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ATF EDGE PLASMA TURBULENCE STUDIES USING A FAST RECIPROCATING LANGMUIR PROBE*

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Electrostatic turbulence on the edge of the Advanced Toroidal Facility (ATF) torsatron is investigated experimentally with a fast reciprocating Langmuir probe (FRLP) array. Initial measurements of plasma electron density n_e and temperature T_e and fluctuations in density ($\tilde{n}_e$) and plasma floating potential ($\tilde{\phi}_f$) are made in ECH plasmas at 1 T. At the last closed flux surface (LCFS, $r/\bar{a} \sim 1$), $T_e \approx 20$–40 eV and $n_e \approx 10^{12}$ cm^{-3} for a line-averaged electron density $\bar{n}_e = (3–6) \times 10^{12}$ cm^{-3}. Relative fluctuation levels, as the FRLP is moved into core plasma where $T_e > 20$ eV, are $\tilde{n}_e/n_e \approx 5\%$, and $e\tilde{\phi}_f/T_e \approx 2\tilde{n}_e/n_e$ about 2 cm inside the LCFS. The observed fluctuation spectra are broadband (40–300 kHz) with $\bar{k}\rho_s \leq 0.1$, where $\bar{k}$ is the wavenumber of the fluctuations and ρ_s is the ion Larmor radius at the sound speed. The propagation direction of the fluctuations reverses to the electron diamagnetic direction around $r/\bar{a} < 1$. The phase velocity and the electron drift velocity are comparable ($v_{ph} \sim v_{de}$). The fluctuation-induced particle flux is comparable to fluxes estimated from the particle balance using the H_α spectroscopic measurements. Many of the features seen in these experiments resemble the features of ohmically heated plasmas in the Texas Experimental Tokamak (TEXT).

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc., and DE-FG05-89ER53295 with the University of Texas at Austin.

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DISCLAIMER

1. Introduction

Energy and particle confinement in tokamaks and stellarators is anomalous, and results from the two types of devices show similar dependences on plasma parameters [1]. The study of electrostatic fluctuations [2] in different magnetic configurations may help to identify the underlying physics mechanisms responsible for plasma transport. To investigate the effects of the magnetic configuration on the characteristics of edge turbulence, recent measurements of electrostatic fluctuations at the edge of the Texas Experimental Tokamak (TEXT) [3] have been extended to the Advanced Toroidal Facility (ATF) [4] torsatron. Experimental observations on TEXT indicate that electrostatic fluctuations are the dominant mechanism for energy and particle losses in the edge [3,5]. To understand the driving forces on the edge turbulence in terms of the plasma current and the magnetic configuration, initial edge fluctuation measurements have been carried out on the currentless ATF device with a diagnostic setup similar to that used in the TEXT experiments, that is, a fast reciprocating Langmuir probe (FRLP) array [6].

The FRLP has been used to characterize, from an experimental point of view, the electrostatic turbulence on the edge of the ATF torsatron. The experimental setup and the analysis method are described in section 2. Measurements of plasma electron density n_e, electron temperature T_e, and fluctuations in density ($\tilde{n}_e$) and plasma floating potential ($\tilde{\phi}_f$) at the edge of electron cyclotron heated (ECH) plasmas in ATF are presented and their turbulence characteristics are discussed in section 3. Brief conclusions follow in section 4.

2. Experimental setup

The stellarator configuration of the ATF torsatron has a poloidal multipolarity $\ell = 2$, 12 field periods ($M = 12$), a major radius $R_0 = 2.1$ m, and an average plasma radius $\bar{a} = 0.27$ m. The externally produced currentless magnetic configuration has moderate shear; that is, the central rotational transform ($\iota/2\pi = 1/q$) of 0.3 becomes 1.0 at the last closed flux surface (LCFS). Initial fluctuation measurements in ATF were carried out around the LCFS with the FRLP in ECH plasmas at a magnetic field B = 1 T. Plasmas were created using a gyrotron source at 53 GHz with heating power P = 200 kW. In these ECH plasmas, a representative range for the line-averaged plasma density is $\bar{n}_e = (3\text{–}6) \times 10^{12}$ cm^{-3}, and the plasma stored energy $W_p \approx 1\text{–}2$ kJ.

The FRLP is located one field period away from the instrumented rail limiter [7]. The probe is inserted into the edge plasma from the top, moves 5 cm into the plasma in 50 ms, and remains there about for 40 ms to carry out the fluctuation measurements. The FRLP head consists of a square array of four tips, 0.5 mm in diameter, that are 2 mm long and 2 mm apart. Double Langmuir probe operation of two tips, aligned perpendicular to the local magnetic field, makes it possible to measure the edge plasma n_e, T_e, and $\tilde{n}_e/n_e$ profiles inside (about 2 cm) and outside the LCFS, as indicated in fig. 1. The other two tips are used to measure $\tilde{\phi}_f$ and the wavenumber k perpendicular to the local magnetic field. The data have been analysed using spectral analysis techniques [8]. That is, the fluctuation signals are digitized at 1 MHz, and fast Fourier transform (FFT) is used to obtain their power spectrum $S(k,\omega)$ as a function of frequency ω and k using the two-probe technique described in ref. [9]. Ensemble averaging of the spectral distribution of the flux $\tilde{\Gamma}(\omega)$, obtained from the correlation of density and plasma potential fluctuations ($\tilde{\phi}_p$), gives the turbulence-induced radial particle flux:

$$\tilde{\Gamma} = \langle \tilde{n}_e \tilde{v}_r \rangle = 2 \Sigma_{\omega>0} \tilde{\Gamma}(\omega). \tag{1}$$

Here $\tilde{v}_r = -ik\tilde{\phi}_p/B$ is the radial velocity due to the electrostatic fluctuations, and the frequency-resolved flux is estimated from many independent realizations using a triple correlation technique [10]:

$$\tilde{\Gamma}(\omega) = \mathrm{Re}[\langle -ik(\omega)\tilde{n}_e^*(\omega)\tilde{\phi}_p(\omega)\rangle]/B. \tag{2}$$

Further, to gain an insight into the physical process, $\tilde{\Gamma}(\omega)$ can be expressed as [8]

$$\tilde{\Gamma}(\omega) \approx (k/B)\gamma_{\tilde{n}\tilde{\phi}} n_{rms}\phi_{rms}\sin\theta_{\tilde{n}\tilde{\phi}}, \tag{3}$$

where $\gamma_{\tilde{n}\tilde{\phi}}$ is the coherence, $\theta_{\tilde{n}\tilde{\phi}}$ is the phase angle between the density and potential fluctuations, and n_{rms} and ϕ_{rms} are the rms values of the fluctuations.

3. Results and discussion

Spatial profiles of the edge plasma density and temperature and the plasma floating potential ϕ_f are shown in fig. 2 for $0.95 < r/\bar{a} < 1.15$. These measurements were made during the steady-state phase of the plasma discharge. The plasma potential ϕ_p may be estimated from the measurements of ϕ_f and T_e as $\phi_p \approx \phi_f + \delta_p T_e$, where δ_p depends on the probe material, the heat load on the probe, the ion species and its temperature, and the secondary electron emission coefficient. Typically, $\delta_p \sim$ 1–3 for hydrogen plasmas [11]. Around the LCFS, $r/\bar{a} \approx 1$, the plasma parameters are $n_e = (1–1.2) \times 10^{12}$ cm^{-3} and $T_e = 30–40$ eV. The characteristic density and temperature scale lengths are $L_n = [-(1/n_e)(dn_e/dr)]^{-1} \approx 3–4$ cm and $L_T \approx 2L_n$, respectively. These values are comparable (within a factor of 2) to those for ohmically heated plasmas in TEXT at 2 T [3].

Typical values for the normalized density ($\tilde{n}_e/n_e$) and potential ($\tilde{\phi}_f/T_e$) fluctuations (see fig. 3 for profiles) around the LCFS are $\tilde{n}_e/n_e \approx 0.05–0.1$ and $\tilde{\phi}_f/T_e \approx 0.1–0.2$, which are lower than those in TEXT plasmas [3]. Although the correlation between $\tilde{\phi}_f$ and temperature fluctuations $\tilde{T}_e$ in ATF is not yet known, the contribution of $\tilde{T}_e$ to $\tilde{\phi}_p$ has been neglected because the measured values of $\tilde{T}_e$ on TEXT were relatively small ($\tilde{T}_e/T_e \approx 0.4\tilde{n}_e/n_e$) [12]. Fluctuation levels decrease as the probe is moved into the core plasma, where $T_e > 20$ eV and $\tilde{\phi}_f/T_e \approx 2\tilde{n}_e/n_e$ at $r/\bar{a} \approx 0.95$.

Fluctuation spectra of $\tilde{n}_e$ and $\tilde{\phi}_f$ have been examined for frequencies up to 400 kHz. Observed wavenumber-frequency power spectra $S(k,\omega)$ are broadband and mostly in the range 40–300 kHz (as seen in figs. 4 and 5). The estimated mean value of the wavenumbers from the two probe measurements is $\bar{k} = 1–3$ cm^{-1}, which satisfies $\bar{k}\rho_s \approx 0.05–0.1$, where ρ_s is the ion Larmor radius at the sound speed, as observed in TEXT [3]. Analysis of the wavenumber spectra shows that inside the LCFS the spectral width σ_k, the rms deviation about $\bar{k}$, decreases with increasing local electron temperature (fig. 6), indicating that the correlation length $L_c = 1/\sigma_k$ increases with temperature [13] and typically $L_c \approx 1$ cm, which is much larger than the probe tip separation, for $T_e > 35$ eV. The integrated potential fluctuation power spectra $S(\omega)$ and $S(k)$ decrease for large ω (>200 kHz) and k (as illustrated in fig. 5) with dependences given by $S(\omega) \sim \omega^{-\alpha}$ and $S(k) \sim k^{-\beta}$, where $\alpha \sim \beta \approx 4 \pm 1$. The shape of the $\tilde{n}$ spectrum is generally similar to that of $\tilde{\phi}_f$.

The fluctuation-induced particle flux is estimated from eqs. (1) and (2) by taking $\tilde{\phi}_p \approx \tilde{\phi}_f$. The coherence between the density and the floating potential fluctuations is $\gamma_{\tilde{n}\tilde{\phi}} \approx 0.8$ up to 150 kHz, dropping to ~0.2 beyond 250 kHz, and the corresponding phase angle is $\theta_{\tilde{n}\tilde{\phi}} \approx 70°$ around 150 kHz. The frequency-resolved particle flux $\tilde{\Gamma}(\omega)$ is dominated by frequencies below 250 kHz

(fig. 7) and reaches a maximum at 100–150 kHz, where the phase angle has its maximum. The spatial profile of the total particle flux $\tilde{\Gamma}$, eq. (1), is given in fig. 8 for two representative line-averaged densities $\bar{n}_e = 3.5 \times 10^{12}$ cm^{-3} and 5.5×10^{12} cm^{-3}. The radial flux is always outward and at the LCFS has a value $\tilde{\Gamma} \sim 3 \times 10^{15}$ cm^{-2}•s^{-1} for $\bar{n}_e = 3.5 \times 10^{12}$ cm^{-3} and 1.2×10^{15} cm^{-2}•s^{-1} for $\bar{n}_e = 5.5 \times 10^{12}$ cm^{-3}. For the nearly flat core density profiles observed in ATF, the corresponding fluctuation-induced particle confinement times, assuming that $\tilde{\Gamma}$ is constant on flux surfaces, are $\tau_p = (\bar{a}/2)\bar{n}_e/\tilde{\Gamma} \sim 16$ ms and 60 ms, respectively. The associated local density diffusion coefficient is $D_n = \tilde{\Gamma}L_n/n_e \sim 1 \times 10^4$ cm^2•s^{-1}, where n_e(edge) $\sim 10^{12}$ cm^{-3} and $L_n \sim 4$ cm for both $\bar{n}_e$ cases. Although detailed scans of $\bar{n}_e$ have not yet been carried out in ATF to determine the scaling of $\tilde{\Gamma}$ with $\bar{n}_e$, results from the present limited scans indicate that τ_p increases with $\bar{n}_e$ in these low-density regime studies. This observation is consistent with the TEXT results [14]. In ATF, it is rather difficult to use H_α spectroscopic measurements for estimating the particle fluxes at the edge because of the lack of a full set of spectroscopic monitors to cover the complicated edge geometry and the existence of particle sources from the divertor stripes around the LCFS [15]. Nonetheless, some comparisons can be made. Based on available data from H_α measurements, the estimated particle flux from the particle balance is $\Gamma_{H_\alpha} \sim (1\text{–}1.5) \times 10^{15}$ cm^{-2}•s^{-1} for $\bar{n}_e = 5.5 \times 10^{12}$ cm^{-3}, which is comparable to $\tilde{\Gamma}$. This suggests that the electrostatic edge turbulence may be responsible for particle confinement characteristics in ATF.

A spatial profile of the mean phase velocity of the fluctuations, $v_{ph} = 2\Sigma_{\omega>0} v_{ph}(\omega)$ with $v_{ph}(\omega) = \Sigma_k(\omega/k)S(k,\omega)/\Sigma_k S(k,\omega)$, is given in fig. 9. As observed on TEXT [2], the propagation of the fluctuations is in the ion diamagnetic direction for $r/\bar{a} > 1$, but it reverses to the electron diamagnetic direction for $r/\bar{a} < 1$. The location of the v_{ph} shear layer nearly coincides with the peak of the plasma potential where the radial electric field $E_r = -d\phi_p/dr$ changes its direction from outward to inward, as shown in fig. 10 for $\delta_p \sim 2.5$. At this location, the density and electron temperature gradients are nearly zero and $v_{ph} \sim v_e \sim 0$, where $v_e = (T_e/eB)(1/L_n + 1/L_T) - E_r/B$ is the electron drift velocity. Also, well inside the LCFS, where $E_r \approx 0$, it is found that $v_{de} \approx v_{ph} \approx 10^3$ m/s.

Future experiments will include measuring the electron temperature fluctuations using the techniques given in refs. [12,16] to determine the relationship between $\tilde{\phi}_p/T_e$ and $\tilde{n}_e/n_e$, scaling of the edge fluctuation parameters with $\bar{n}_e$, and extending the experiments to ECH plasmas with B = 2 T and neutral-beam-heated plasmas. The heavy ion beam probe diagnostic [17] should provide additional information on the plasma potential and its fluctuations.

4. Conclusion

The initial results indicate substantial similarities in the characteristics of edge turbulence in the ohmically heated TEXT tokamak and the currentless ATF torsatron. The fluctuation-induced particle flux is consistent with the total particle flux estimated from the global particle balance. Thus, electrostatic turbulence may be responsible for the edge particle transport. Detailed comparison of the ATF and TEXT results can serve as the basis for development of a unified physics interpretation of edge turbulence in toroidal devices.

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References

[1] S. Sudo et al., Nucl. Fusion 30 (1990) 11.

[2] P. Liewer, Nucl. Fusion 15 (1975) 487.

[3] Ch.P. Ritz, R.D. Bengtson, S.J. Levinson, and E.J. Powers, Phys. Fluids 27 (1984) 2956; Ch.P. Ritz et al., Nucl. Fusion 27 (1987) 1125.

[4] J.F. Lyon et al., Fusion Technol. 10 (1986) 179.

[5] Ch.P. Ritz et al., Phys. Rev. Lett. 62 (1989) 1844.

[6] Ch. P. Ritz, to be published.

[7] T. Uckan et al., Bull. Am. Phys. Soc. 33 (1988) 2069.

[8] E.J. Powers, Nucl. Fusion 14 (1974) 749.

[9] J.M. Beall, Y.C. Kim, and E.J. Powers, J. Appl. Phys. 43 (1982) 3993.

[10] Ch.P. Ritz et al., Rev. Sci. Instrum. 59 (1988) 1739.

[11] P.C. Stangeby, Plasma sheath, in: Physics of Plasma-Wall Interactions in Controlled Fusion, Eds. D.E. Post and R. Behrisch (Plenum, New York, 1986) p. 41.

[12] H. Lin, R.D. Bengtson, and Ch.P. Ritz, Univ. of Texas, Report FRCR-334 (1989).

[13] C. Hidalgo et al., to be presented at the 17th European Conference on Controlled Fusion and Plasma Physics, Amsterdam, The Netherlands, June 25–29, 1990.

[14] W.L. Rowan et al., Nucl. Fusion 27 (1987) 1105.

[15] P.K. Mioduszewski et al., in: Proc. 16th Eur. Conf. Controlled Fusion and Plasma Physics, Venice, 1989 (European Physical Society, 1989), Vol. 13B, p. 623.

[16] D.C. Robinson and M. G. Rusbridge, Plasma Phys. 11 (1969) 73.

[17] A. Carnevali et al., Rev. Sci. Instrum. 59 (1988) 1670.

Figure Captions

Fig. 1. Constant flux surfaces and the location of the FRLP on ATF.

Fig. 2. Spatial profiles of the ATF edge plasma density, temperature, and floating potential.

Fig. 3. Relative fluctuation levels for edge density and potential.

Fig. 4. Wavenumber-frequency power spectrum for potential fluctuations.

Fig. 5. (a) Power spectrum of the potential fluctuations. (b) Wavenumber spectrum S(k).

Fig. 6. Variations of σ_k with T_e inside the LCFS.

Fig. 7. Typical spectrum of the fluctuation-induced particle flux.

Fig. 8. Spatial profile of the fluctuation-induced particle flux at the edge.

Fig. 9. Spatial profile of the mean phase velocity v_{ph} of the fluctuations. Beyond the shear layer, the wave propagation is in the ion diamagnetic direction.

Fig. 10. Spatial profile of the estimated edge plasma potential ϕ_p. The location of the v_{ph} shear layer nearly coincides with the peak of the plasma potential where the radial electric field $E_r = -d\phi_p/dr$ changes its direction from outward to inward.

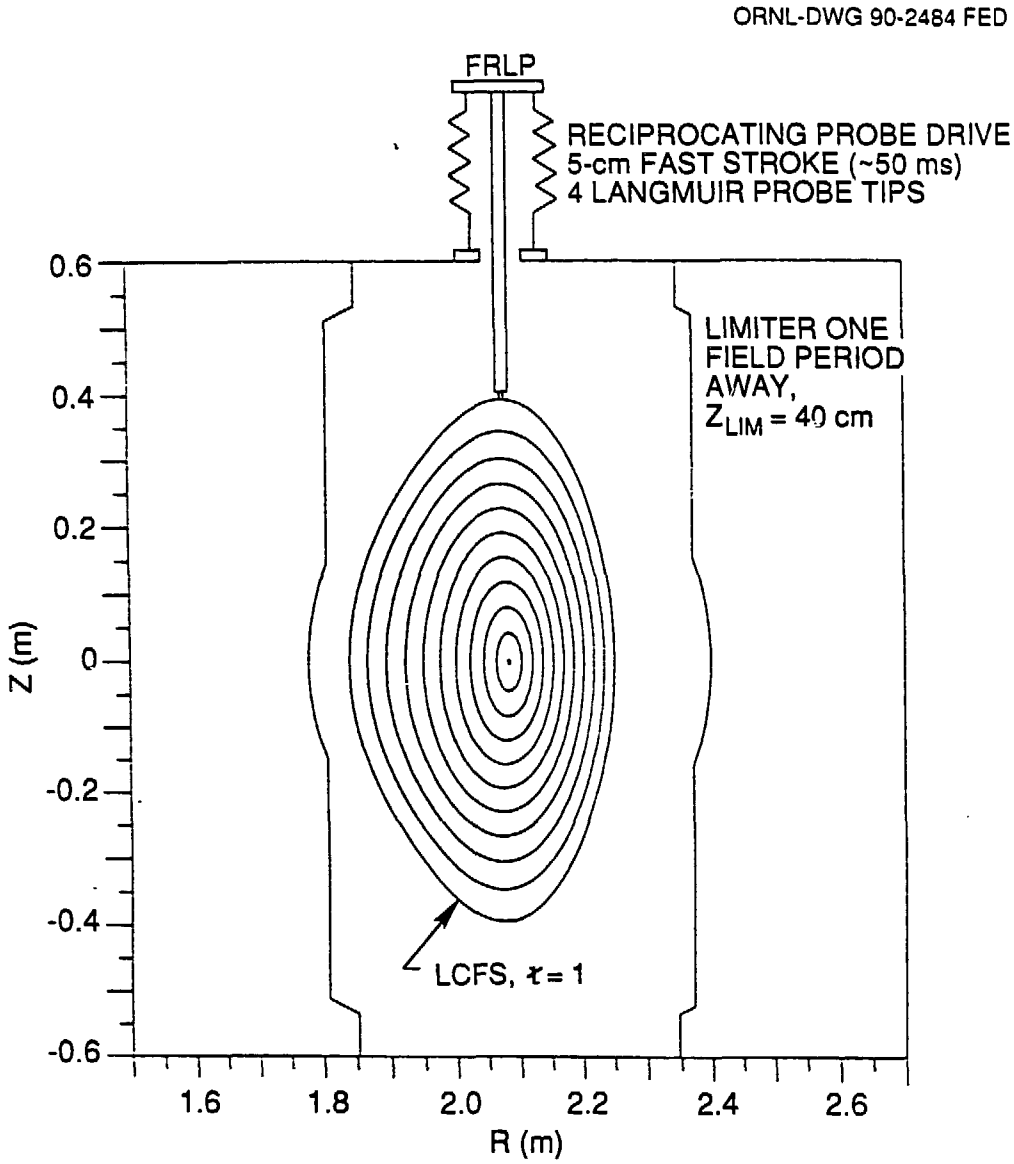

ORNL-DWG 90-2484 FED
FRLP
RECIPROCATING PROBE DRIVE
5-cm FAST STROKE (~50 ms)
4 LANGMUIR PROBE TIPS
LIMITER ONE
FIELD PERIOD
AWAY,
Z_{LIM} = 40 cm
LCFS, ι = 1
Z (m)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
1.6
1.8
2.0
2.2
2.4
2.6
R (m)

Fig. 1.

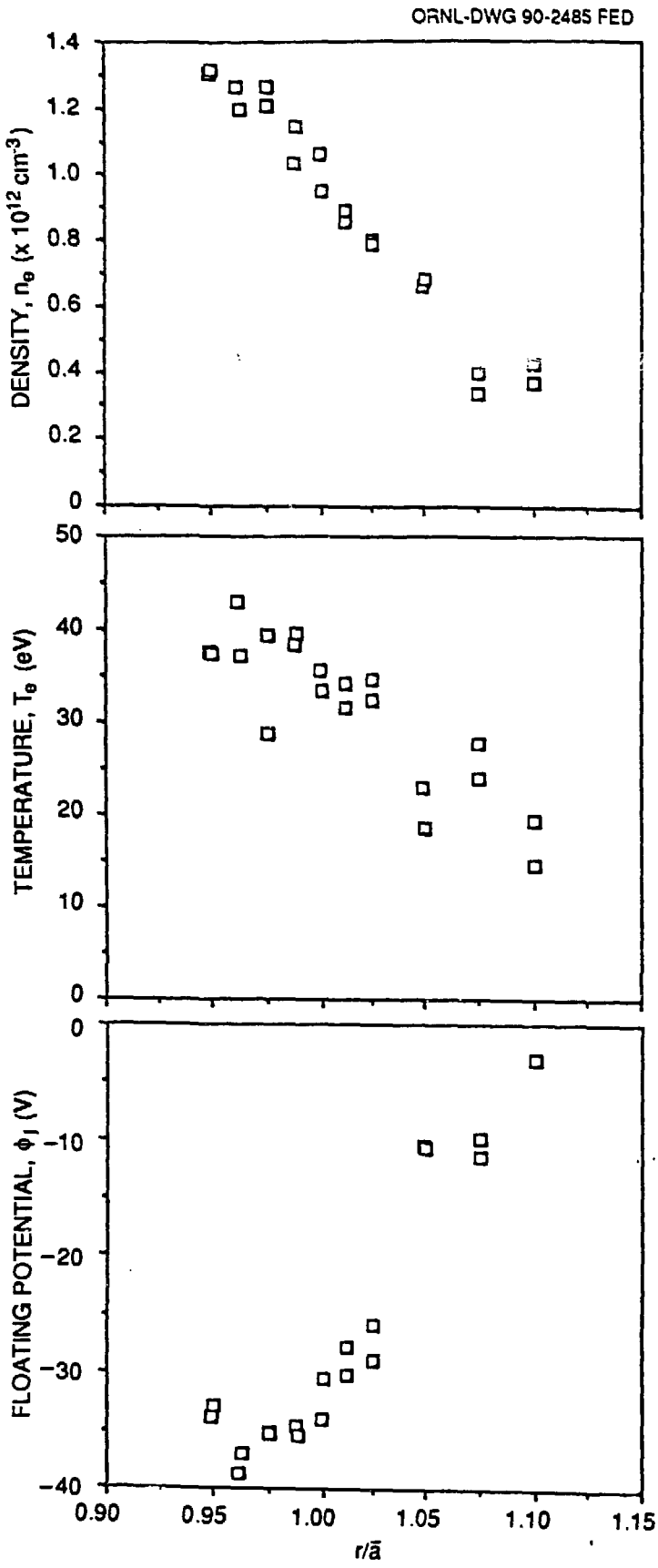

ORNL-DWG 90-2485 FED
DENSITY, n_e ($\times 10^{12}$ cm^{-3})
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
TEMPERATURE, T_e (eV)
50
40
30
20
10
0
FLOATING POTENTIAL, ϕ_f (V)
0
−10
−20
−30
−40
0.90
0.95
1.00
1.05
1.10
1.15
r/ā

Fig. 2.

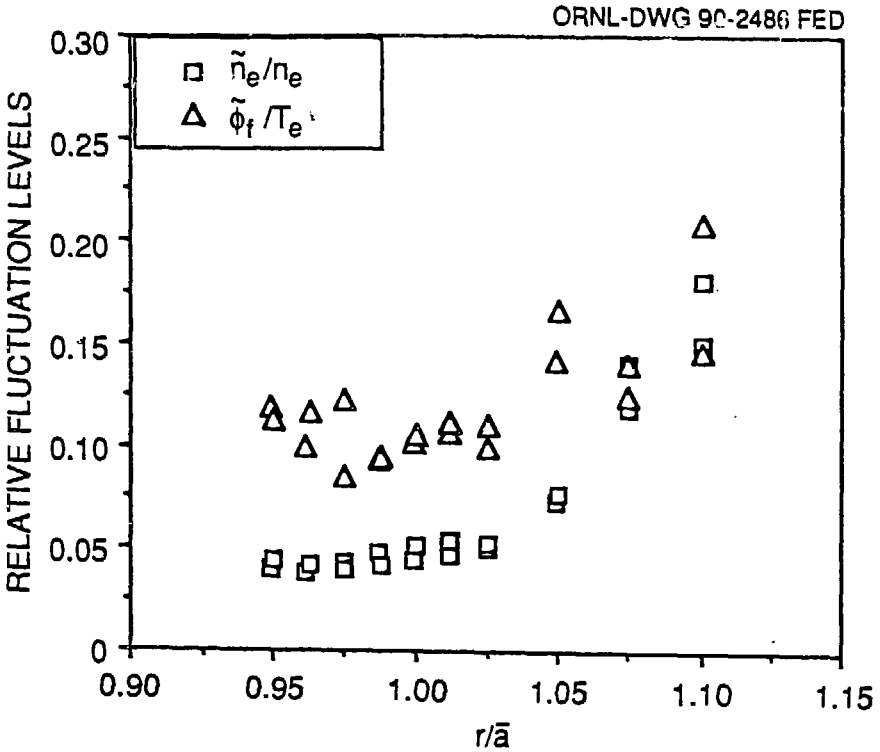

ORNL-DWG 90-2486 FED
$\tilde{n}_e/n_e$
$\tilde{\phi}_f/T_e$
RELATIVE FLUCTUATION LEVELS
0.30
0.25
0.20
0.15
0.10
0.05
0
0.90
0.95
1.00
1.05
1.10
1.15
r/ā

Fig. 3.

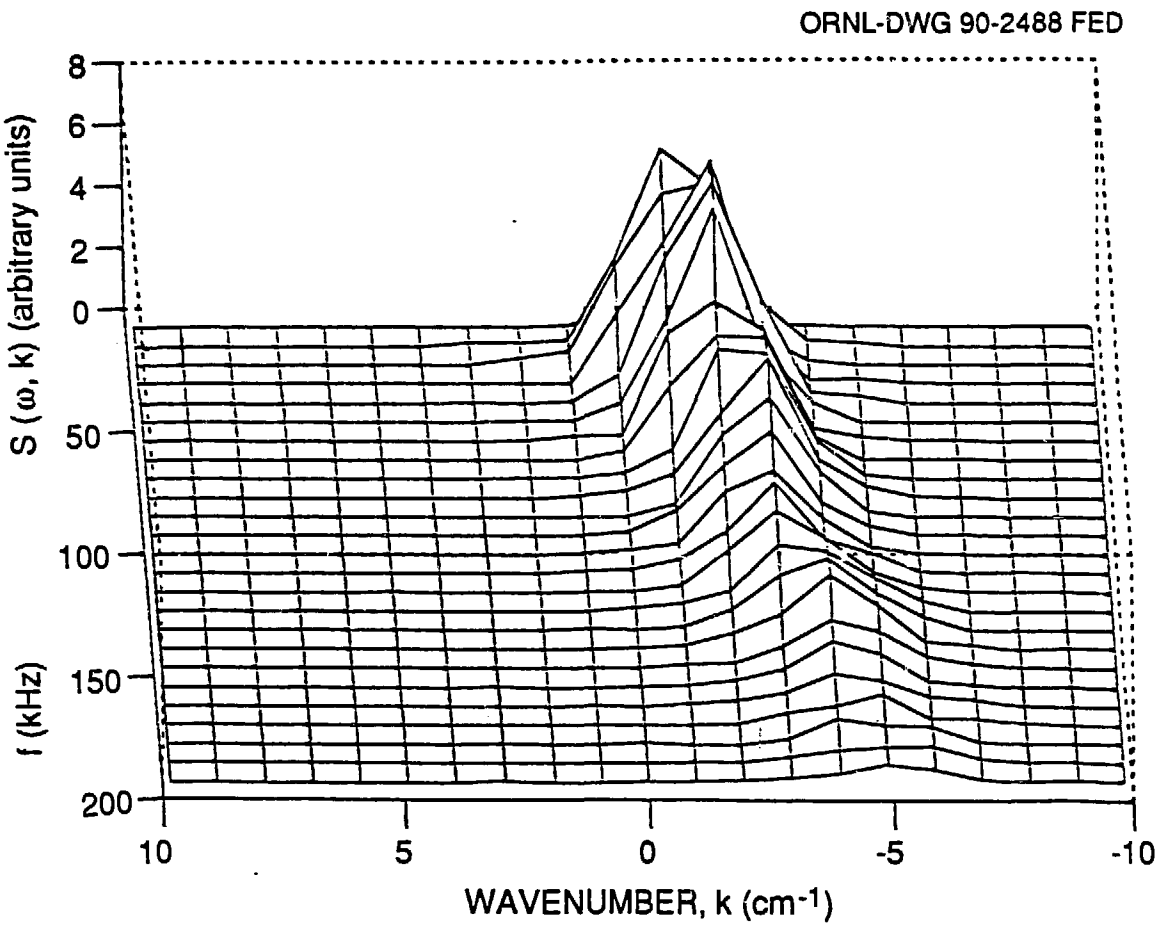
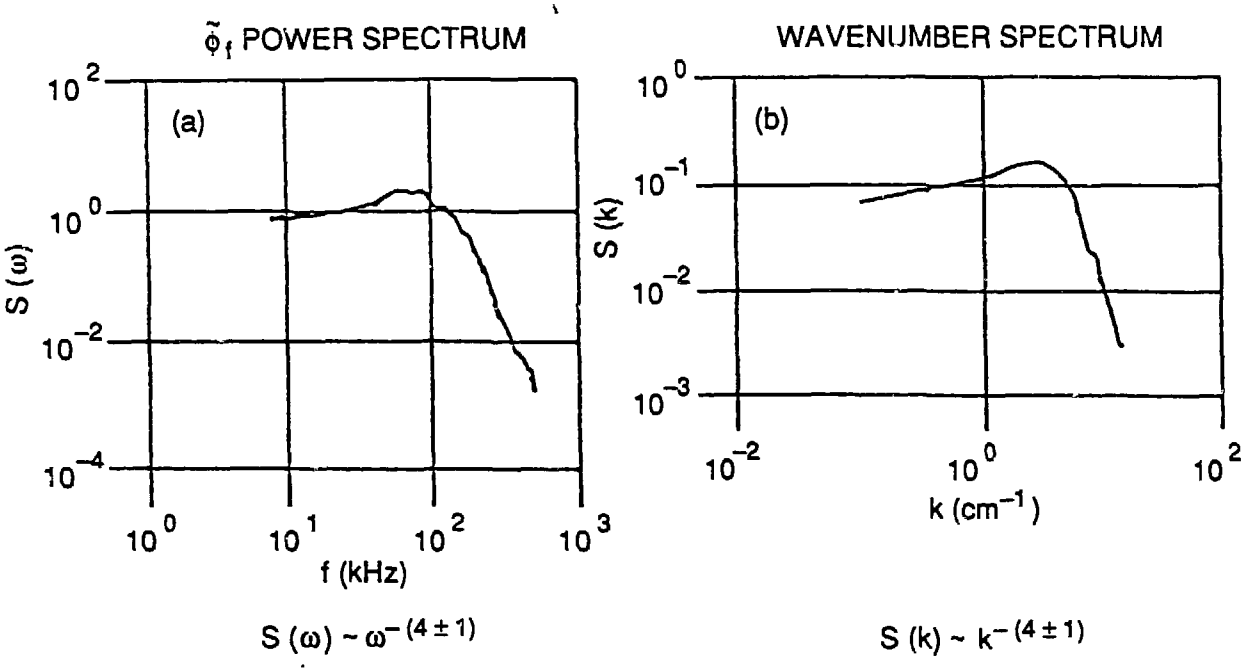

ORNL-DWG 90-2488 FED
S (ω, k) (arbitrary units)
8
6
4
2
0
f (kHz)
50
100
150
200
10
5
0
-5
-10
WAVENUMBER, k (cm-1)

Fig. 4.

ORNL-DWG 90-2531 FED



$S(\omega) \sim \omega^{-(4 \pm 1)}$

$S(k) \sim k^{-(4 \pm 1)}$

Fig. 5.

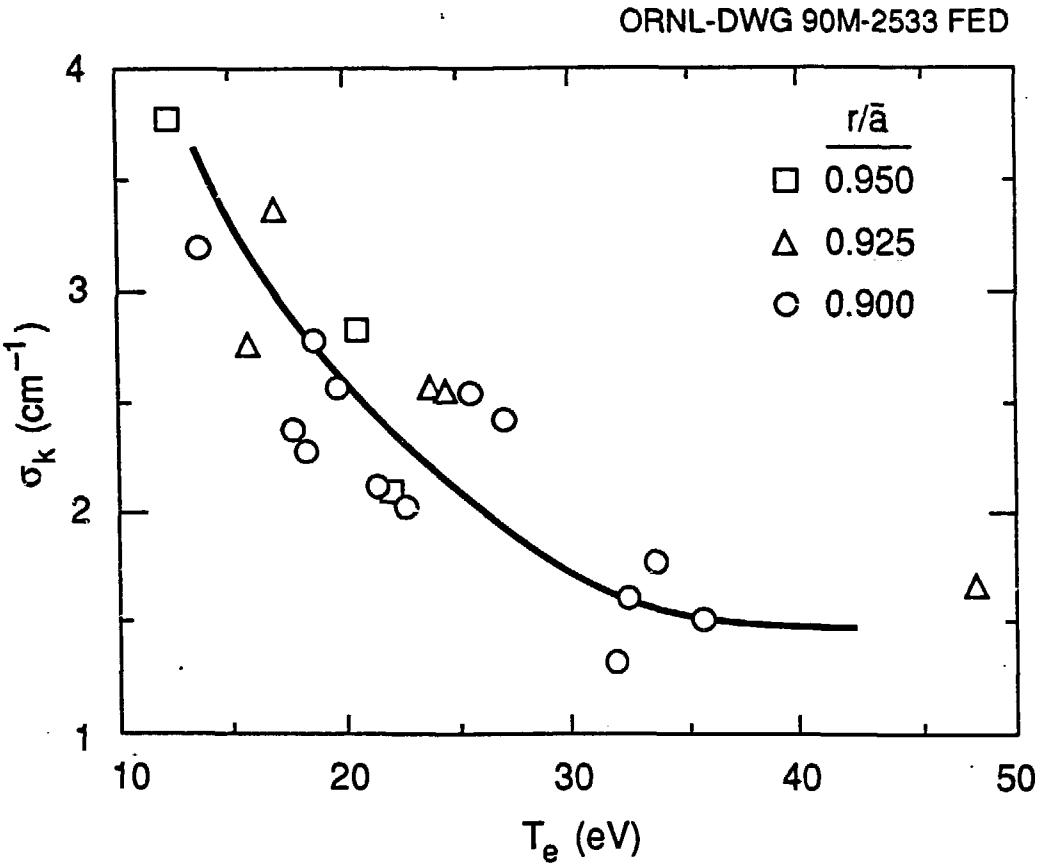

ORNL-DWG 90M-2533 FED
r/ā
0.950
0.925
0.900
σ_k (cm^{-1})
T_e (eV)
1
2
3
4
10
20
30
40
50

Fig. 6

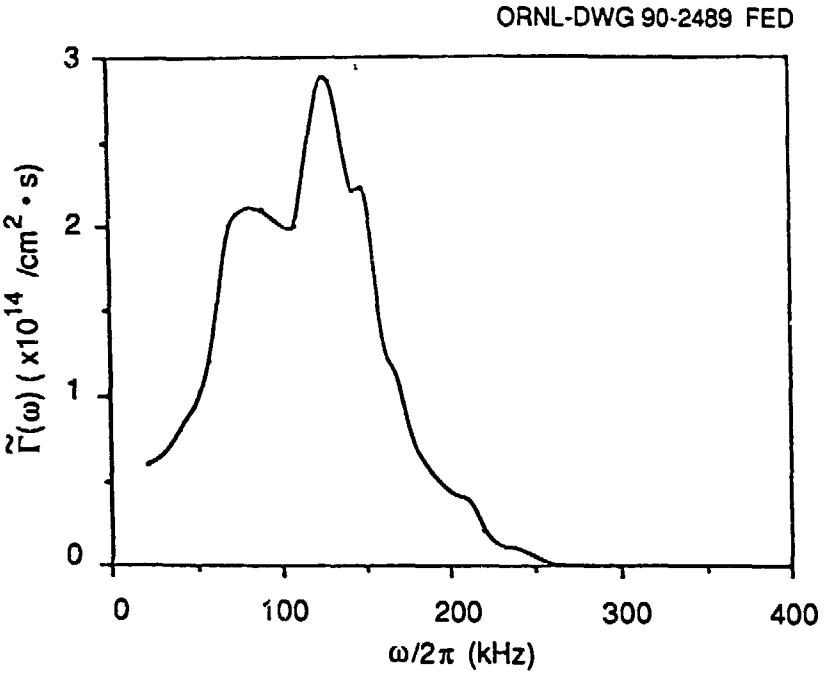

ORNL-DWG 90-2489 FED
3
2
1
0
0
100
200
300
400
$\tilde{\Gamma}(\omega)$ (x10^{14} /cm^2 • s)
ω/2π (kHz)

Fig. 7

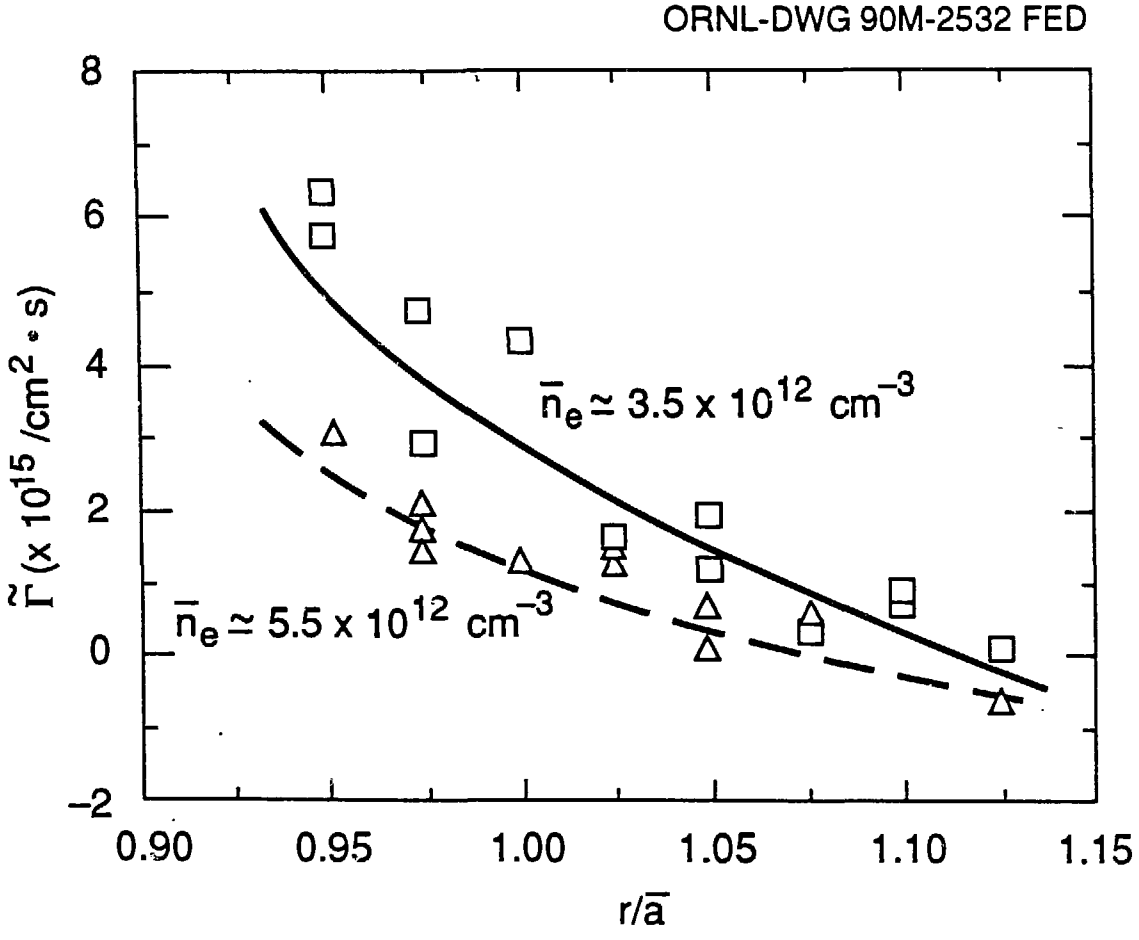

ORNL-DWG 90M-2532 FED
8
6
4
2
0
−2
0.90
0.95
1.00
1.05
1.10
1.15
r/ā
$\tilde{\Gamma}$ (x 10^{15} /cm^2 • s)
$\bar{n}_e \simeq 3.5 \times 10^{12}$ cm^{-3}
$\bar{n}_e \simeq 5.5 \times 10^{12}$ cm^{-3}

Fig. 8.

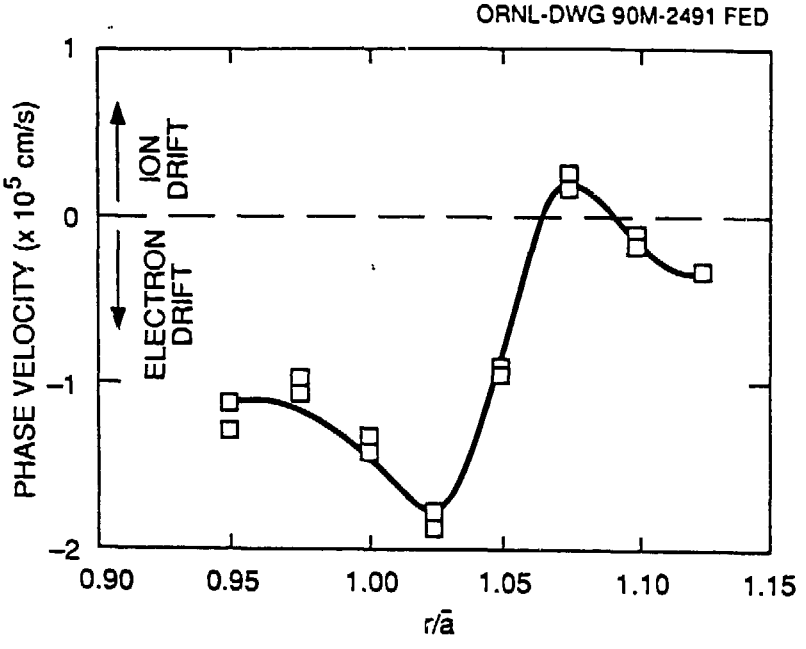

ORNL-DWG 90M-2491 FED
PHASE VELOCITY (x 10^5 cm/s)
1
0
-1
-2
ION DRIFT
ELECTRON DRIFT
0.90
0.95
1.00
1.05
1.10
1.15
r/ā

Fig. 9

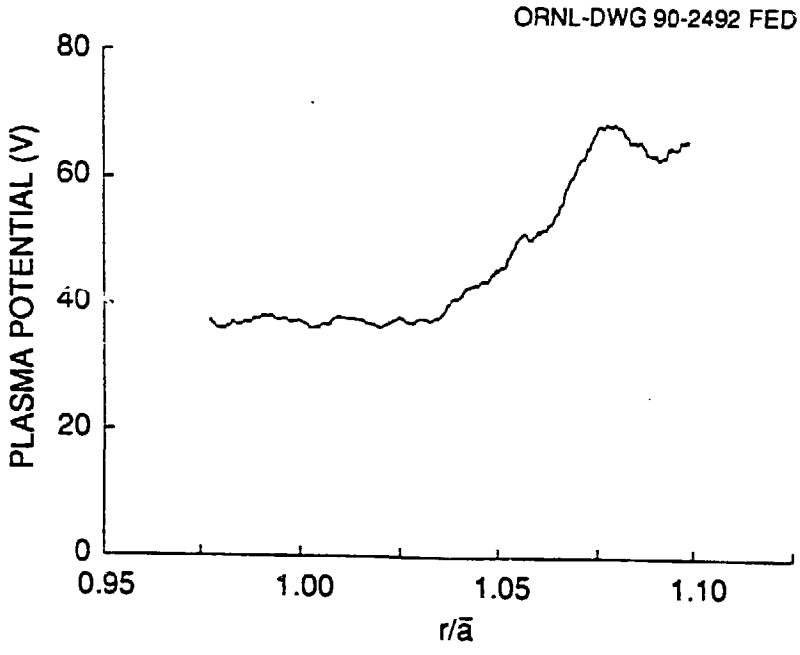

ORNL-DWG 90-2492 FED
PLASMA POTENTIAL (V)
80
60
40
20
0
0.95
1.00
1.05
1.10
r/ā

Fig. 10.

ATF EDGE PLASMA TURBULENCE STUDIES USING A FAST RECIPROCATING LANGMUIR PROBE *

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DISCLAIMER

ABSTRACT*

Experimental investigation of electrostatic turbulence on the edge of the ATF torsatron is carried out with a fast reciprocating Langmuir probe (FRLP) array. Initial measurements of plasma electron density n_e and temperature T_e and fluctuations in density ($\tilde{n}_e$) and plasma floating potential ($\tilde{\phi}_f$) are made in ECH plasmas at 1 T. At the last closed flux surface (LCFS, $r/\bar{a} \sim 1$), $T_e \approx 20$–40 eV and $n_e \approx 10^{12}$ cm^{-3} for a line-average electron density $\bar{n}_e = (3\text{–}6) \times 10^{12}$ cm^{-3}. Relative fluctuation levels, as the FRLP is moved into core plasma where $T_e > 20$ eV, are $\tilde{n}_e/n_e \approx 5\%$, and $e\tilde{\phi}_f/T_e \approx 2\tilde{n}_e/n_e$ about 2 cm inside the LCFS. Observed fluctuation spectra are broadband (40-300 kHz) with $\bar{k}\rho_s \leq 0.1$. Propagation of the fluctuations reverses to electron diamagnetic direction around $r/\bar{a} < 1$. The phase velocity and the electron diamagnetic drift velocity are comparable ($v_{ph} \sim v_{de}$). Fluctuation-induced particle flux is comparable to those estimated from the particle balance using the H_α spectroscopic measurements. Many of the features seen in these experiments resemble to those of ohmically heated plasmas in the TEXT tokamak.

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Motivation, Purpose, and Summary

Motivation:

- Experimental observations on TEXT indicate that the electrostatic fluctuations are the dominant mechanism for energy and particle loses in the edge [1,2].

Purpose:

- Extend measurements of electrostatic fluctuations on the edge of TEXT to currentless ATF torsatron to investigate the effects of the magnetic configuration on the characteristics of the edge turbulence

⇒ **Characterize the electrostatic edge turbulence in ATF**

Summary:

- **Results from initial measurements indicate substantial similarities in characteristics of edge turbulence in ohmically heated TEXT tokamak and the currentless ATF torsatron.**

Tools and Outline

Tools:

- Diagnostic setup: Similar to one in TEXT

  $\Rightarrow$ Fast reciprocating Langmuir probe (FRLP) array.

- Same statistical data analysis techniques are used between TEXT and ATF

Outline:

- Experimental setup and analysis method
- Measurements of edge profiles of n_e, T_e, plasma floating potential (ϕ_f) and relative fluctuation levels,($\tilde{n}_e/n_e$) and ($\tilde{\phi}_f/T_e$), in ECH plasmas
- Turbulence characteristics
- Observations on the particle balance and the shear layer
- Conclusions

Experimental Set-up

- Initial fluctuation measurements in ATF were carried out around the LCFS ($r/\bar{a} \sim 1$) with the FRLP in ECH plasmas at B = 1 T. (Measurements are made during the steady-state phase of the plasma discharge.)

- Double Langmuir probe operation of two tips, aligned $\perp$ B,

  measure $\Rightarrow$ edge n_e, T_e, and $\tilde{n}_e/n_e$ profiles inside (about 2 cm) and outside LCFS -- see **Fig. 1.**

- Other two tips are floating,

  measure $\Rightarrow$ $\tilde{\phi}_f$ and k ($\perp$ B)

Representative ATF Parameters

Major radius, R_o (m)	2.1
Averaged plasma radius $\bar{a}$ (m)	0.27
Magnetic field, B (T)	1.0
Multipolarity, ℓ	2
Number of field periods, $\mathcal{M}$	12
Central rotational transform, $\iota(0)/2\pi$	0.3
Edge rotational transform, $\iota(\bar{a})/2\pi$	1.0
P_{ECH} (@53 GHz) (kW)	200
$\bar{n}_e$ (10^{12} cm^{-3})	3–6
Plasma stored energy, W_p (kJ)	1-2

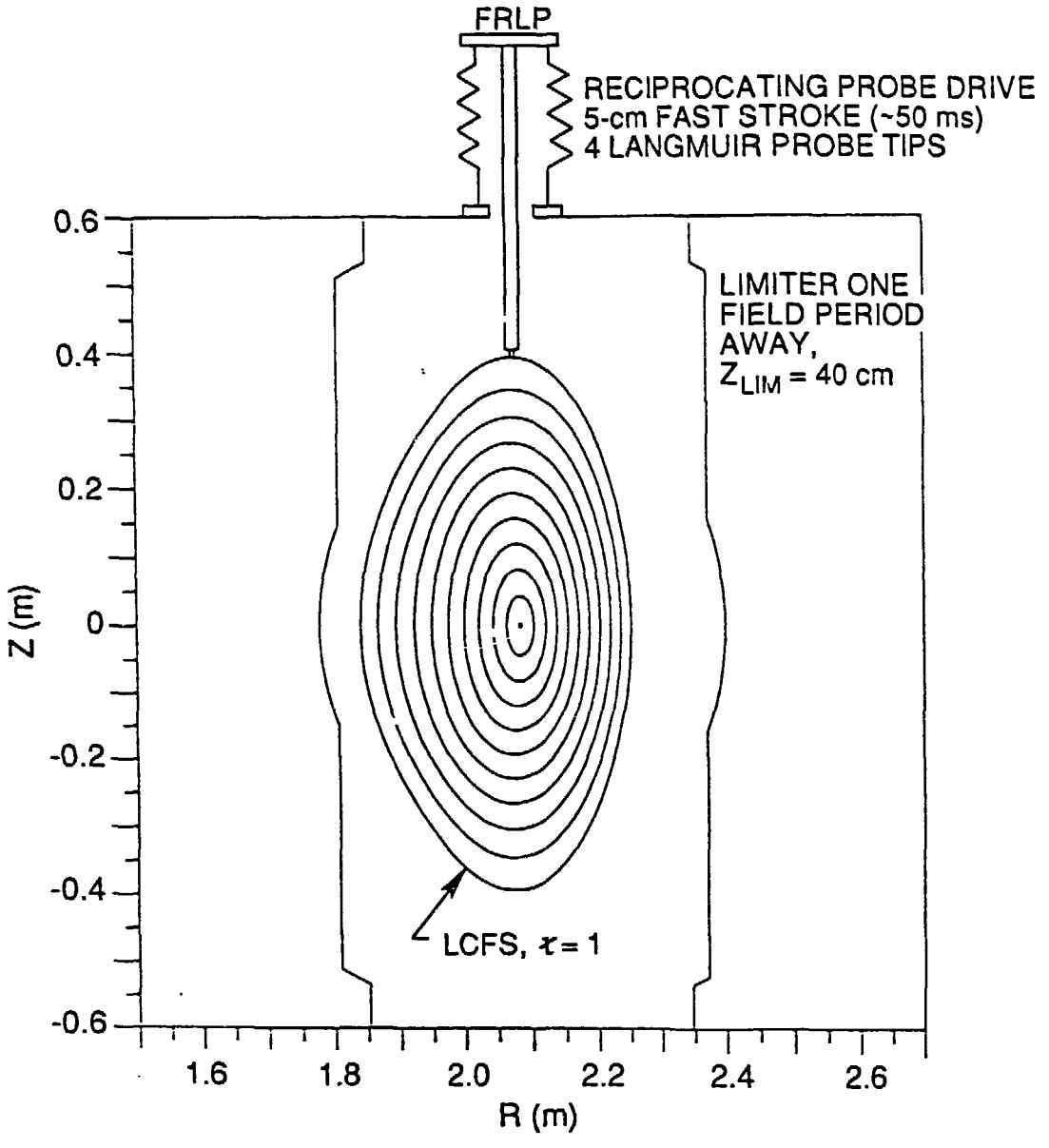

Fig. 1 Flux surfaces and the location of the FRLP in ATF. FRLP head consists of a square array of four tips: 2 mm long and 2 mm apart. Probe moves 5 cm into the plasma in 50 ms, remains there ~40 ms.

Data analysis:

- Data analysed using spectral analysis techniques [3].

  $\Longrightarrow$ Fluctuation signals digitized at 1 MHz

  $\Longrightarrow$ FFT used to obtain their power spectrum $S(k,\omega)$ as a function of ω and k using the two-probe technique [4].

- $\tilde{\Gamma}(\omega)$ obtained from the correlation of density and plasma potential fluctuations ($\tilde{\phi}_p$), gives the turbulence-induced radial particle flux:

$$\tilde{\Gamma} = \langle \tilde{n}_e \, \tilde{v}_r \rangle = 2 \, \Sigma_{\omega>0} \; \tilde{\Gamma}(\omega), \qquad (1)$$

$\tilde{v}_r = -ik\tilde{\phi}_p/B$, for the electrostatic fluctuations.

From the triple correlation technique [5] :

$$\tilde{\Gamma}(\omega) = \mathrm{Re}[\langle -ik(\omega)\, \tilde{n}_e^*(\omega)\, \tilde{\phi}_p(\omega) \rangle]/B. \qquad (2)$$

$$\approx (k/B)\, \gamma_{n\phi}\, n_{rms}\, \phi_{rms} \sin\theta_{n\phi}, \qquad (3)$$

$\gamma_{n\phi}$ = coherence, $\theta_{n\phi}$ = phase angle between $\tilde{n}_e$ and $\tilde{\phi}_p$ fluctuations, n_{rms} and ϕ_{rms} = r.m.s. values of fluctuations.

Results and Discussion

Edge Plasma Properties

⇒ **Figure 2:** Spatial profiles of edge plasma n_e, T_e, and floating potential ϕ_f for $0.95 < r/\bar{a} < 1.15$.

⇒ Plasma potential ϕ_p can be estimated from $\phi_p \approx \phi_f + \delta_p T_e$, where δ_p depends on probe material, heat load on the probe, the ion spice and its temperature, and the secondary electron emission coefficient. Typically, $\delta_p \sim$ (1–3).
[see **Fig. 10:** ϕ_p is displayed for $\delta_p \approx 2.5$]

⇒ Plasma parameters around LCFS, $r/\bar{a} \approx 1$:

$n_e = (1\text{–}1.2) \times 10^{12}$ cm^{-3} and $T_e = (30\text{–}40)$ eV.

⇒ Densisty and Temperature scale lengths:

$L_n = [-(1/n_e)(dn_e/dr)]^{-1} \approx (3\text{–}4)$ cm and $L_T \approx 2L_n$.

These valuse are comparable (within a factor of 2) to those for ohmic plasmas in TEXT at 2 T.

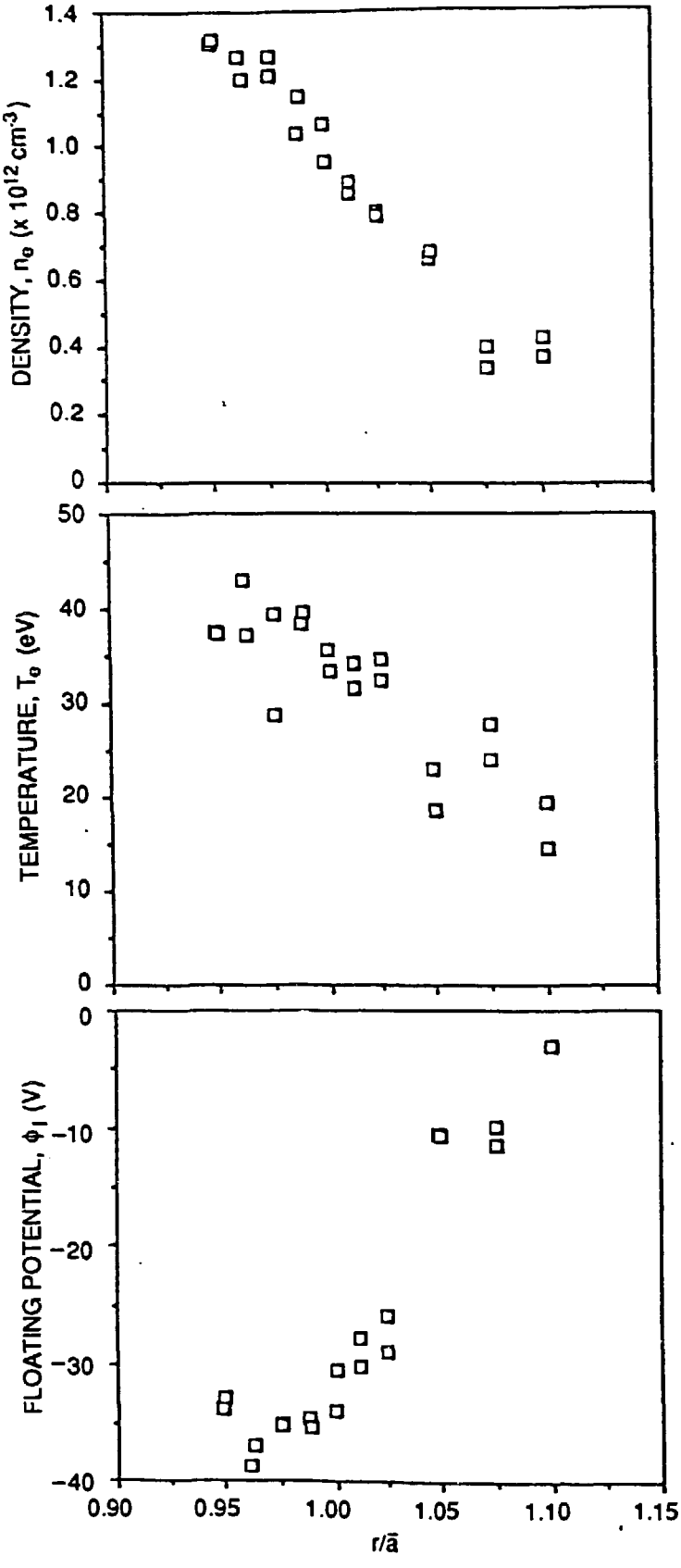

Fig. 2 Spatial profiles of the ATF edge plasma density, temperature, and floating potential.

Edge Fluctuations Characteristics

Relative Fluctuation Levels

⇒ **Figure 3:** Spatial profiles of $\tilde{n}_e/n_e$ and $\tilde{\phi}_f/T_e$. Typical values around the LCFS: $\tilde{n}_e/n_e \approx (0.05–0.1)$ and $\tilde{\phi}_f/T_e \approx (0.1–0.2)$, lower than TEXT.

⇒ Fluctuations decrease at $r/\bar{a} \sim 0.95$, where $T_e > 20$ eV and $\tilde{\phi}_f/T_e \approx 2\tilde{n}_e/n_e$.

note In ATF correlation between $\tilde{\phi}_f$ and $\tilde{T}_e$ is not known, however, the contribution of $\tilde{T}_e$ to $\tilde{\phi}_p$ is neglected. recall: measured values of $\tilde{T}_e$ on TEXT were relatively small ($\tilde{T}_e/T_e \approx 0.4\tilde{n}_e/n_e$) [6].

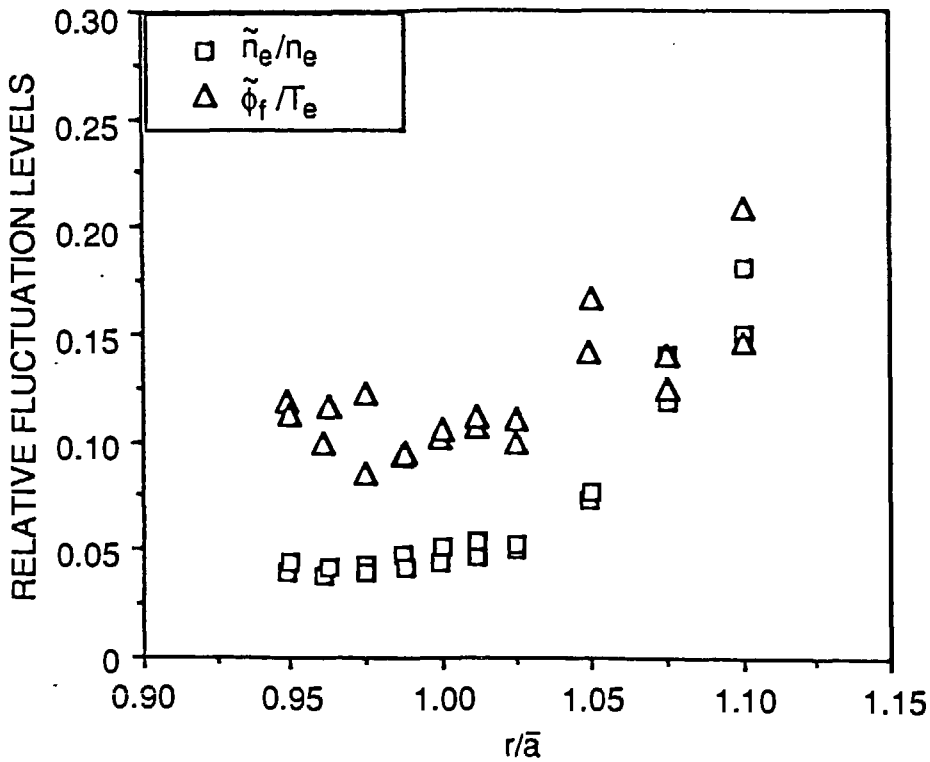

Fig. 3 Relative fluctuation levels for edge density and plasma floating potential.

Edge Fluctuations Characteristics (cont'd)

Spectrum and Wavenumber

⇒ Fluctuation spectra examined up to 400 kHz.

⇒ S(k,ω) is broadband and mostly in 40–300 kHz range (see **Figs. 4 and 5**).

⇒ Estimated mean k value: $\bar{k} = (1–3)\ cm^{-1}$, satisfies $\bar{k}\rho_s \approx (0.05\text{-}0.1)$, as observed in TEXT

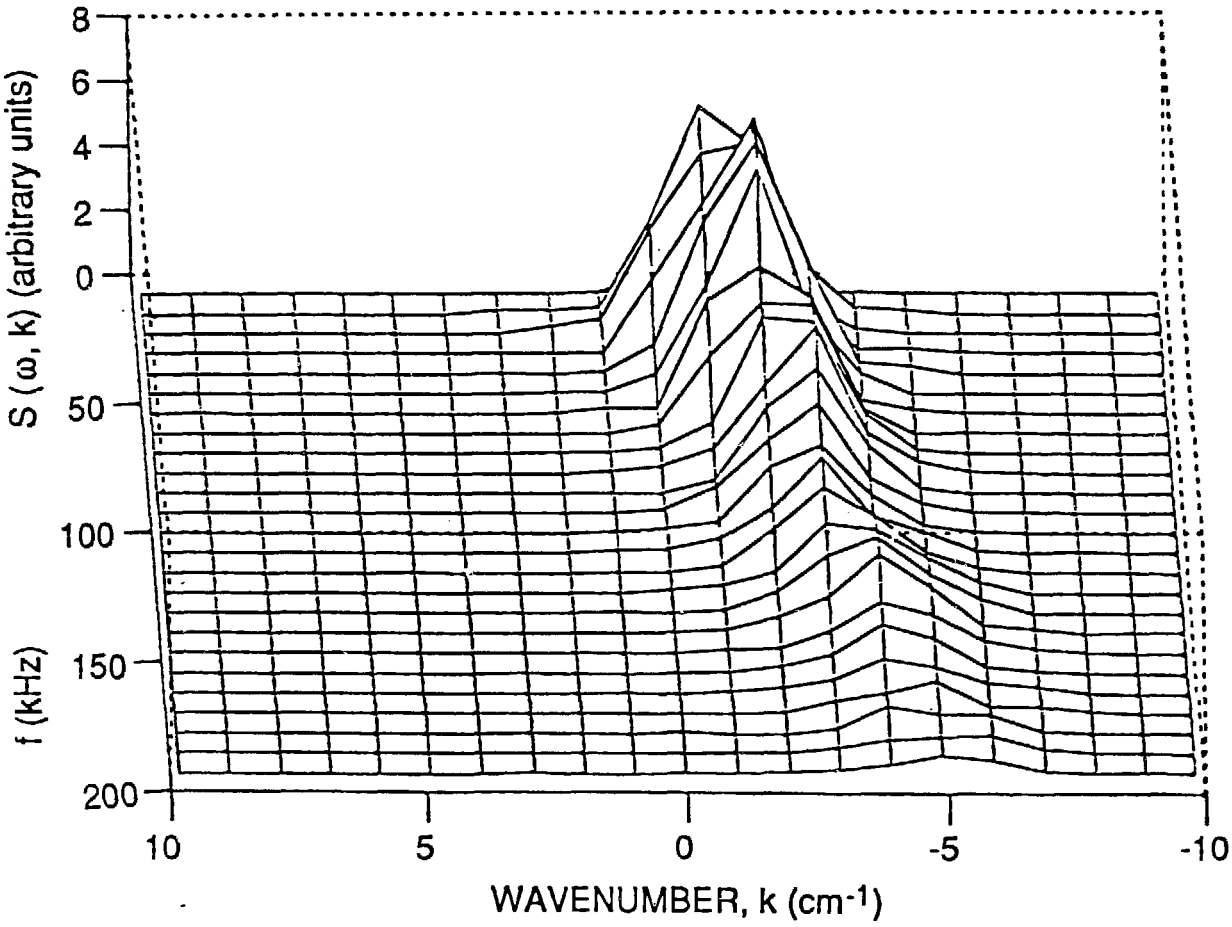

Fig. 4 Wave number-frequency power spectrum for potential fluctuations.

Edge Fluctuations Characteristics (cont'd)

Spectrum and Wavenumber (cont'd)

⇒ **Figure 5:** Integrated $\tilde{\phi}_f$ power spectra S(ω) and S(k) decrease for large ω (> 200 kHz) and k: $S(\omega) \sim \omega^{-\alpha}$ and $S(k) \sim k^{-\beta}$, with $\alpha \sim \beta \approx 4 \pm 1$.

⇒ Shape of $\tilde{n}_e$ power spectrum is similar to $\tilde{\phi}_f$.

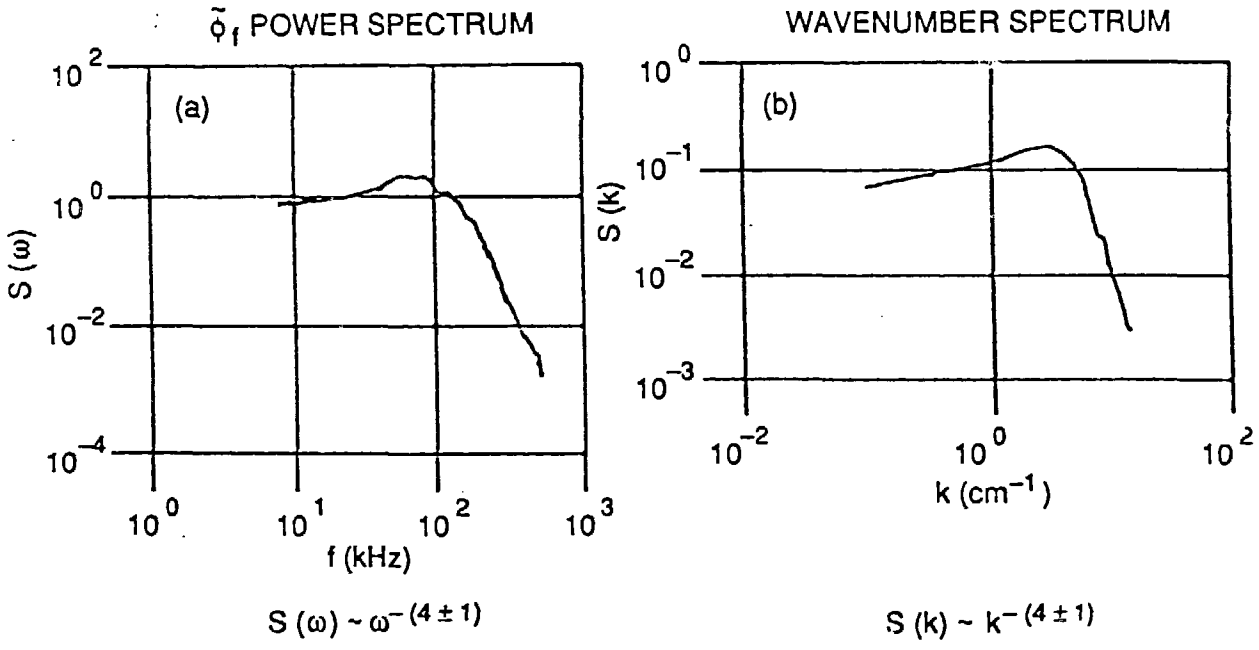

Fig. 5 (a) Power spectrum of the potential fluctuations, (b) Wave number spectrum S(k).

Edge Fluctuations Characteristics (cont'd)

Spectral Width

⇒ **Figure 6:** Inside LCFS, spectral width σ_k decreases with T_e, indicating correlation length $L_c = 1/\sigma_k$ increases with T_e and $L_c \approx 1$ cm for $T_e > 35$ eV.

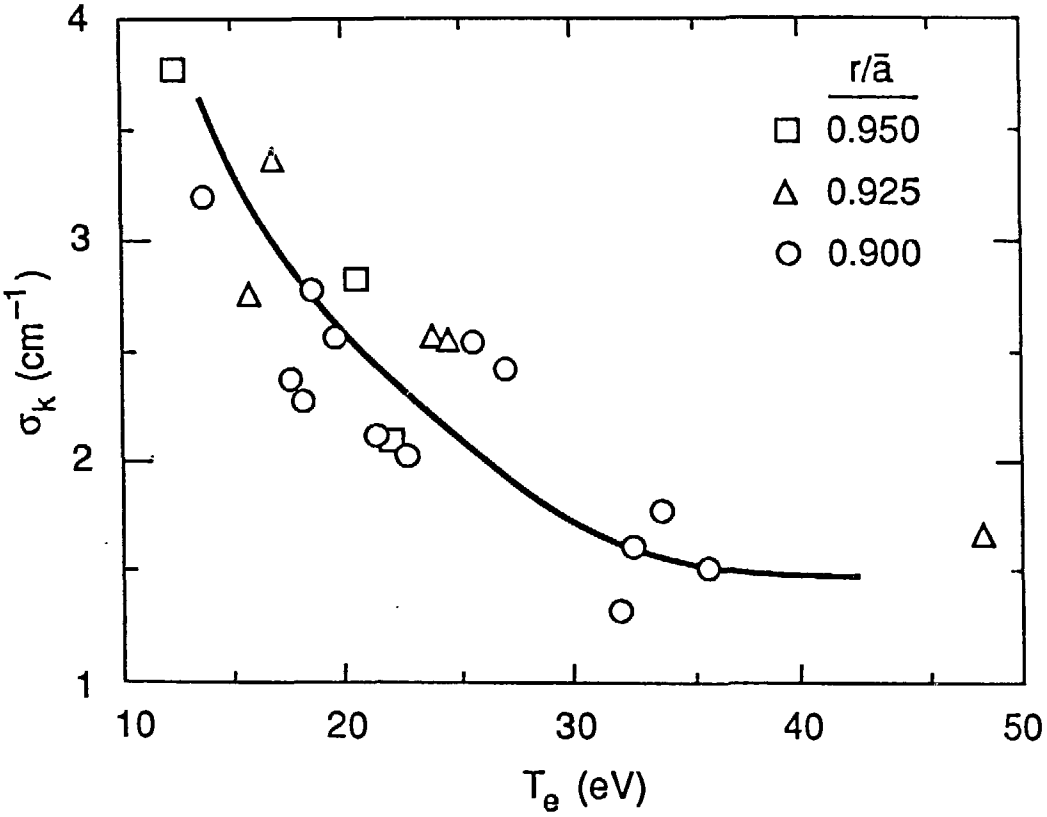

Fig. 6 Variations of σ_k with T_e inside the LCFS.

Edge Fluctuations Characteristics (cont'd)

Fluctuation-induced Particle Fluxes

⇒ The fluctuation-induced total particle flux $\tilde{\Gamma}$ is estimated from Eqs. (1) and (2) by taking $\tilde{\phi}_p \approx \tilde{\phi}_f$.

The coherence is $\gamma_{n\phi} \approx 0.8$ up to 150 kHz, dropping to about 0.2 beyond 250 kHz.

The phase angle is $\theta_{n\phi} \approx 70°$ around 150 kHz.

⇒ $\tilde{\Gamma}(\omega)$ dominated by below 250 kHz, (**Fig. 7**), and reaches a maximum at 100-150 kHz, where the phase angle has its maximum.

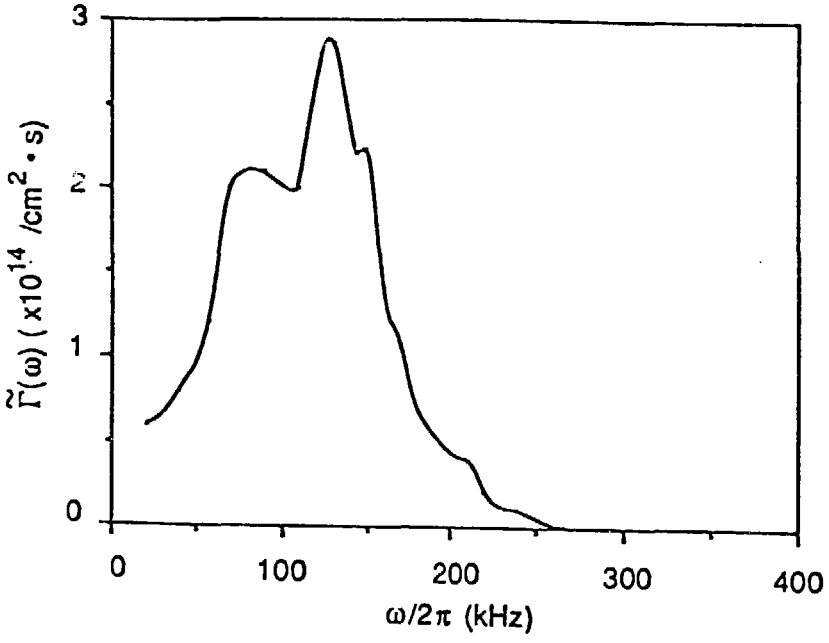

Fig. 7 Typical spectrum of the fluctuations-induced particle flux.

Edge Fluctuations Characteristics (cont'd)

Fluctuation-induced Particle Fluxes (cont'd)

⇒ **Figure 8:** $\tilde{\Gamma}$ profile for $\bar{n}_e/10^{12}$ cm^{-3} = 3.5 and 5.5. Radial flux is always outward and at the LCFS: $\tilde{\Gamma} \sim 3 \times 10^{15}$ cm^{-2}•s^{-1} for $\bar{n}_e = 3.5 \times 10^{12}$ cm^{-3} ($\tilde{\Gamma} \sim 1.2 \times 10^{15}$ cm^{-2}•s^{-1} for $\bar{n}_e = 5.5 \times 10^{12}$ cm^{-3}).

⇒ For nearly flat core density profiles observed in ATF, the fluctuation-induced τ_p is $\tau_p = (\bar{a}/2)\bar{n}_e/\tilde{\Gamma} \sim 16$ ms and 60 ms, respectively.

⇒ Associated local density diffusion coefficient is $D_n = \tilde{\Gamma}L_n/n_e \sim 10^4$ cm^2•s^{-1}, n_e(edge) $\sim 10^{12}$ cm^{-3}, $L_n \sim 4$ cm for both $\bar{n}_e$ cases.

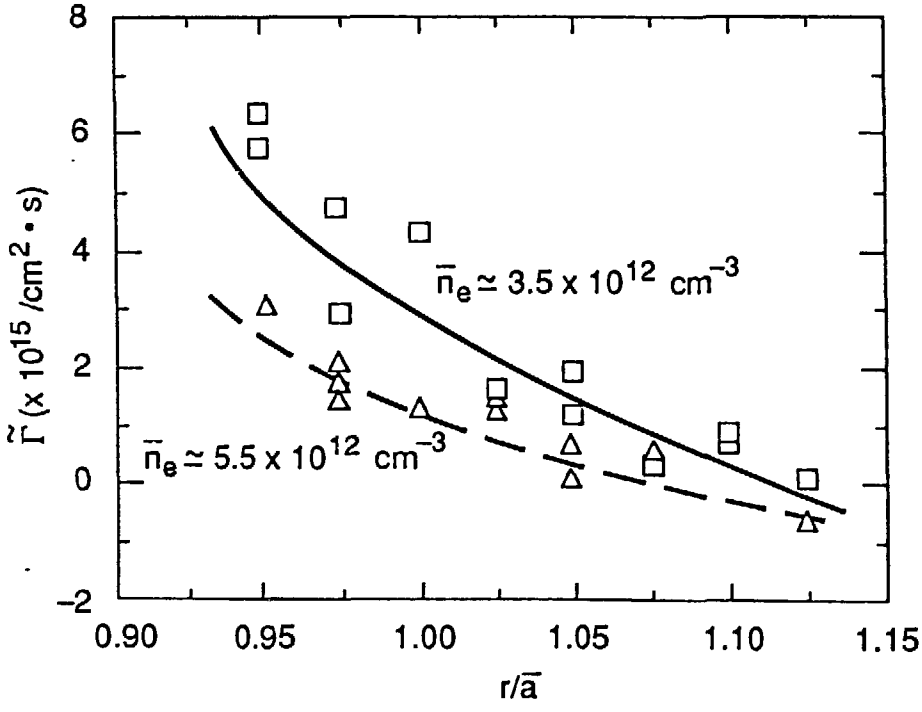

Fig. 8 Profile of the fluctuations-induced particle flux

Observations

Particle Balance

⇒ Detailed $\bar{n}_e$ scan experiments are not yet available. But, the limited scans indicate that $\tilde{\tau}_p$ increases with $\bar{n}_e$ in low density regime.

☞ This observation is consistent with the TEXT results [7].

⇒ Particle flux from the particle balance using H_α measurements is $\Gamma_{H\alpha} \sim (1\text{–}1.5) \times 10^{15}$ cm^{-2}•s^{-1} for $\bar{n}_e = 5.5 \times 10^{12}$ cm^{-3};

⇒ $\Gamma_{H\alpha}$ comparable to $\tilde{\Gamma}$, suggesting that electrostatic edge turbulence may be responsible for particle confinement characteristics in ATF.

Observations

Shear Layer

⇒ **Figure 9**: Spatial profile of mean phase velocity of the fluctuations, $v_{ph} = 2\Sigma_{\omega>0} v_{ph}(\omega)$. As observed on TEXT, fluctuations propagate in ion diamagnetic direction for $r/\bar{a} > 1$, but it reverses to electron diamagnetic direction for $r/\bar{a} < 1$.

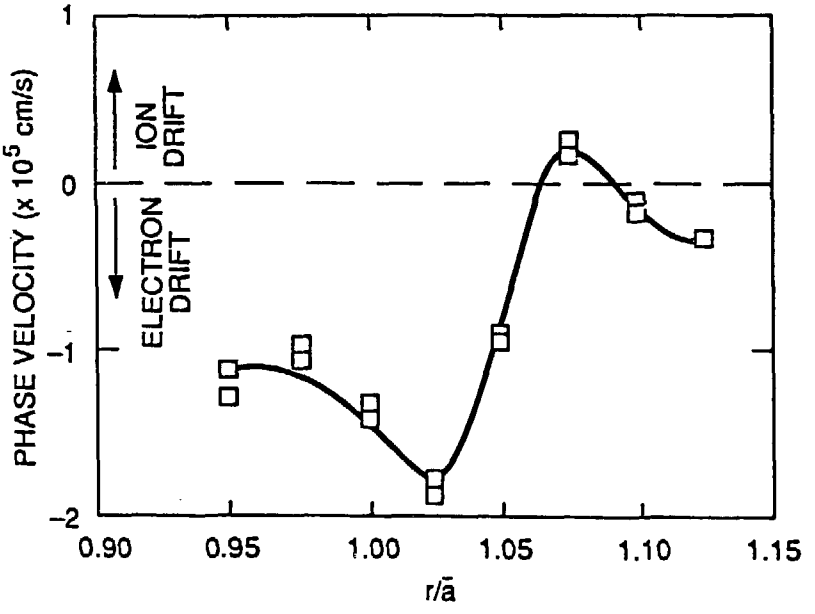

Fig. 9 Spatial profile of $\bar{v}_{ph}$ of fluctuations. Beyond the shear layer the wave propagation is in the ion diamagnetic direction.

Observations (cont'd)

Shear Layer

⇒ **Figure 10**: Location of v_{ph} shear layer coincides with peak of plasma potential, where $E_r = -d\phi_p/dr$ changes direction from outward to inward

- At this location, ∇n_e and $\nabla T_e \sim 0$ and $v_{ph} \sim v_{de} \sim 0$, where $v_{de} = (T_e/eB)(1/L_n + 1/L_T) - E_r/B$ = electron drift velocity.
- Well inside LCFS, where $E_r \approx 0$, $v_{de} \approx v_{ph} \approx 10^3$ m/s.

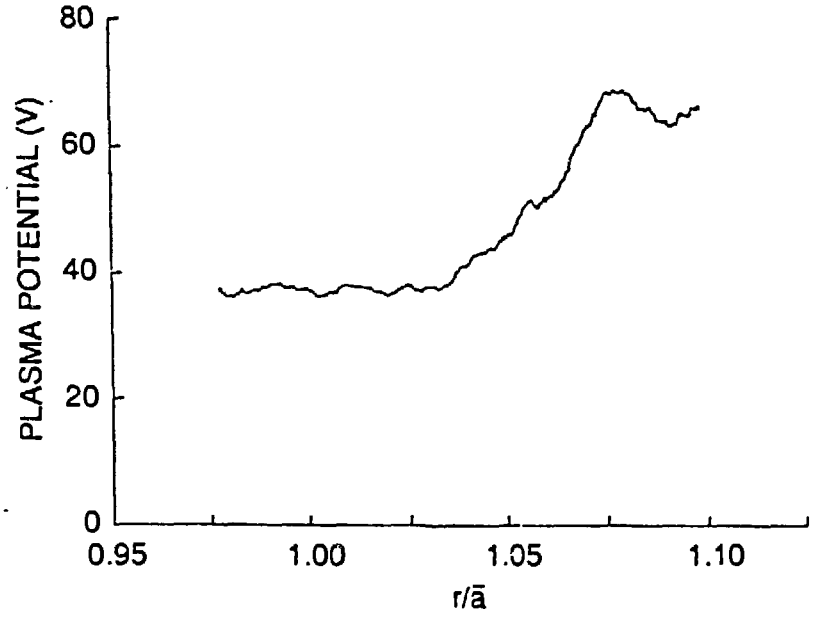

Fig. 10 Plasma potential profile

CONCLUSIONS

Results from initial measurements indicate substantial similarities in characteristics of edge turbulence in ohmically heated TEXT tokamak and the currentless ATF torsatron.

☞ Fluctuation characteristics are insensitive to plasma current.

Fluctuation-induced particle flux is consistent with the total particle flux estimated from the global particle balance (spectroscopic measurements).

☞ Electrostatic turbulence may be responsible for the edge particle transport.

Detailed comparisons of ATF and TEXT results can serve as basis for development of a unified physics interpretation of edge turbulence in toroidal devices.

Future Plans

⇒ Future experiments will include

- measurement of T_e fluctuations [8] to determine relationship between $\tilde{\phi}_p/T_e$ and $\tilde{n}_e/n_e$,
- scaling of the edge fluctuation parameters with $\bar{n}_e$,
- extension of experiments to ECH plasmas at 2 T,
- extension of experiments to neutral-beam-heated plasmas.

⇒ Additional information will be available from heavy ion beam probe diagnostic on plasma potential that will help to better characterize the edge turbulence on ATF.

References

[1] Ch. P. Ritz, R. D. Bengtson, S. J. Levinson, and E. J. Powers, Phys. Fluids **27**, (1984) 2956, and Ch. P. Ritz, et al., Nucl. Fusion **27** (1987) 1125.

[2] Ch. P. Ritz, R. V. Bravenec, R. V. Schoch et al., Phys. Rev. Letters **62** (1989) 1844.

[3] E. J. Powers, Nucl. Fusion **14**, (1974) 749.

[4] J. M. Beall, Y. C. Kim, E.J. Powers, J. Appl. Phys. **43** (1982) 3933.

[5] Ch.P.Ritz, E J. Powers, T. L. Rhodes, et al., Rev. Sci. Inst. **59**, (1988) 1739.

[6] H. Lin, R. D. Bengtson, and Ch. P. Ritz, Univ. of Texas FRCR **334** (1989).

[7] W. L. Rowan, et al., Nucl. Fusion **27** (1989) 1105.

[8] D. C. Robinson and M. G. Rusbridge, Plasma Physics **11** (1969) 73.