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Inward Transport of a Toroidally Confined Plasma Subject to Strong Radial Electric Fields

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The NASA Lewis bumpy torus experiment confines and heats a toroidal plasma by the simultaneous application of strong dc magnetic fields *and* electric fields. Digitally implemented spectral analysis techniques were used to investigate experimentally the frequency-dependent fluctuation-induced transport across the toroidal magnetic field. It was observed that when the electric field pointed radially inward, the fluctuation-induced ion flux was inward and a significant enhancement of the plasma density resulted.

George[1] suggested that a suitable combination of magnetic and electric fields might be used to confine as well as heat a plasma of fusion interest. Theoretical papers by Kovrizhnykh[2,3] and Stix[4] have examined the effects of ambipolar electric fields on radial transport in toroidal plasmas. The purpose of the present paper is to show that the density of a toroidal plasma can be enhanced by radial electric fields far stronger than the ambipolar values, and that, if such electric fields point into the plasma, radially inward fluctuation-induced transport can result.

The steady-state plasma in the NASA Lewis bumpy torus facility is generated by a modified Penning discharge operated in a 12-coil bumpy-torus magnetic field of 1.5-m major diameter.[5] The toroidal plasma is biased to high potentials by water-cooled electrode rings which encircle the minor circumference of the plasma and are located in the midplanes of two sectors of the toroidal array. Previous investigations[5] have shown that, in common with Penning discharges and magnetronlike devices, the plasma forms rotating spokes which gyrate around the minor circumference of the plasma with velocities comparable to the spoke rotation velocity.[5] Electron kinetic temperatures are on the order of 10 eV.

Radial profiles of the floating potential of the plasma were measured with a hydraulically actuated Langmuir probe.[5,6] Some results from these measurements are as follows: (1) The entire toroidal plasma floats to potentials comparable with the electrode ring voltage; (2) the entire plasma can be biased to high potential with positive- or negative-electrode rings; (3) the electric field strength within the plasma often exceeds 1 kV/cm; (4) the radial electric fields point radially outward in the vicinity of the plasma boundary for positive midplane electrode polarities, and point radially inward toward the plasma when negative potentials are applied to the electrode rings, as shown in Fig. 1.

The plasma density profiles are triangular (negative polarity) or flat (positive polarity) for the conditions discussed here.[6] The effects of toroidicity of the electric field and weak magnetic "error" fields on plasma confinement are discussed elsewhere.[7,8] These two effects were minimized (except for the illustrative data in Figs. 4 and 5) so that the radial transport was dominated by the magnitude and direction of the radial electric field.

The effect of the direction of the electric field on particle containment is shown in Fig. 2(a), where the average electron number density is shown for a paired comparison in which the only factors which differed were the polarity of the two midplane electrode rings and the geometric position of the midplane electrodes, which was optimized for each polarity.[7,8] The average electron number density is at least a factor of 5 higher when the radial electric field points inward, than is the case when it points outward.

In order to investigate this apparent difference in confinement, measurements of the fluctuation-induced particle transport were made with a new technique, the key ideas of which are described elsewhere.[9,10,11] Low-frequency ($\omega \ll \omega_{ci}$) electrostatic potential fluctuations are assumed so that a particle's fluctuating velocity may be estimated in terms of $\tilde{E}/B$ drift, where $\tilde{E}$ is a fluctuating electric field and B is the static confining toroidal magnetic field. The fluctuating electrostatic potential had rms values on the order of 50 V, which was associated with rotating spokes and background turbulence. The time-average radial particle flux is then given by

$$\langle \tilde{n}\tilde{v}_r \rangle = \langle \tilde{n}\tilde{E}_\theta \rangle / B. \qquad (1)$$

In Ref. 9 it is shown that the particle flux due to a small band of frequencies centered at ω is derivable from Eq. (1) and is given by

$$T(\omega) = \frac{K_\theta(\omega)\hat{\varphi}(\omega)\hat{n}(\omega)\sin\alpha_{n\varphi}(\omega)|\gamma_{n\varphi}(\omega)|}{B}.$$

The flux given by $T(\omega)$ depends upon the product of the rms values of density $\hat{n}(\omega)$ and potential fluctuations $\hat{\varphi}(\omega)$, the sine of the phase angle $\alpha_{n\varphi}(\omega)$ between the density and potential fluctuation, and the degree of mutual coherence $|\gamma_{n\varphi}(\omega)|$ between the potential and density fluctuations in the spectral band under consideration. The wave number $K_\theta(\omega)$ appears since the electrostatic approximation $[E = -\nabla\hat{\varphi} = ik_\theta(\omega)\hat{\varphi}]$ is assumed. The fluctuations required to implement Eq. (2) were measured simultaneously by three probes mounted on a hydraulically actuated assembly which could remain in the plasma for a few tenths of a second while data were being taken. The potential fluctuations and wave number $K_\theta(\omega)$ are measured by two capacitive probes separated by a known angle at the same radius; the ion density fluctuations are measured by a Langmuir probe in ion saturation displaced 1 cm along a magnetic field line from one of the capacitive probes. Since the Langmuir probe was operated in ion saturation, it measures the ion flux. The net flux $T(\omega)$ is a real quantity and may take on either a positive or negative value, indicating that the ion transport is in either an inward or out-

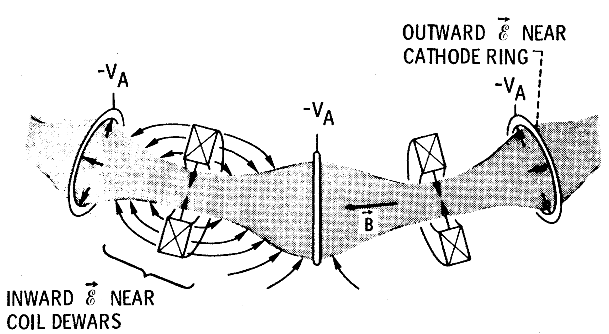

FIG. 1. Schematic of electric field distribution around a negatively biased bumpy-toroidal plasma.

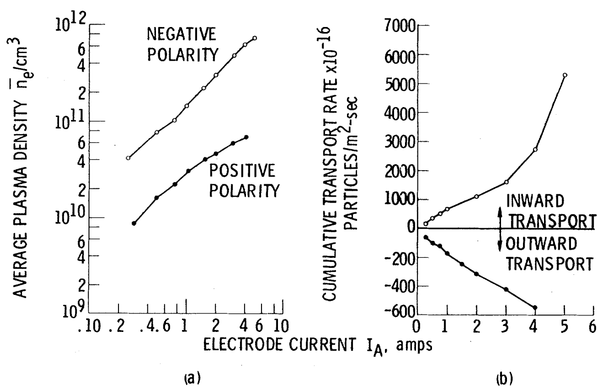

FIG. 2. A paired comparison of the confinement obtained with positive and negative bias of the toroidal plasma for $B_{max} = 2.4$ T. (a) Average plasma number density as a function of electrode current. (b) Asymptotic cumulative transport rate as a function of electrode current.

ward direction, respectively. $T(\omega)$ was measured in the midplane of a sector which did not contain an electrode ring, at the outer boundary of the plasma.

Figure 3 shows the ion flux corresponding to an electrode current of $I_a = 0.75$ A (Fig. 2). The upper graph is the transport spectrum itself. The lower graph is the summation of the transport spectrum up to the frequency shown on the abscissa. All ordinates are plotted in absolute units. In Fig. 3(a) the negative-electrode case, with radially inward electric fields, has a transport spectrum that is positive in sign, indicating radially inward transport. The transport is associated with three discrete frequency bands, all below 150 kHz. For this condition, the ion flux is radially outward in the sectors containing the negative-electrode rings,[7] and the net ion confinement is a balance between volume ionization in the plasma, flow into the empty sectors, losses in the sectors with electrode rings, and possibly other processes. In Fig. 3(b), the positive-electrode case has a transport spectrum which is negative in sign, or radially outward toward the surrounding walls. The outward transport for this case occurs over a broad frequency band out to 350 kHz, and could be considered "turbulent transport." The asymptotic cumulative transport rate for the two electrode polarities is plotted as a function of electrode current in Fig. 2(b). For both electrode polarities, the asymptotic cumulative transport rate increases with increasing electrode current in an almost linear manner.

The particle-containment time and average

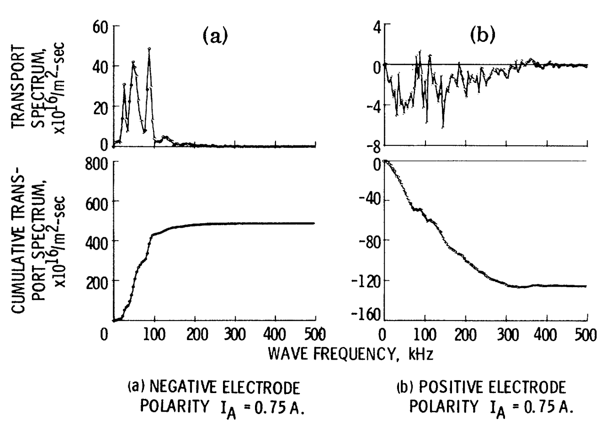

FIG. 3. Transport spectra and asymptotic cumulative transport rates for an electrode current of $I_a = 0.75$ A. (a) Negative electrode polarity, (b) positive electrode polarity.

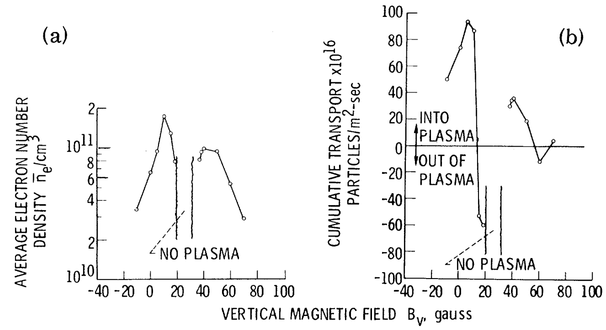

FIG 4. Effect of a weak vertical magnetic field on plasma containment for negative electrode polarity. (a) Average electron number density as a function of vertical magnetic field. (b) Asymptotic cumulative transport rate at the location of the probe as a function of vertical magnetic field.

electron number density in this plasma are extraordinarily sensitive to the value of a weak vertical magnetic field applied to the containment volume, which is about 10^{-3} of the toroidal magnetic field.[8] The effect of this vertical magnetic field on the average electron number density is shown in Fig. 4(a), for negative electrode polarity. When these data were taken, other independent variables were held constant. The asymptotic

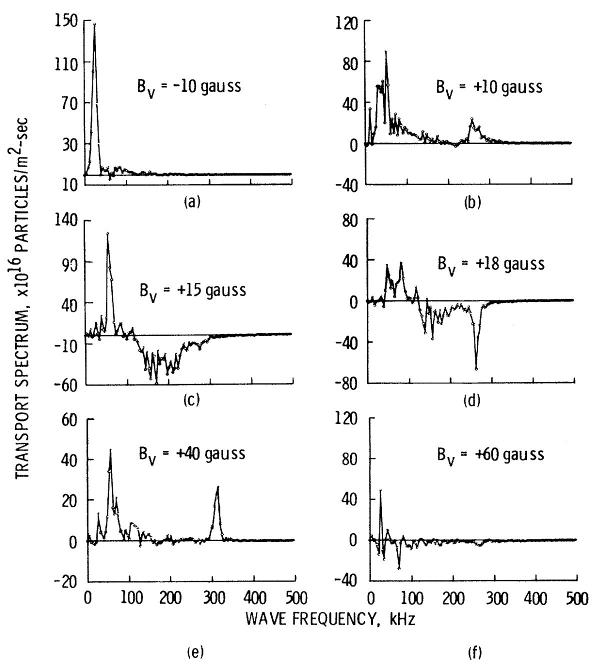

FIG. 5. The transport spectrum as a function of frequency from 0 to 500 kHz. The vertical magnetic field B_v is equal to (a) -10 G, (b) $+10$ G, (c) $+15$ G, (d) $+18$ G, (e) $+40$ G, and (f) $+60$ G.

cumulative transport rate at the probe location is shown in Fig. 4(b) as a function of the vertical magnetic field. We wish to emphasize the strong correlation between the direction of fluctuation-induced transport, and the associated increase (or decrease) in the average plasma density. In particular, the vertical magnetic fields which result in the highest inward radial transport correspond to the highest electron number densities observed, and the outward transport rates correspond to those vertical fields where the density is low, and the plasma is approaching extinction.

The transport spectrum for six values of the vertical magnetic field plotted in Fig. 4 is shown in Fig. 5 in absolute units for frequencies up to 500 kHz. When the vertical magnetic field is −10 G, the radially inward transport is dominated by a large peak at 20 kHz. As the vertical magnetic field is increased to +10 G, the inward transport is found over a broad, almost turbulent, spectrum from 0 to 150 kHz, and a peak of inward transport also appears at about 250 kHz. As the vertical magnetic field is increased to +15 and +18 G, which are near the region of plasma extinction in Fig. 4, the transport in the vicinity of 200 kHz reverses direction and flows radially outward. The area under the curve in this portion of the spectrum dominates the total transport and results in net outward transport of plasma. Beyond the region of plasma quenching from 20 to 32 G, two major peaks at a vertical field of 40 G dominate the transport and are radially inward. As the vertical magnetic field is further increased to 60 G, the importance of the high-frequency peak diminishes, and the total transport rate becomes much smaller in magnitude.

In summary, we have investigated (1) low-frequency ($\omega \ll \omega_{ci}$) fluctuation-induced transport using digitally implemented spectral analysis techniques, and (2) the role of strong applied radial electric fields and weak vertical magnetic fields on fluctuation-induced transport and plasma density in a bumpy-torus geometry. The data demonstrate that application of sufficiently strong radially inward electric fields results in radially inward fluctuation-induced transport which is associated with higher average electron densities in the toroidal plasma. There may, of course, be other competing transport processes (e.g., transport due to static $\vec{E}\times\vec{B}/B^2$ drifts or binary collisions); however, the correlation between the magnitude and direction of the fluctuation-induced transport and the resulting increase (or decrease) in the plasma density (see Figs. 2 and 4) strongly suggest that fluctuation-induced transport is playing an important role in determining the average plasma density in the bumpy-torus experiment.

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