ eV and $n_e=10^{12}\,\mathrm{m}^{-3}$. This would yield the following parameters: Debye length $\lambda_D=0.012\,\mathrm{m}$, core plasma potential $\phi_{\mathrm{axis}}\approx-180\,\mathrm{V}$, ratio of perpendicular to parallel equilibration time $\tau_\perp/\tau_\parallel=16$, electron–electron collision time $\tau_e\approx 1$ s, electron confinement time $\tau_p\approx 6\times 10^4$ s, ion accumulation time $\tau_i=12$ s (at $p_n=3\times 10^{-10}$ Torr, assuming neutral hydrogen atoms). Another operating point could at $B=0.1\,\mathrm{T}$, constricting the plasma to have a minor radius of $a=0.05\,\mathrm{m}$. With a $n_e=2\times 10^{13}\,\mathrm{m}^{-3}$, $T_e=2$ eV plasma, one would get the following parameters: $\lambda_D=0.002\,\mathrm{m}$, $\phi_{\mathrm{axis}}\approx-226\,\mathrm{V}$, $\tau_\perp/\tau_\parallel\approx 0.2$, $\tau_e\approx 0.03\,\mathrm{s}$, $\tau_p\approx 6\times 10^3\,\mathrm{s}$, $\tau_i\approx 145\,\mathrm{s}$.

These two operating points illustrate the capability of CNT to access the relevant physics regimes of a pure electron plasma confined on magnetic surfaces.

VI. CONCLUSION

The physics of non-neutral plasmas confined on stellarator magnetic surfaces will be different from previously studied configurations with respect to equilibrium, stability, and transport. The entire spectrum of charge neutralization from pure electron to quasineutral plasma can be studied in a stellarator. Additionally, a non-neutral, electron-rich stellarator may be the ideal confinement device for creation of electron–positron plasmas. The CNT device is under construction and will be able to study the equilibrium, stability, and confinement of non-neutral plasmas on magnetic surfaces.

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