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ABSTRACT

The approach of the NASA Lewis Bumpy Torus Experiment is to confine and heat a toroidal plasma by the simultaneous application of strong dc magnetic fields and electric fields. Digitally implemented spectral analysis techniques were used to experimentally investigate the frequency-dependent fluctuation-induced particle transport across the toroidal mangetic field. It was observed that when the electric field pointed radially inward, the transport was inward and a significant enhancement of the plasma density and confinement time 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 and confinement time 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 transport can result.

The steady-state plasma in the NASA Lewis Bumpy Torus facility is generated by a modified Penning discharge operated in conjunction with a 12-coil bumpy torus magnetic field 1.5 meters in 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 magnetron-like devices, the plasma forms rotating spokes which gyrate around the minor circumference of the plasma with velocities comparable to the E/B drift velocity. Ion kinetic temperatures up to 2.5 keV in deuterium have been measured. The thermal velocity of these hot ions is comparable to the spoke rotational velocity[5].

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: 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 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; 4) the electric field strength within the plasma often exceeds 1 kV/cm.

The particle containment time τ_p in this steady-state plasma can be obtained from the average electron number density, $\bar{n}_e$, measured with the microwave interferometer, the plasma volume V_p, and the dc current, I_a, flowing to the power supply[6],

$$\tau_p = \frac{\bar{n}_e \, e \, V_p}{I_a} \quad \text{sec.} \tag{1}$$

The effect of the direction of the electric field on particle containment is shown in figure 2A, where the particle containment time and the average electron number density are shown for a paired comparison in which the only factors which differed were the polarity of the 2 midplane electrode rings used and the geometric position of the midplane electrodes, which was optimized for each polarity[7]. The solid symbols represent positive polarity, for which the radial electric fields point (and push ions) radially outward. The open symbols in Fig. 2 represent negative polarity, which result in electric fields which point (and push ions) radially inward. Both the particle containment time and the average electron number density are at least a factor of five higher with the radial electric field pointing inward than is the case with it pointing outward.

In order to understand this largo difference in confinement, measurements of the fluctuation-induced particle transport rates were made with a new technique, the key ideas of which are described elsewhere[8,9,10]. Low frequency ($\omega \ll \omega_{ci}$) electrostatic potential fluctuations are assumed so that a particle's fluctuating velocity may be modeled 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 time averaged particle flux is then given by:

$$\langle \tilde{n}\tilde{v} \rangle = \langle \tilde{n}\tilde{E}_{\perp} \rangle / B , \qquad (2)$$

In ref. 8, it is shown that the transport due to a small band of frequencies centered at ω is given by

$$T(\omega) = \frac{k_\theta(\omega)}{B} \hat{n}(\omega)\,\hat{\varphi}(\omega)\,\mathrm{SIN}\,\alpha_{n\varphi}(\omega) \left| \gamma_{n\varphi}(\omega) \right| . \qquad (3)$$

The transport associated with $T(\omega)$ 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 wavenumber $k_\theta(\omega)$ ppears since the electrostatic approximation ($\tilde{E} = -\nabla\tilde{\varphi} = -ik_\theta(\omega)\tilde{\varphi}$) is assumed. The transport spectrum $T(\omega)$ is a real quantity and may take on either a positive or negative value, indicating that the transport is in either an inward or outward direction, respectively. The transport spectrum $T(\omega)$ was measured in a sector which did not contain an electrode ring, at the outer boundary of the plasma.

On figure 3 are shown transport spectra corresponding to the data for an electrode current of I_a = .75 amps plotted in figure 2. The upper graph is the transport spectral density function. The lower graph is the cumulative transport rate up to the frequency shown on the abscissa. All ordinates are plotted in absolute units. In figure 3a, the negative electrode case with radially inward electric fields, has a transport that is positive in sign, indicating radially inward transport. The transport is associated with three discrete peaks, 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 confinement is a balance between infusion in the empty sectors and losses in the sectors with electrode rings. In Fig. 3B, the positive electrode case has a transport 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 350kHz, and could be considered "turbulent transport." The cumulative transport for the two electrode polarities is plotted as a function of electrode current in figure 2b. For both electrode polarities, the radial transport increases with increasing electrode current in an almost linear manner.

The particle contianment time and average 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[11]. These vertical fields are generated by 2 coils wrapped around the exterior of the vacuum tank and range from minus to plus 100 gauss (positive is upward). The effect of this vertical magnetic field on the average electron number density is shown in figure 4a. When these data were taken the electrode voltage, background pressure of deuterium, maximum magnetic field, and other independent variables were held constant. There exists a region between 20 and 32 gauss in which no plasma could be generated.

The cumulative transport at the probe location in shown in figure 4b as a function of the vertical magnetic field. 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 spectral density function for six values of the vertical magnetic field plotted in figure 4 is shown in figure 5 in absolute units for frequencies up to 500 kHz. When the vertical magnetic field is -10 gauss, the radially inward transport is dominated by a large peak at 20 kHz. As the vertical magnetic field is increased to +10 gauss, the inward transport is found over a broad, almost turbulent, spectrum from 0-150 kHz, and a peak of inward transport also appears at about 250 kHz. As the vertical magnetic field is increased to +15 and +18 gauss, which are near the region of plasma extinction in figure 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 radially outward transport of plasma. Beyond the region of plasma quenching from 20-32 gauss, two major peaks at a vertical field of 40 gauss dominate the transport and are radially inward. As the vertical magnetic field is further increased to 60 gauss, the importance of the high frequency peak diminishes, and the total transport rate becomes much smaller in magnitude.

The phase difference $\alpha_{n\varphi}(\omega)$ between density and potential fluctuations was computed and plotted using standard digital spectral analysis techniques[10]. Examination of these plots indicate that reversal of the direction of transport associated with the peak near 250 kHz in Fig. 5 occurs because $\alpha_{n\varphi}(\omega)$ changes sign as the vertical magnetic field is changed from run to run. As indicated by Eq. (3), a change in sign of $\alpha_{n\varphi}(\omega)$ will result in a change in the direction of fluctuation-induced transport $T(\omega)$.

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 plasma density and particle confinement times in a Bumpy Torus geometry. The data demonstrate that application of sufficiently strong radially inward electric fields result in radially inward fluctuation-induced transport into the toroidal electrostatic potential well. This inward transport is associated with higher average electron densities and longer particle confinement times in the toroidal plasma.

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Figure Captions

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

Figure 2 - A paired comparison of the confinement obtained with positive and negative bias of the toroidal plasma for B_{max} = 2.4 tesla.

Figure 2a - Average plasma number density and particle containment time as functions of electrode current.

Figure 2b - Cumulative transport rate as a function of electrode current.

Figure 3 - Transport spectral density function and cumulative transport rates for an electrode current of I_a = .75 amps. a) negative electrode polarity, b) positive electrode polarity.

Figure 4 - Effect of a weak vertical magnetic field on plasma containment

Figure 4a - Average electron number density as a function of vertical magnetic field.

Figure 4b - Cumulative transport at the location of the probe as a function of vertical magnetic field.

Figure 5 - The transport spectral density function as a function of frequency from 0-500 kHz. The vertical magnetic field By is equal to: a) -10 gauss, b) +10 gauss, c) +15 gauss, d) +18 gauss, e) +40 gauss, and f) +60 gauss.

ELECTRIC FIELD STRUCTURE IN BUMPY TORUS
WITH NEGATIVE MIDPLANE ELECTRODES

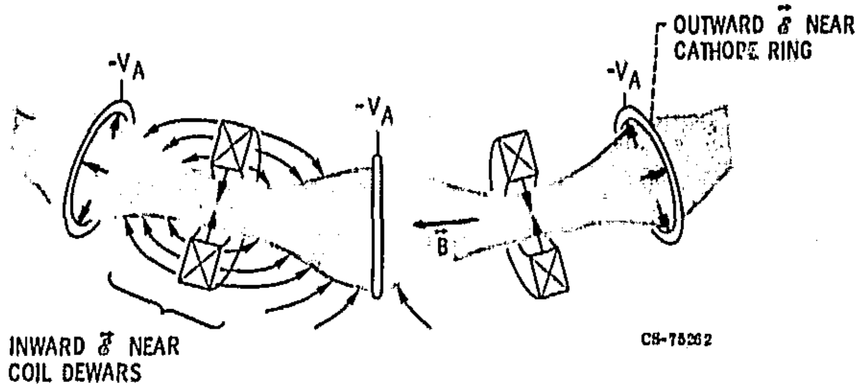
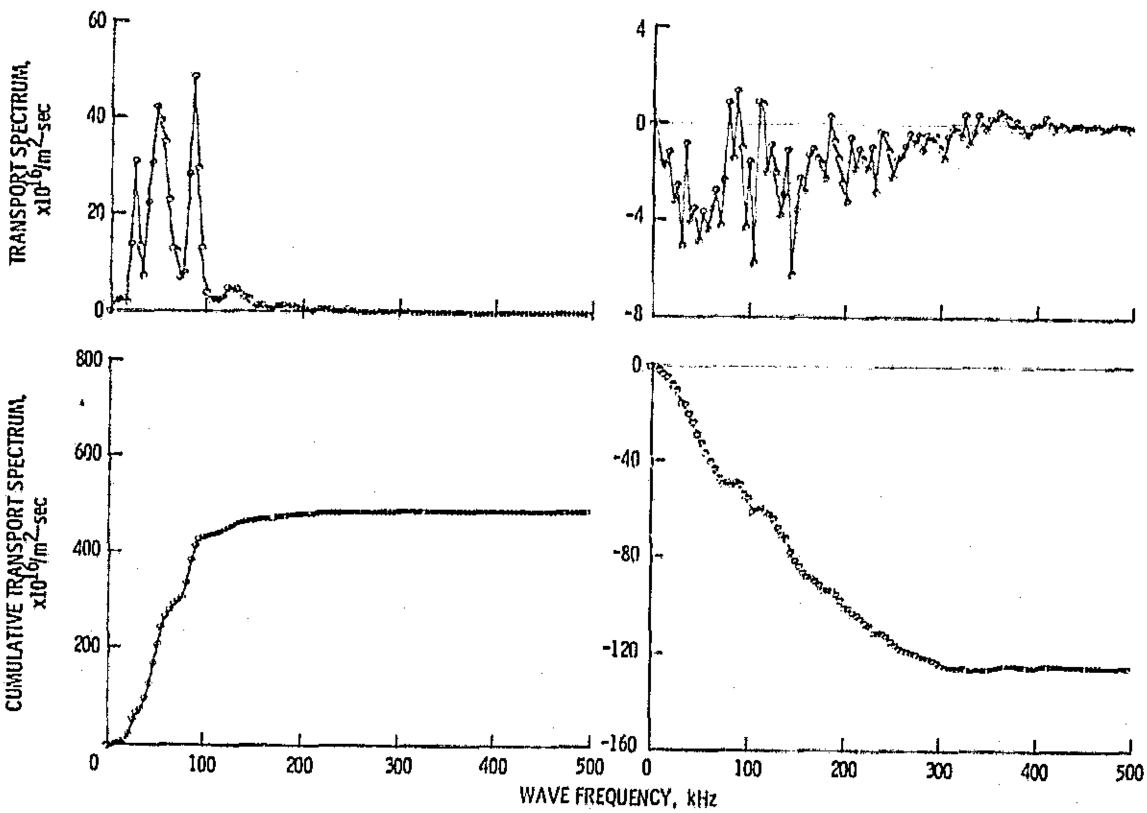
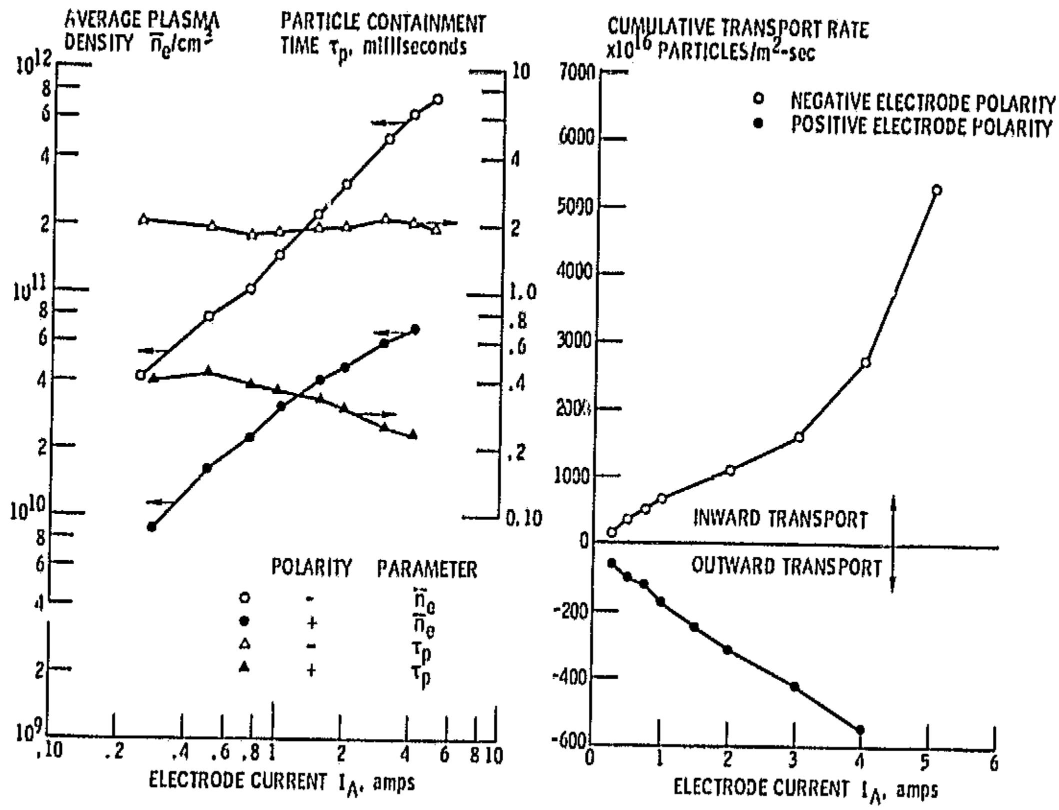


Figure 1.

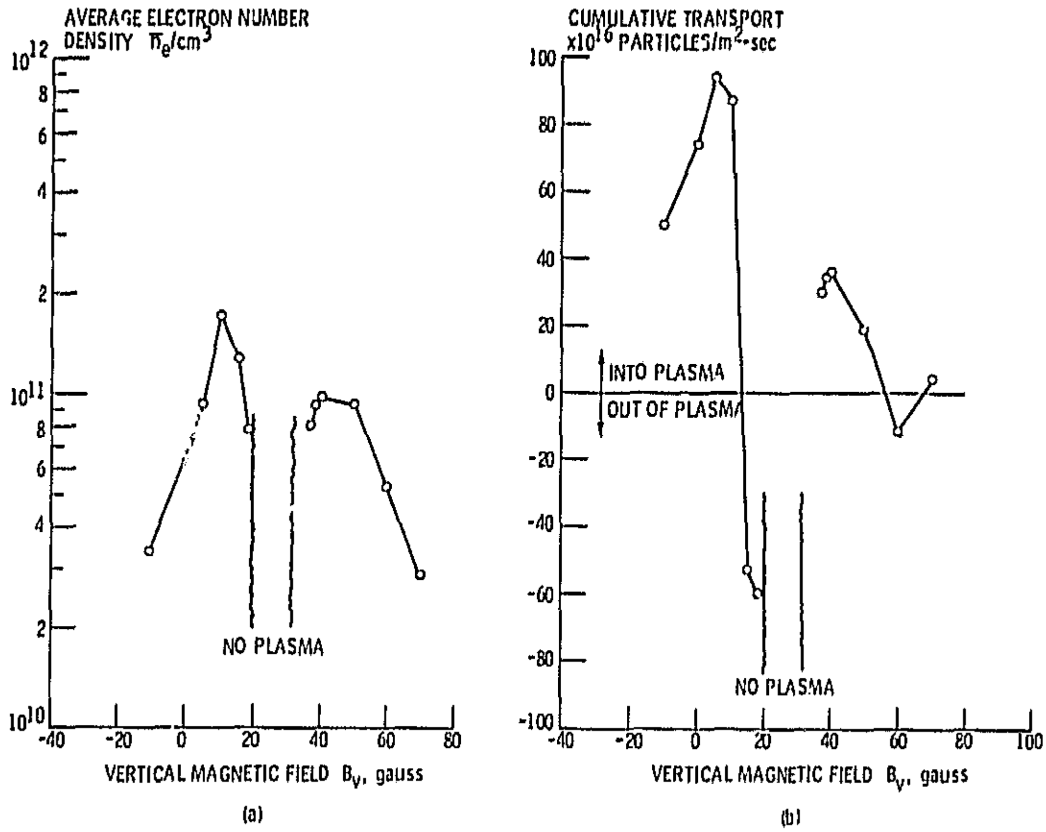


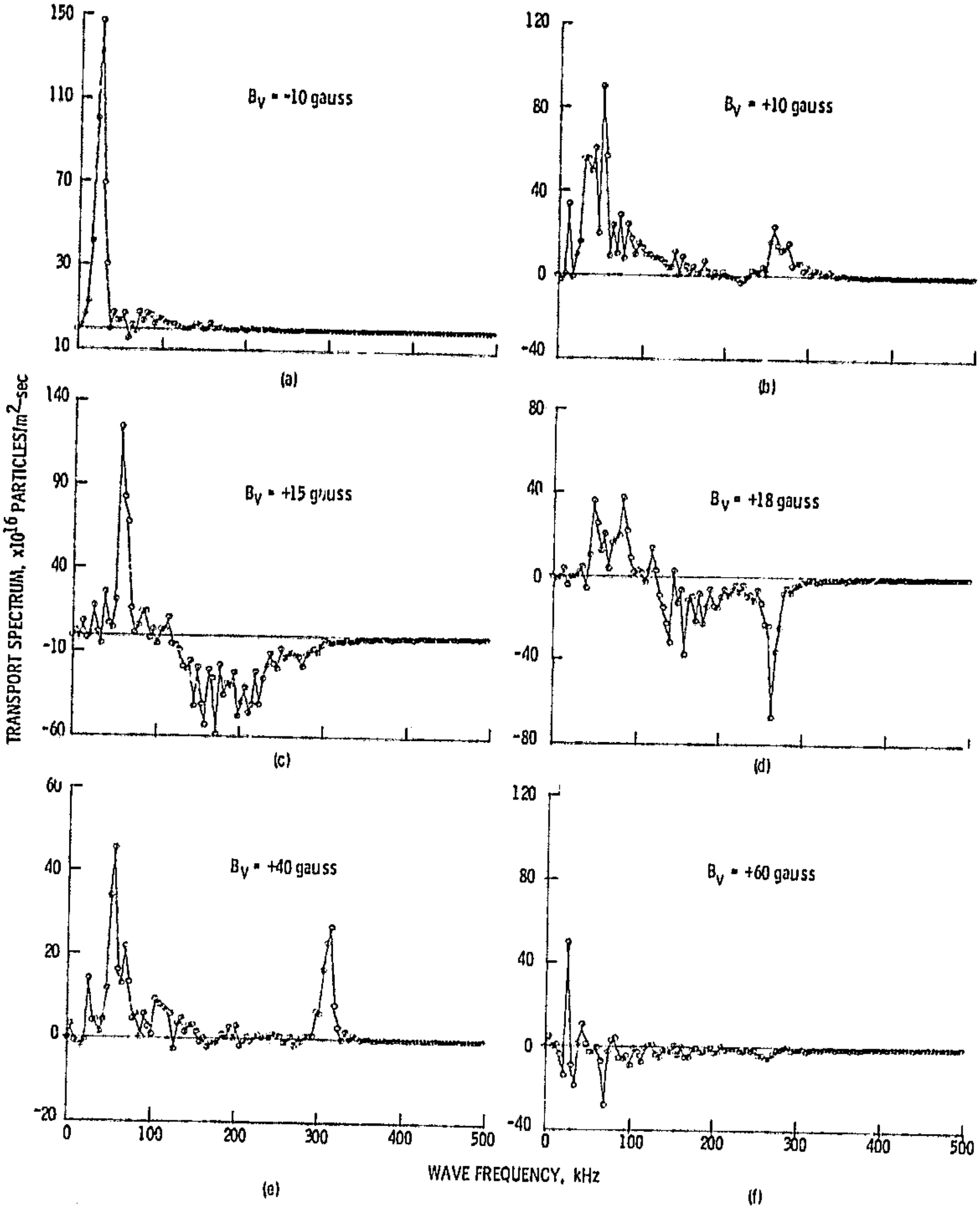
(a) NEGATIVE ELECTRODE POLARITY $I_A = 0.75$ A.

(b) POSITIVE ELECTRODE POLARITY $I_A = 0.75$ A.


AVERAGE PLASMA DENSITY $\bar{n}_e$/cm^3
PARTICLE CONTAINMENT TIME τ_p, milliseconds
POLARITY PARAMETER
ELECTRODE CURRENT I_A, amps
CUMULATIVE TRANSPORT RATE x10^{16} PARTICLES/m^2-sec
NEGATIVE ELECTRODE POLARITY
POSITIVE ELECTRODE POLARITY
INWARD TRANSPORT
OUTWARD TRANSPORT
ELECTRODE CURRENT I_A, amps

(a) (b)


AVERAGE ELECTRON NUMBER DENSITY $\overline{n}_e$/cm^3
NO PLASMA
VERTICAL MAGNETIC FIELD B_V, gauss
(a)
CUMULATIVE TRANSPORT x10^{16} PARTICLES/m^2-sec
INTO PLASMA
OUT OF PLASMA
NO PLASMA
VERTICAL MAGNETIC FIELD B_V, gauss
(b)



TRANSPORT SPECTRUM, x10^16 PARTICLES/m^2-sec
WAVE FREQUENCY, kHz
B_V = -10 gauss
B_V = +10 gauss
B_V = +15 gauss
B_V = +18 gauss
B_V = +40 gauss
B_V = +60 gauss
(a)
(b)
(c)
(d)
(e)
(f)