Ciemat 721
Sp ISSN 614-087-X

ON THE ROLE OF IMPURITY RADIATION ON EDGE TURBULENCE IN THE TJ-I TOKAMAK

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CENTRO DE INVESTIGACIONES
ENERGETICAS, MEDIOAMBIENTALES Y TECNOLOGICAS

MADRID, 1994

CLASIFICACION DOE Y DESCRIPTORES:

700330
PLASMA
EDGE LOCALIZED MODES
TURBULENCE
PLASMA INSTABILITIES
ELECTRON TEMPERATURE
FLUCTUATIONS
DENSITY
TJ-I TOKAMAK

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Los descriptores se han seleccionado del Thesauro del DOE para describir las materias que contiene este informe con vistas a su recuperación. La catalogación se ha hecho utilizando el documento DOE/TIC-4602 (Rev. 1) Descriptive Cataloguing On-Line, y la clasificación de acuerdo con el documento DOE/TIC.4584-R7 Subject Categories and Scope publicados por el Office of Scientific and Technical Information del Departamento de Energía de los Estados Unidos.

Este trabajo se ha recibido para su impresión en Marzo de 1.993

Depósito Legal nº M-12366-1993
ISBN 84-7834-193-5
ISSN 614-087-X
NIPO 238-94-007-4

IMPRIME CIEMAT

Radiative instabilities have been considered as a possible driving term to partially explain the measured levels of plasma edge fluctuations. Much experimental work is being carried out in order to evidence the role of the two radiation related mechanisms likely contributing to the edge turbulent transport [1-7]. At present, it is well stated that the main experimental signature of radiative instabilities is the presence of substantial temperature fluctuations. Condensation instabilities, for which a significant coupling between density and temperature fluctuations is expected, are under study in a number of devices. In our previous work in the TJ-I tokamak [8], it has been reported that in the bulk side region of the velocity shear layer, temperature and density fluctuate at about the same level and in phase close to opposition. Evidence of density and temperature fluctuating almost in antiphase has also been reported in the TEXT tokamak [9] and in the REPUTE-I reverse field pinch [10]. On the other hand, thermal instabilities, extremely sensitive to the detailed radiation cooling profile, are difficult to be studied separately because the plasma region where $\partial I_z(T_e)/\partial T_e < 0$, being I_z the impurity radiation cooling, is typically well inside the magnetic separatrix and hardly accessible to probe measurements. Nevertheless, under some conditions, the thermal instability contribution to the radiatively driven turbulence can be significantly more relevant than the one due to condensation related phenomena [11].

In this letter we present experimental evidence of radiation enhanced edge turbulence due to the presence of a high density of impurities.

Density and temperature fluctuations have been measured in the plasma edge region of the TJ-I tokamak (R = 30 cm, a = 10 cm) by means of Langmuir probes. Measurements were performed in ohmically heated discharges with $B_t = 1$ T, $\bar{n}_e \approx 1.0 - 1.5 \times 10^{13}$ cm^{-3} and $I_p \approx 40$ kA. The probe system consists of a square array of four tips (2 mm x 2 mm); pins are 2 mm long and 0.4 mm in diameter.

In order to measure electron temperature fluctuations one of the probes is working as a fast swept probe. A 500 W broadband amplifier was used to supply the swept voltage (≈ 200 V) at 400 kHz to that single probe. To avoid the electron saturation regime in the Langmuir characteristic a variable off-set was applied. Under these conditions, the electron temperature and the deduced electron density can be determined on a time scale of about 1μs and the threshold above which temperature fluctuations are meaningful is less than 15%. In figure 1a we are showing the raw data from the swept Langmuir probe. Further details of the measurement procedure and analysis have been described elsewhere [8, 12, 13]. Other two tips, aligned in the poloidal magnetic field direction, were used to measure the floating potential and the poloidal phase velocity of the fluctuations. The fourth tip was biased at a fixed voltage (V= -180 V) in the ion saturation current regime. Measurements of the ion saturation current, floating potential, and their fluctuations, obtained by the later method and by the fast swept probe technique, are in very good agreement as shown in figure 1b.

Radial profiles of the total radiation losses have been measured using a 10-channels bolometer array with a radial resolution of the viewing chords at the plasma center of about 2 cm. Detectors (germanium bolometers [14]) are arranged in a parallel geometry and look at the same plasma poloidal section than the probes, as displayed in figure 2a. A movable stainless steel poloidal limiter was placed in the same port of the vacuum chamber (rectangular section vertically elongated) than the probes (see fig. 2). The resulting setup designed for this experiment enables us to obtain a strong plasma-limiter interaction at the cross-talk volume of the uppermost detector in the bolometer array and the Langmuir probes. Consequently, different radiation profiles due to different impurity concentrations can be obtained as figure 2b illustrates.

For the present experiment we have run series of repetitive discharges and studied plasmas were limited with the stainless steel limiter located at r_{lim} = 10.3 and at r_{lim} = 10.8 cm with respect to the equatorial plane of the vacuum vessel. The edge radial profiles of both, electron temperature and density, practically do not change with the limiter position. Figure 3a shows the radial profile of the electron temperature and figure 3b, the radial profile of the electron density (deduced from the ion saturation current and the local electron temperature, $n_e \propto I_s T_e^{-1/2}$) versus the probe radial position (r_p), for the series of discharges with the limiter at 10.3 cm. The density profile is much steeper in the bulk side of the shear layer (localized at the limiter position) than in the scrape-off side.

To investigate the possible influence on the turbulence strength of changes induced by the limiter in the edge radiation, we have compared the behaviour of the edge turbulence between corresponding discharges of the two series (i.e., discharges in which probes were located at the same relative distance to the limiter, $r_{lim} - r_p$). Figures 4a and 4b show the typical time evolution of the chord integral measurements of the total power losses for discharges with the limiter placed at 10.8 cm (a) and at 10.3 cm (b). As can be seen, power losses profiles remain basically unchanged with exception of the uppermost detector signal. In both cases, losses coming from the edge were increasing all along the discharge, due to the strong interaction of plasmas with the limiter, but in fig. 4b, a more pronounced increase is observed. Contributions to these signals due to charged particles reaching the detectors through their long collimators can be neglected [15], and the flux of charge-exchange neutrals can be considered rather constant [16]. Therefore, the observed increase in bolometer signals is due to the enhancement of impurity radiation near the limiter. The usual Abel inversion technique does not yield satisfactory results when strong up-down asymmetries are evident and noticeable uncertainties are obtained at the plasma edge unless high spatial resolution (few mm) is available. Fortunately, in the present case there is no need for an inversion to realize that the emissivity profile is heavily peaked at the upper plasma edge.

In figure 4c, we have plotted the normalized root mean square (rms) values of the ion saturation current, ($\tilde{I}_{sat}/I_{sat}$), electron density, ($\tilde{n}_e/n_e$), and electron temperature fluctuation levels, ($\tilde{T}_e/T_e$), versus the edge radiation for shots belonging to the above mentioned series in which probes were located inside the viewing chord of the uppermost bolometer and at $r_{lim} - r_p \approx 0.2$ cm. Analyses of fluctuation levels were performed during 6 ms in each discharge (the time intervals are delimited by the arrows drawn in figures 4a and 4b). For shots with profiles like the shown in figure 4a, at the lower levels of edge radiation, the rms values of the three magnitudes are very similar. As edge radiation increases, temperature fluctuations slightly increase and density and ion saturation current fluctuations slightly decrease, resulting in a ratio $(\tilde{T}_e/T_e) / (\tilde{n}_e/n_e)$ of about 2 (see open symbols). However, and although edge radiation is notably higher and further increasing (up to a factor 3), as is the case shown in figure 4b, the rms values of $(\tilde{T}_e/T_e)$, $(\tilde{n}_e/n_e)$ and $(\tilde{I}_{sat}/I_{sat})$ remain constant (see full symbols).

Fourier analysis of the temperature and density fluctuations deduced from the fast swept probe technique show that fluctuations are dominated by frequencies below 100 kHz (see figures 5a and 5b). Figures 5c and 5d show the coherence and crossphase between $\tilde{T}_e$ and $\tilde{n}_e$. The phase seems to change from zero (for $r / a_{lim} \leq 1$) to close to opposition (for $r / a_{lim} \geq 1$) in the frequency range in which the coherence is above the noise level (~ 0.2).

Considering that impurity radiation cooling drives electron temperature fluctuations, the high values of the rms electron temperature fluctuations observed in the plasma edge region of the TJ-I tokamak point out the possible role of radiative instabilities as a driving mechanism of edge turbulence [7].

As mentioned above, the present experiment shows an increase of the ratio $(\tilde{T}_e/T_e) / (\tilde{n}_e/n_e)$ as the radiation profile tends to peak near the limiter radius (i.e., when $\partial I_z(T_e)/\partial T_e$ tends to be negative). Once the radiation profile peaks at the upper plasma edge, no relationship between the strength of the radiation ($R \propto n_z I_z$) and edge fluctuation levels is observed.

Taking into account that temperature fluctuations can be larger than density fluctuations in the plasma region where $\partial I_z(T_e)/\partial T_e$ is the dominant drive for turbulence (thermal drive), the observed correlation between edge radiation and fluctuation levels reveals that thermal instabilities likely are an important drive for the edge turbulence measured at the upper plasma edge.

Although density and temperature fluctuations are in phase close to opposition in the plasma bulk side of the limiter radius, the absence of any dependence of temperature fluctuation levels on the absolute level of the total radiated power from the edge ($\propto$ R), shows that under these experimental conditions, the condensation instabilities, if present, are not the dominant drive of edge turbulence.

Finally, it has to be noticed that the fluctuation levels, especially those of electron density, measured in the present experiment in the proximity of the shear layer location at the upper plasma region of TJ-I, are significantly smaller than those previously reported in the outer region of the equatorial plane [8]. Therefore, and taking into account the additional asymmetry introduced by the presence of the limiter, these results demonstrate the existence of strong poloidal asymmetries in the edge turbulence of the TJ-I tokamak.

In summary, the present experiments show that when impurity radiation is strongly peaked in the vicinity of the limiter of the TJ-I tokamak there are substantial temperature fluctuations and that these are notably higher than density fluctuations. The results indicate that modifying the radiation cooling profile at the plasma edge significantly affects turbulence levels. While no effects of condensation related phenomena have been observed so far, we have found experimental evidence of edge turbulence driven by thermal instabilities.

ACKNOWLEDGMENTS

The authors would like to thank L. Giannone for his contribution to improve the fast swept probe electronics. We are also indebted to the TJ-I Technical Team. This work has been partially supported by DGICYT (Dirección General de Investigaciones Científicas y Técnicas) of Spain under Project No. PB90-0639-C02-02.

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Figure Captions

Figure 1. a) Raw data from the fast swept Langmuir probe. b) Comparison between the rms values of the ion saturation current fluctuations measured with the fast swept probe and with the probe at a fixed bias in the ion saturation regime.

Figure 2. a) Experimental setup (D, germanium detectors; C, collimator tubes). b) Standard and perturbed vertical profiles of the total radiation in the TJ-I tokamak. (-10.0 cm, bottom; +10.0, cm, top).

Figure 3. a) Electron temperature and b) electron density profiles for the series of discharges with the limiter at $r_{lim} = 10.3$ cm.

Figure 4. Time evolution of the line integrated profiles of plasma emissivity for shots with the limiter at a) 10.8 cm and b) 10.3 cm. c) normalized rms fluctuations of the ion saturation current (o, ●), electron density (Δ, ▲) and electron temperature (◊, ◆) as a function of the edge radiation. Open symbols refer to fig. 4 a) and black ones to fig. 4 b).

Figure 5. a) Electron density and b) temperature normalized fluctuation power spectra; c) coherence ($\gamma_{T_en_e}$) and d) crossphase ($\alpha_{T_en_e}$) between them, for two shots with the probes located at the bulk side (dotted lines) and at the scrape-off layer side of the limiter radius (bold lines).

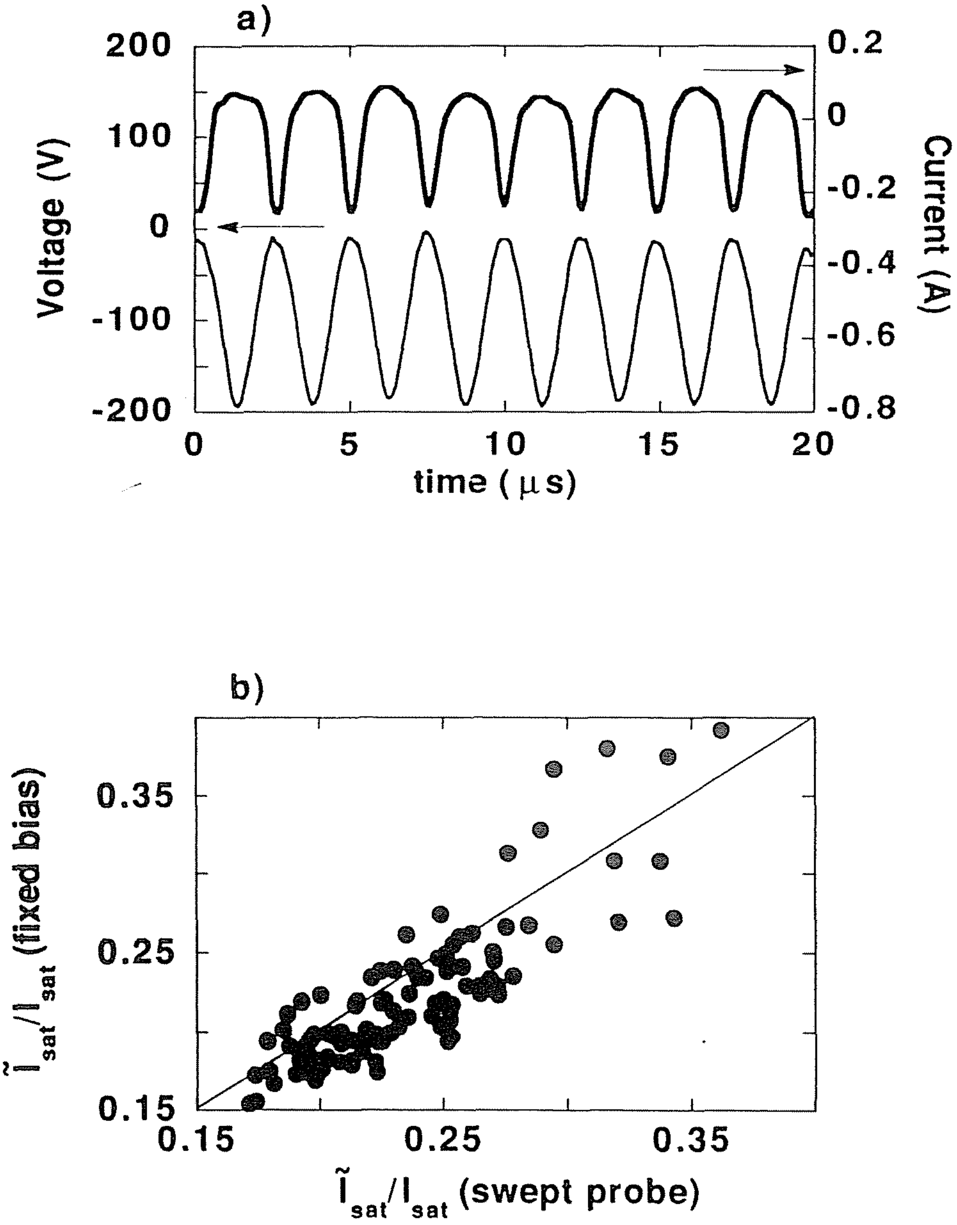

a)
200
100
0
-100
-200
Voltage (V)
0.2
0
-0.2
-0.4
-0.6
-0.8
Current (A)
0
5
10
15
20
time (μ s)
b)
0.35
0.25
0.15
$\tilde{I}_{sat}/I_{sat}$ (fixed bias)
0.15
0.25
0.35
$\tilde{I}_{sat}/I_{sat}$ (swept probe)

Figura 1

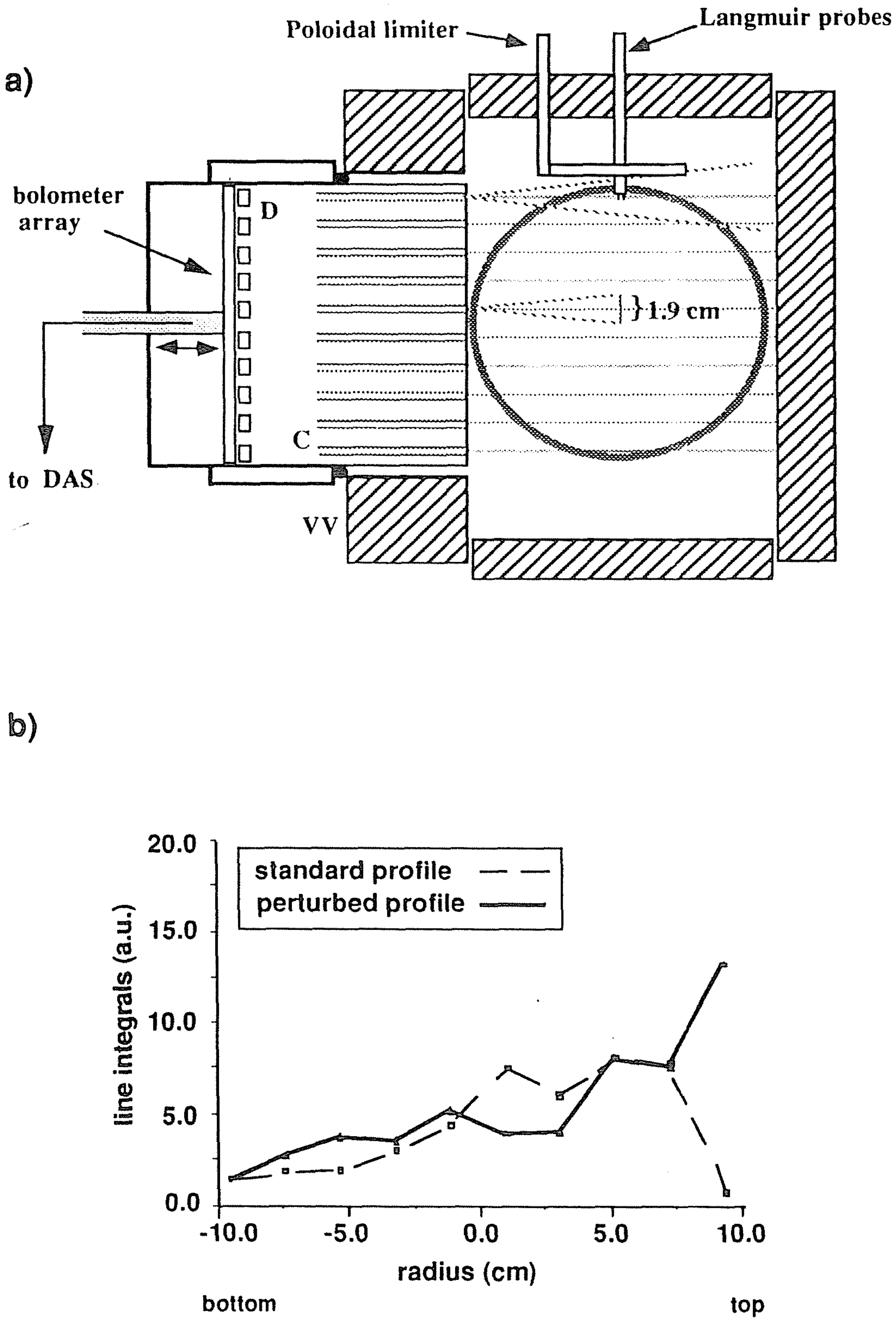
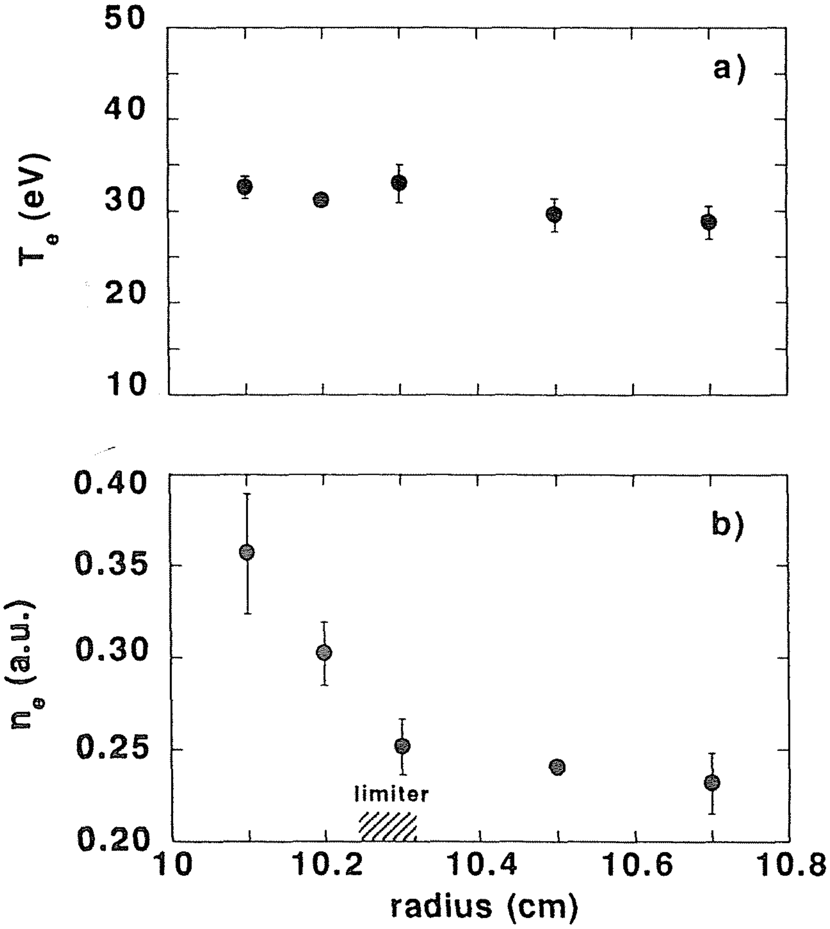

a)
Poloidal limiter
Langmuir probes
bolometer array
D
C
to DAS
VV
1.9 cm
b)
standard profile
perturbed profile
line integrals (a.u.)
20.0
15.0
10.0
5.0
0.0
-10.0
-5.0
0.0
5.0
10.0
radius (cm)
bottom
top

Figura 2



a)
b)
T_e (eV)
50
40
30
20
10
n_e (a.u.)
0.40
0.35
0.30
0.25
0.20
limiter
10
10.2
10.4
10.6
10.8
radius (cm)

Figura 3

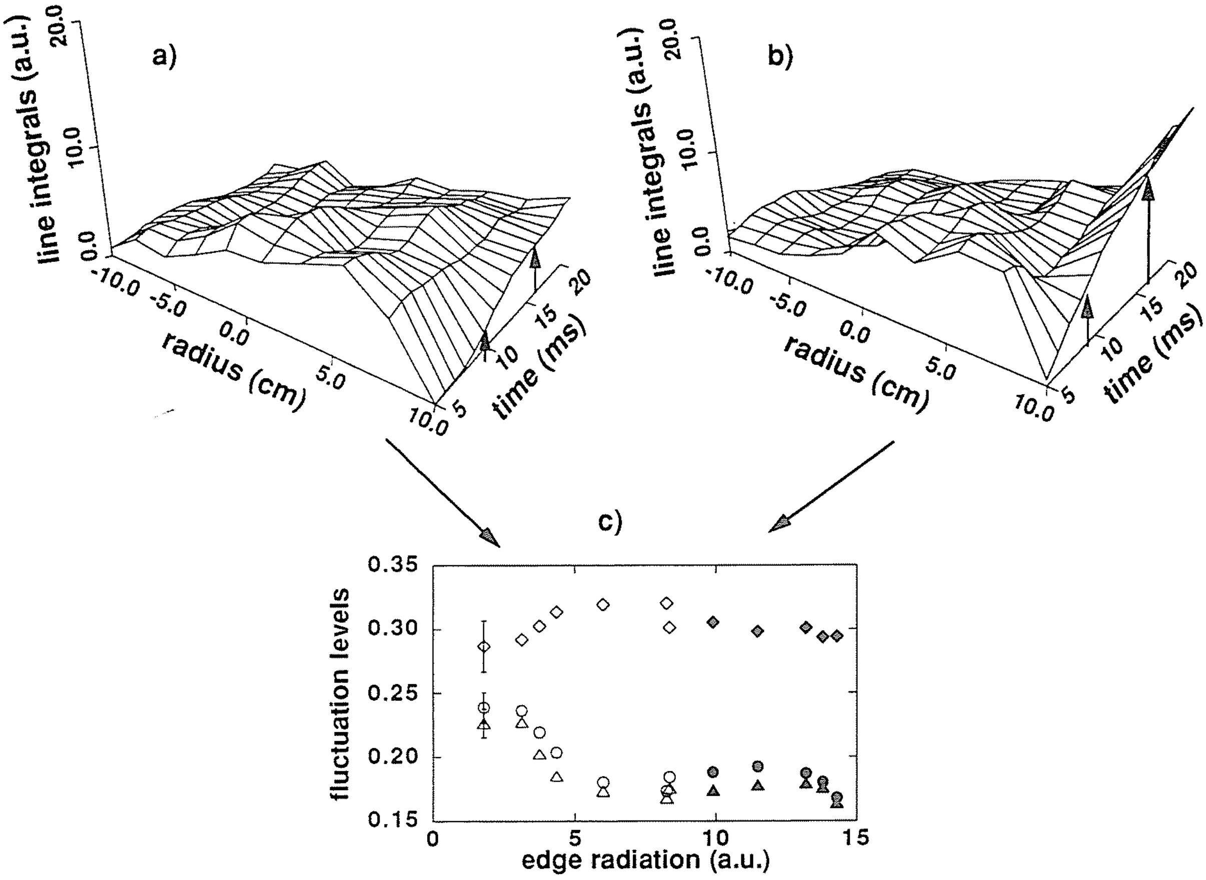

a)
line integrals (a.u.)
0.0
10.0
20.0
-10.0
-5.0
0.0
5.0
10.0
radius (cm)
5
10
15
20
time (ms)
b)
line integrals (a.u.)
0.0
10.0
20.0
-10.0
-5.0
0.0
5.0
10.0
radius (cm)
5
10
15
20
time (ms)
c)
fluctuation levels
0.15
0.20
0.25
0.30
0.35
0
5
10
15
edge radiation (a.u.)

Figura 4

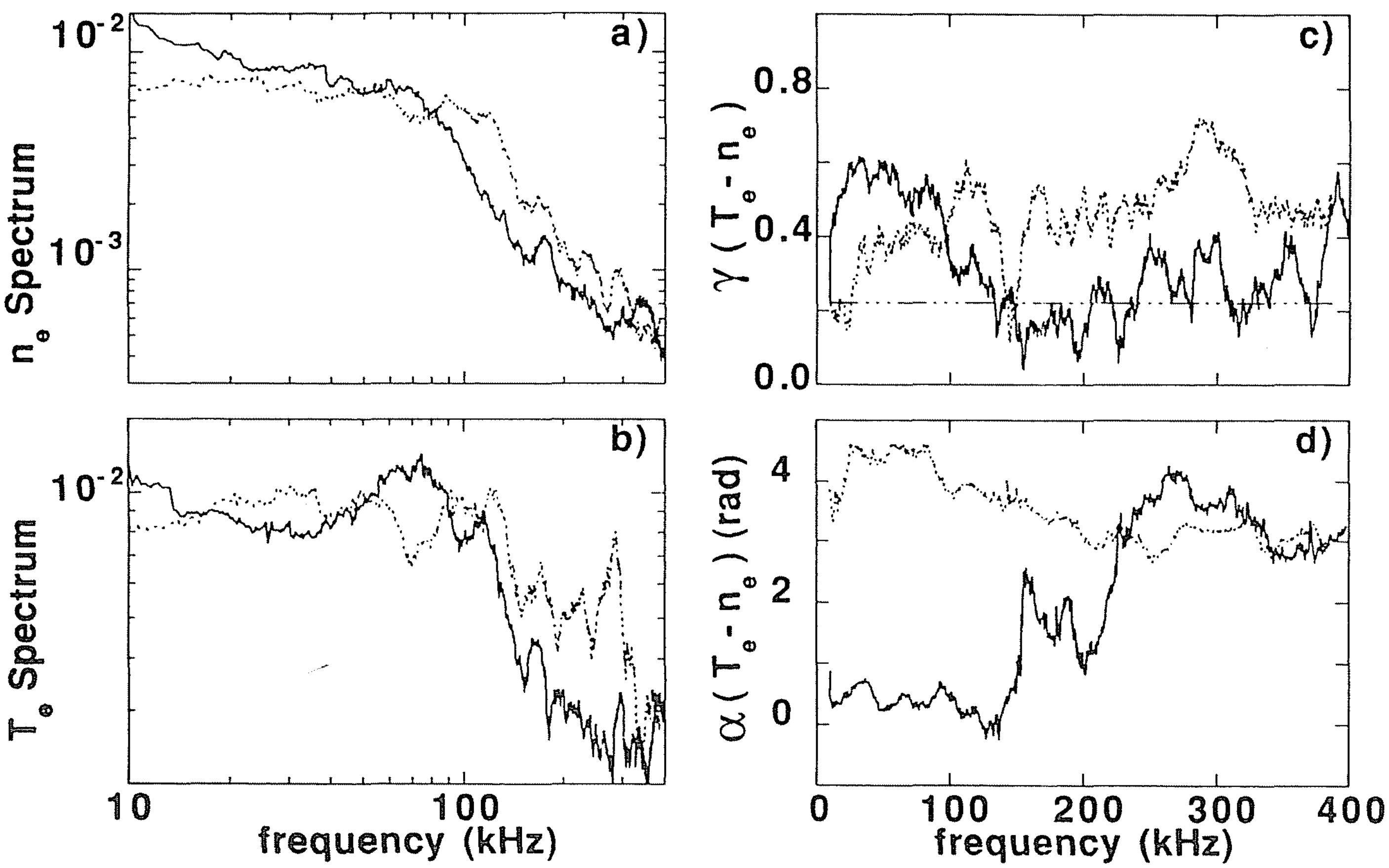

10⁻²
10⁻³
nₑ Spectrum
a)
Tₑ Spectrum
b)
10
100
frequency (kHz)
0.8
0.4
0.0
γ (Tₑ - nₑ)
c)
4
2
0
α (Tₑ - nₑ) (rad)
d)
0
100
200
300
400
frequency (kHz)

Figura 5

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"Influencia de la Radiacion en la Turbulencia del Borde en el Tokamak TJ-I."

OCHANDO, M.A.; PEDROSA, M.A.; BALBIN, R.; GARCIA-CORTES, I.; HIDALGO, C.
(1994) 26 pp., 5 figs., 16 refs.

Se ha estudiado la correlación entre las fluctuaciones de temperatura y densidad electrónicas y la radiacción procedente del borde superior del plasma, cerca del limitador, en el tokamak TJ-I. Se ha comprobado que cuando el perfil de radiación tiene un máximo en las proximidades del radio del limitador las fluctuaciones de temperatura exceden ampliamente a las de densidad. Los presentes resultados son una evidencia experimental de que inestabilidades térmicas pueden generar o modificar la magnitud de la turbulencia en el borde del plasma.

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