ELMO Bumpy Torus with Enhanced Confinement

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A toroidal array of racetrack-shaped coils whose major axes are alternately oriented vertically and horizontally ("Andreoletti coils") provides neoclassical confinement that is strikingly superior to a simple bumpy torus of similar aspect ratio but circular coils. For suitable parameters, the drift surfaces of deeply trapped and passing particles can be made concentric. At large minor radii, near the stabilizing ELMO rings, there exist closed, almost concentric drift surfaces for *all* pitch angles.

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In experiments carried out over the past decade, the ELMO Bumpy Torus[1] has been shown to operate in regimes that are free of large-amplitude fluctuations in the steady-state plasma parameters. In these quiescent regimes, the confinement of plasma particles and energy has been interpreted by use of the neoclassical theory of transport.[1,2] This theoretical model derives plasma transport rates from the geometrical characteristics of the surfaces traced out by the guiding-center drifts of the energetic plasma particles (drift surfaces). For most orientations of particle velocity relative to the magnetic lines of force (pitch angles), and within a central region of the magnetic volume, the drift surfaces are closed and nested with roughly circular cross sections in reference planes that are generally chosen at the midplane of any sector of the bumpy torus. These sections are not, however, concentric; the locations of their centers depend on the particle pitch angle. This dependence upon pitch angle and the associated dispersion of particle drift surfaces about the plasma pressure surfaces determine the transport rates in present-day neoclassical theories. For pitch angles in a narrow range near the transition from trapped- to passing-particle orbits, the azimuthal component of the guiding-center drift velocity can vanish,[3] and the drift surfaces then become vertically elongated. These so-called resonant particles can exhibit large radial excursions and are consequently confined only in a restricted region of the magnetic volume that vanishes for small enough toroidal aspect ratio. The role of these resonant particles in determining the overall confinement properties of the ELMO Bumpy Torus is not adequately understood at present, but in a nearly collisionless plasma the resulting loss of particles scattering slowly through the resonant interval in pitch angle seems likely to have serious consequences.

Strictly speaking, the above picture of confinement applies only for high-energy particles. For particles of moderate energy ($\epsilon \sim e\varphi \sim kT$), the radial ambipolar potential can significantly modify the drift surfaces. However, previous work[4] has shown that the vacuum field drift surfaces, when compared with more accurate ambipolar results, provide a good measure of relative confinement properties among various coil configurations.

It has been recognized for many years that the geometrical characteristics of the drift surfaces can be affected by varying the magnetic coil configuration relative to the elementary bumpy torus with simple circular coils, and several variants have been analyzed extensively.[4,5] Roughly speaking, these alternative coil configurations were more successful in improving the confinement of trapped particles than of passing particles, and little qualitative change in resonant-particle behavior was possible.

Here we report a remarkable improvement in the drift-surface geometry for trapped, passing, and resonant particles in a bumpy torus made up of a toroidal array of racetrack-shaped coils whose major axes are alternately oriented vertically and horizontally. Because of the resemblance of one sector of this torus to parallel, magnetic-mirror coils analyzed by Andreoletti,[6] the coils may appropriately be called "Andreoletti coils." But the elongations discussed here are only 2:1, in contrast to the extreme elongations required for the magnetic well of interest in the early mirror studies.

The basic parameters that define the ELMO Bumpy Torus/enhanced confinement (EBTEC) configuration are as follows: the elongation of the racetrack-shaped coils, H/W; the major radius of the torus, R, relative to the minor radius in which plasma is confined, a; the position of the "limiter," which can be either a material limiter or the surface on which the stabilizing ELMO ring is located; the relative shift in the centers of alternate coils, ΔR; and the mirror ratio in each sector, M. In this Letter, the confinement characteristics of an EBTEC configuration (similar in overall dimensions to the proposed EBT-P device[7]) are compared to those of a circular-coil torus that has identical values of R, a, and M. For the EBTEC configuration reported here, the shift parameter, ΔR, has been chosen to align the centers of the trapped- and passing-particle drift surfaces exactly. One quadrant of the resulting EBTEC is shown projected onto the equatorial plane of the torus in Fig. 1. It is qualitatively clear from the two field lines shown in Fig. 1 that EBTEC achieves a magnetic configuration somewhat reminiscent of that studied by Meyer and Schmidt.[8]

In the work reported here, drift surfaces are calculated numerically with the magnetic field geometry code EFFI[9] and the entire technique is described in Ref. 3. We first compare midplane drift orbits of deeply trapped ($V_\parallel/V \to 0$) and fully passing ($V_\parallel/V \to 1$) particles for EBTEC, Fig. 2(a), and the corresponding elementary bumpy torus, Fig. 2(b). $(V_\parallel/V)^2$ is defined as $(\epsilon - \mu B_{00})/\epsilon$, where ϵ and μ are the energy and magnetic moment of the particle and B_{00} is the maximum magnetic intensity in the midplane between two successive coils. For the deeply trapped particles, the center of the section of surface is indicated by the open circle ($V_\parallel/V = 0$).

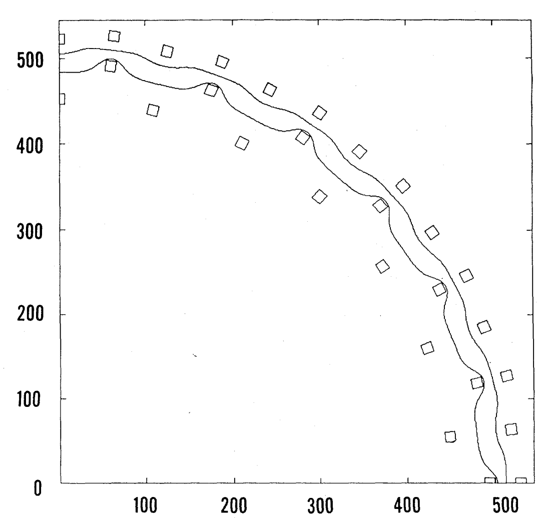

FIG. 1. One quadrant of EBTEC projected onto the equatorial plane, with two magnetic lines of force shown.

The largest section of surface for fully passing particles contained within the surface for trapped particles is also shown in these figures, and the center is indicated by the solid dot ($V_\parallel/V = 1$). Note that in EBTEC the two surfaces are nearly concentric, whereas in the elementary bumpy torus the centers are separated by 7 cm. It is this separation that is usually taken as the basic step size in a random-walk picture of neoclassical diffusion in the absence of any ambipolar field.

The centering of the drift surfaces results from the outward coil shift. It is suggested by Fig. 1 and borne out by detailed study that the inner field lines are preferentially displaced by this shift. Since the passing-particle drift surfaces have constant $\oint dl$, the passing-particle drift surfaces move outward. By comparison, the surfaces of constant mod$B$, on which the deeply trapped particles drift, are not as responsive to the outward shift. Thus, a shift can exist for which the two drift surfaces are aligned, and approximately that value was used in Fig. 2.

Also shown in this figure are the projections of the outline of a material limiter, along magnetic lines of force, onto the reference plane. The position of the material limiter was dictated by consideration of shielding of the magnetic coils in all cases. Note that the circular-coil (CC) drift surfaces do not touch the limiting surface because they are constrainted to be within $|B| \lesssim 0.6 B_{00}$ to ensure adiabatic confinement of the energetic electrons comprising the ELMO rings. The EBTEC configuration has a larger magnetic field scale length, R_c ($R_{c,\mathrm{EBTEC}} \sim \frac{4}{3} R_{c,\mathrm{CC}}$), and is limited by the material limiter rather than by

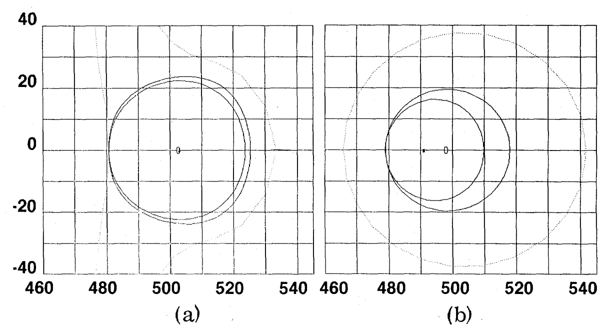

FIG. 2. (a) Sections of surface of deeply trapped and fully passing particles in EBTEC (solid curves) and the projection of the material limiter onto the reference plane. (b) Sections of surface of deeply trapped and fully passing particles in a simple bumpy torus of equal R, a, and M.

considerations of adiabaticity. Although R_c is primarily determined by the coil "size" and mirror ratio, the coil size required to provide a given plasma minor radius, a, varies with aspect ratio, R/a, because of the toroidal shift and the resultant "scrapeoff." For this reason, $R_{c,\mathrm{EBTEC}}/R_{c,\mathrm{CC}}$ decreases with increasing aspect ratio. This property of EBTEC may influence some properties of the ELMO rings and the associated electron-cyclotron heating processes.

The cross-sectional areas (in the reference plane) of drift surfaces of particles with pitch angles intermediate to those of Fig. 2 are shown in Fig. 3, where the resonant particles are clearly visible in the elementary-bumpy-torus case. Note that closed drift surfaces with nearly the full cross-sectional area exist for *all* pitch angles in EBTEC, whereas particles with $V/V_{\parallel} \sim 0.8$ are not confined in any region of the elementary bumpy torus. Resonant-particle behavior (resonance width and location in pitch angle) in the elementary bumpy torus is strongly affected by mirror ratio, M; a larger M reduces the resonance width. However, M is limited by both physics (e.g., adiabaticity) and engineering (magnet technology) considerations.

The nature of the near-resonant drift surfaces is further clarified in Figs. 4(a) and 4(b), for EBTEC and the elementary bumpy torus, respectively. Again, the figures show sections of surface nested inside the outermost confined surface. Note that in EBTEC, the *outermost* surfaces retain their nearly concentric and circular (in the midplane) cross sections, while the resonant phenomena is apparent in the distortion of the *inner* surfaces. For the elementary case, no resonant-particle drift surfaces close within the adiabatic confinement volume at this toroidal aspect ratio. Instead, the resonant-particle drift surfaces, shaped like inverted dees, are shifted inward and vertically elongated to such an extent that they close only outside the maximum radius for adiabatic confinement, as shown in Fig. 4(b).

The improved resonant-particle behavior in EBTEC can be interpreted as due to the combined effects of (1) reducing the extent of the radial interval within which the resonance condition[3] is satisfied, and (2) centering the drift surfaces of the transitional and passing particles.[8] Both of these effects are evident in comparing Figs. 4(a) and 4(b).

The reduced symmetry of the noncircular Andreoletti coils leads to a significant reduction in the size of the radial interval within which particles of a given pitch angle can satisfy the resonance condition, viz., that the poloidal component of the guiding-center drift velocity $r\Omega_p = 0$.[3] The vertical drift due to toroidicity is uncompensated only in this radial interval, and the vertical elongation of the resonant-particle drift surfaces is proportional to the extent of the resonant regions. Outside of this resonance region, the orbits become nearly circular.

The centering of transitional-particle drift surfaces which results from the outward shift of the vertical coils can be qualitatively understood in terms of the second adiabatic invariant, $J = \oint dl\, v_{\parallel}$. As noted earlier, the coil shift preferentially

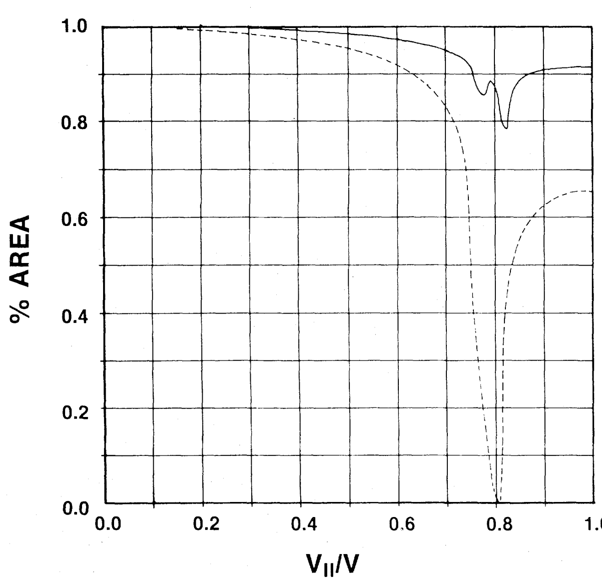

FIG. 3. The fraction of the cross-sectional area occupied by closed drift surfaces for varying pitch angle in ECTEC (solid curve) and the corresponding simple bumpy torus (dashed curve).

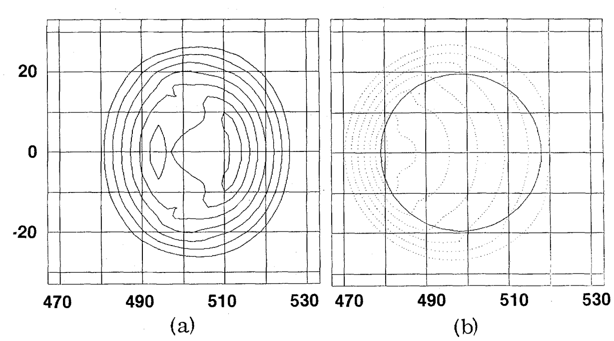

FIG. 4. (a) Sections of surface for resonant particles in EBTEC ($V_{\parallel}/V = 0.8$). (b) Sections of surface for nearly resonant particles in the simple bumpy torus of equal R, a, and M.

lengthens the inside field lines and, since the resonant particles sample the full length of the field lines, the orbits will be shifted outward, much the same as are the passing-particle orbits.

In conclusion, we have exhibited a new magnetic configuration, EBTEC, with remarkably improved confinement characteristics as inferred from the geometric properties of the guiding-center drift surfaces, in accordance with neoclassical theory. Note that the "effective aspect ratio" for EBTEC cannot be determined, as in earlier aspect-ratio–enhancement studies, by direct comparison with elementary bumpy tori of varying aspect ratio. The dispersion in the centers of the drift surfaces can vanish in EBTEC, whereas this only occurs at infinite aspect ratio in an elementary bumpy torus. The behavior of resonant particles is also radically different in EBTEC than in an elementary bumpy torus: EBTEC provides a large volume of absolute confinement that suggests the possibility of a qualitatively different collisionless equilibrium. In the elementary bumpy torus, the resonant loss region required an anisotropic equilibrium with special reserviors of free energy to drive collective fluctuations. In EBTEC, it appears entirely feasible to confine an isotropic collisionless equilibrium.

We have reported results for only one aspect ratio, but study of other aspect ratios indicates similar behavior. For smaller R/a, a larger ΔR is required to center the orbits, e.g., for $a=20$ and $M=2.25$, $\Delta R=24$ cm for $R=500$ cm, while $\Delta R=36$ cm for $R=350$ cm. The resonant drift surfaces become more distorted at this lower R/a but still enclose nearly the same area. Reactor-size EBTEC's must include blanket and shielding which cause some scrapeoff of the outer drift surfaces. Nevertheless, preliminary studies have shown that it is still possible to make trapped- and passing-particle drift orbits concentric. One drawback of the present EBTEC coil configuration, relative to the elementary bumpy torus, is the poorer volume utilization of the magnetic field (see Fig. 1). However, having demonstrated a superior magnetic field configuration, it may be possible to optimize with respect to volume utilization the coil configuration which creates this field.[10]

Although it remains to analyze self-consistent, ambipolar transport equilibria in EBTEC, it is clear that ambipolar potentials in EBTEC are far less likely to alter the geometry of the guiding-center drift surfaces than in the elementary bumpy torus. Indeed, moderate ambipolar potentials could further circularize the inner drift surfaces of resonant particles in EBTEC. The striking potential for enhanced confinement indicated by the present results provides a strong incentive for detailed studies of design issues that have been considered previously in the conceptual design of the EBT-P and EBT reactor concepts.

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