Fluctuation-Induced Energy Flux in the Tokamak Edge

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(Received 31 October 1988)

A quantitative comparison of the fluctuation-induced energy flux with the total energy flux has been made in the edge region of the TEXT tokamak using fluctuation measurements from Langmuir, heavy-ion-beam, and magnetic probes. At all but the lowest densities the convected energy flux due to electrostatic fluctuations dominates the energy losses caused by plasma transport. Energy loss through magnetic fluctuations is insignificant in the edge region.

PACS numbers: 52.55.Fa, 52.25.Gj

It is well known that the energy lost from tokamaks through transport processes is much larger than predicted by neoclassical theory (Refs. 1 and 2, and references therein). Plasma turbulence is generally invoked to account for the anomalous losses. Unlike neoclassical transport which depends on the mean plasma parameters and collisions, turbulent transport results from fluctuations in plasma parameters (electric and magnetic fields, density, temperature, etc.). Fluctuation-induced particle and energy fluxes have been measured in the edge region of several tokamaks.[3-7] It has been established in the Texas Experimental Tokamak (TEXT) that the total particle flux in the edge plasma is primarily due to electrostatic fluctuations.[8] In this work we investigate the role fluctuations play in the total edge *energy* transport. Specifically, we compare radial profiles of the energy flux due to fluctuations with profiles of the total plasma energy flux in the edge of TEXT. The importance of the edge region is demonstrated by the improved global energy confinement in *H*-mode discharges, TFTR supershots,[9] and recent Ohmic discharges, in ASDEX.[10]

TEXT is a medium size tokamak with a major radius R of 1 m and a minor radius a of 0.26 m defined by a full poloidal limiter. The data presented here were taken in steady-state, Ohmically heated discharges with sawteeth and low Mirnov activity. The radial profiles were collected over a number of similar shots, with at least three shots for each radial position. The density, potential, and temperature fluctuation data were collected with Langmuir probes (LP) in the far edge region of the discharge and in the scrape-off layer (SOL) outside of the outermost closed flux surface ($r/a \equiv 1$). With a heavy-ion-beam probe[11] (HIBP) the density and potential fluctuation data can be measured in the plasma interior. We use data in to $r/a \simeq 0.8$. Magnetic fluctuation data were collected with magnetic probes (MP) located in the SOL. The fluctuation measurements of both the LP and the HIBP were taken approximately 180° away in the toroidal direction from the poloidal limiter; the MP was positioned about halfway between these diagnostics and the limiter. The fluctuation data were digitized with a 10-bit digitizer at a 1-μs sampling interval and were analog filtered at 500 kHz to prevent aliasing. The data were recorded over a 16-ms interval. A characterization of the electrostatic fluctuations in TEXT has been reported previously,[5,11,12] and the results are similar to the results obtained on other tokamaks.[4,13-15]

The radial profiles of the relative root mean square (rms) fluctuation levels for density $\tilde{n}/n$, plasma potential $e\tilde{\varphi}_{\text{pl}}/k_B T_e$, electron temperature $\tilde{T}_e/T_e$, and radial magnetic field $\tilde{B}_r/B_\phi$, where k_B is the Boltzmann constant, are shown in Fig. 1 (toroidal magnetic field $B_\phi = 2$ T, plasma current $I_{\text{pl}} = 200$ kA, and line-averaged density $\bar{n}_e = 3 \times 10^{19}$ m^{-3}). The rms values include frequencies up to 500 kHz and wave numbers up to approximately 30 cm^{-1} for LP data and 15 cm^{-1} for HIBP data. The $\tilde{B}_r/B_\phi$ profile includes only frequencies above 50 kHz, which avoids contributions of the global modes. The relative fluctuation levels of density and potential are substantial in the far edge region ($r/a \gtrsim 0.9$). In addition, the Boltzmann relationship ($\tilde{n}/n = e\tilde{\varphi}_{\text{pl}}/k_B T_e$) is not satisfied, in contrast to the interior where the density and potential fluctuation levels become comparable. The

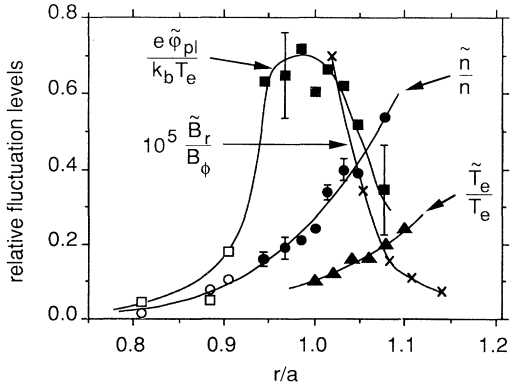

FIG. 1. Relative fluxuation levels of density $\tilde{n}/n$, plasma potential $e\tilde{\varphi}_{\text{pl}}/k_B T_e$, electron temperature $\tilde{T}_e/T_e$, and magnetic field $\tilde{B}_r/B_\phi$, as functions of radius. Filled symbols represent data from Langmuir probes, and open symbols from the HIBP.

temperature fluctuation profile, measured behind the limiter using a statistical method,[16] has the same radial shape as the density fluctuations; in fact, $\tilde{T}_e/T_e \simeq (0.3\text{–}0.4)\tilde{n}/n$. The radial magnetic field fluctuations $\tilde{B}_r$ exhibit a broadband turbulent spectrum similar to the spectra of the density and potential fluctuations. The turbulent magnetic fluctuations are correlated with $\tilde{n}$ and $\tilde{\varphi}_{\text{pl}}$ when the magnetic coil is positioned close enough to the edge plasma.[17]

The energy fluxes of the electrons and ions due to fluctuations can be computed and compared with the radial energy fluxes computed in the standard way from power balance,

$$p_e(r) = p_{\text{Oh}}(r) - p_{ei}(r) - p_{\text{rad}}(r) - p_{\text{lim},e}(r)\,,$$

$$p_i(r) = p_{ei}(r) + p_{\text{neut}}(r) - p_{\text{cx}}(r) - p_{\text{lim},i}(r)\,,$$

where the transport power densities $p_j(r)$ of charged species $j = e,i$ are related to the radial energy fluxes by $q_j(r) \equiv (1/r)\int_0^r dr' r' p_j(r')$. The Ohmic input power density $p_{\text{Oh}}(r) = \sigma_S(r)E_0^2$, where $E_0 \equiv V_L/2\pi R$, is determined using the Spitzer conductivity σ_S and the measured loop voltage V_L. The radiated power $p_{\text{rad}}(r)$ is measured with a bolometer array.[18] The power gained by the ions from ionization of neutrals, $p_{\text{neut}}(r)$, and that lost via charge-exchange reactions, $p_{\text{cx}}(r)$, are calculated by a neutral-particle code.[19] In the SOL, the parallel energy fluxes to the limiter are modeled[20] through the terms $p_{\text{lim},j}(r)$.

The radial energy flux $q_j(r)$ for species j can be written as a sum of the convected energy flux $q_{\text{conv},j}$ and the conducted energy flux (often called heat flux) $q_{\text{cond},j}$,

$$q_j = q_{\text{conv},j} + q_{\text{cond},j}\,, \quad \text{where} \quad q_{\text{conv},j} \equiv \tfrac{5}{2} k_B T_j \Gamma_j\,, \tag{1}$$

with Γ_j the radial particle flux of the jth species. The factor $\frac{5}{2}$ results from the choice of the reference frame for the conducted energy flux moving with the velocity $v_i = \Gamma_j/n_j$. We point out that here we use the consistent set of expressions for the convected and conducted fluxes as discussed by Ross.[21] From continuity, the total particle flux is

$$\Gamma_j(r) = (1/r)\int_0^r dr' r' US_j(r') - S_{\text{lim},j}(r')\,,$$

where $S_j(r)$ is the particle source and $S_{\text{lim},j}$ is the particle sink in the SOL due to parallel flow to the limiter. Here $S_j(r)$ is obtained from calculations[19] normalized to yield a value of $\Gamma_j(a)$ in agreement with H_α measurements, while $S_{\text{lim},j}$ is modeled after Ref. 20.

At all but the lowest densities the classical electron-ion power exchange density $p_{ei}(r)$ contributes the largest errors to the power-balance calculations of q_e and q_i because of its dependence on the difference between electron and ion temperatures. In fact, the uncertainties in the individual energy fluxes q_e and q_i in the edge region become larger than their mean values. We therefore consider the total radial energy flux due to plasma transport

$$q(r) \equiv q_e(r) + q_i(r)\,,$$

since $p_{ei}(r)$ cancels out in the definition.

We now turn to the fluctuation-induced energy fluxes. The convected energy flux from electric field fluctuations $\tilde{E}_\theta$ is

$$q^{\tilde{E}}_{\text{conv},j} = \tfrac{5}{2} k_B T_j T^{\tilde{E}}_j\,, \tag{2}$$

where the radial particle flux, convected at the velocity $\tilde{v}_r^{\tilde{E}_\theta} = \tilde{\mathbf{E}}_\theta \times \mathbf{B}_\phi/B_\phi^2$, is

$$\Gamma^{\tilde{E}}_j = \langle \tilde{n}_j \tilde{v}_r^{\tilde{E}_\theta} \rangle = \langle \tilde{n}_j \tilde{E}_\theta \rangle / B_\phi\,. \tag{3}$$

Here the angular brackets denote ensemble averaging and $\tilde{E}_\theta \equiv -\Delta\tilde{\varphi}_{\text{pl}}/\Delta x$ is determined experimentally from two poloidally separated probes. The contribution from $\tilde{\mathbf{E}}_\phi \times \mathbf{B}_\theta/B_\phi^2$ is neglected because $k_\theta > 200 k_\phi$ (Ref. 22) and thus $\tilde{E}_\theta = -ik_\theta\tilde{\varphi}_{\text{pl}} \gg \tilde{E}_\phi = -ik_\phi\tilde{\varphi}_{\text{pl}}$. Measurements show that the phase angle between $\tilde{n}$ and $\tilde{E}_\theta$ is close to 0° in the edge region, causing maximal particle flux,[12] and decreases to about −70° in the plasma interior.[11]

The total plasma transport energy flux $q(r)$, the total convected energy flux $q_{\text{conv}} \equiv q_{\text{conv},e} + q_{\text{conv},i}$, and the fluctuation-induced convected energy flux $q^{\tilde{E}}_{\text{conv}} \equiv q^{\tilde{E}}_{\text{conv},e} + q^{\tilde{E}}_{\text{conv},i}$ are plotted in Fig. 2 for the same plasma parameters as in Fig. 1. The shaded area indicates the error limits of $q(r)$ and is computed by variation of the profiles within their error bars. Confidence in the power-balance calculation is further established by infrared camera measurements of the temperature rise of the limiter.[23] The convected energy fluxes q_{conv} and $q^{\tilde{E}}_{\text{conv}}$ are calculated using an ion temperature T_i equal to the electron temperature. Uncertainties in the T_i measurement in the far edge region give a range of

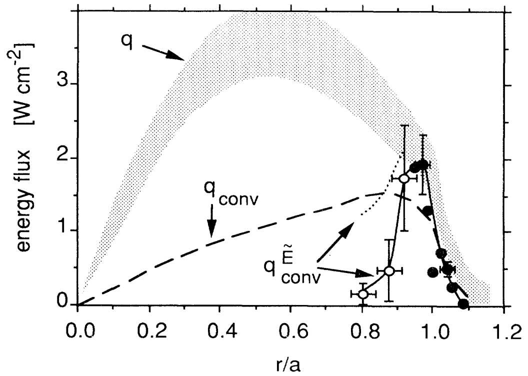

FIG. 2. Radial profiles of the total electron and ion energy flux $q = q_e + q_i$ from power balance (shaded area, defined by the standard deviation), the fluctuation-induced convected flux $q^{\tilde{E}}_{\text{conv}}$ (filled circles from Langmuir probes, and open circles from HIBP; dotted line is upper bound in presence of η_i mode), and the total convected energy flux $q_{\text{conv}}(r)$ from a neutral-penetration code and H_α measurements.

$4T_i/T_e \simeq 1$–1.5. The upper limit on T_i would increase the convected fluxes in the figure by about 25%.

A comparison of the fluc-surface-averaged total flux q and of the local measurement of $q^{\tilde{E}}_{\rm conv}$ is only relevant if $q^{\tilde{E}}_{\rm conv}$ is poloidally symmetric. For the local LP measurements we use the localization of the maximum velocity shear[5] due to the peak in the radial plasma potential profile as the radius of the outermost closed flux surface.[24] All the plasma parameters measured by probes in the bulk plasma are then poloidally symmetric and the measured radial particle flux obeys continuity. Further, the plasma potential maximum then can be explained by a self-consistent model.[25] The substantial up-down asymmetries in the density fluctuations level measured by laser scattering[26] may be due to asymmetries which exist deeper into the plasma than the probes can access.

We first note in Fig. 2 that $q^{\tilde{E}}_{\rm conv}(r)$ measured with the LP and HIBP connect well. The convected energy flux from electrostatic fluctuations is peaked in the plasma edge region and decreases rapidly toward the interior, implying that electrostatic fluctuations no longer play an important role in the transport. However, the values of $\Gamma_j^{\tilde{E}}$ in the interior would be greatly underestimated if there were ion pressure-gradient-driven (η_i) modes, evidence of which has been seen on TEXT.[27] This is because the two-point correlation technique used in this measurement underestimates k_θ and the coherencies between $\tilde{n}$ and $\tilde{\varphi}_{\rm pl}$ for counterpropagating fluctuations. From the rms fluctuation levels of Fig. 1, we can estimate an upper bound on $\Gamma_j^{\tilde{E}}$ and thus $q^{\tilde{E}}_{\rm conv}$ (dotted line in Fig. 2) by using the k_θ value from the edge region and a coherency of unity between density and potential fluctuations. Electrostatic fluctuations would then perhaps explain the convected energy flux in the interior.

Figure 2 illustrates that the convected energy flux due to electrostatic fluctuations is the dominant energy-loss mechanism through the plasma edge region ($r/a > 0.9$) for this discharge condition. The same conclusions can be drawn for all discharges above a density of 2×10^{19} m^{-3} that we studied [$I_{\rm pl}=200$–400 kA, $\bar{n}_e=(3$–$8)\times10^{19}$ m^{-3}, and $B_\phi=1.5$–2.8 T]. For the low-density discharges ($\bar{n}_e \le 2\times10^{19}$ m^{-3}) convection abruptly decreases to less than 30% of the total flux.[7] These low-density discharges may be affected by observed suprathermals, but further work is necessary to determine the transport mechanisms.

As mentioned earlier, it is difficult to quantitatively compare the electron (ion) energy flux $q^{\tilde{E}}_{{\rm conv},j}$ to the total electron (ion) energy flux q_j at the higher densities because of the large error bars in q_j. Nevertheless, the convection of each individual species due to fluctuations must dominate when $q(r)\simeq q^{\tilde{E}}_{\rm conv}(r)$ since $q_j \ge q^{\tilde{E}}_{{\rm conv},j}$ and $q^{\tilde{E}}_{{\rm cond},j}\ge 0$.

The conducted energy flux from electrostatic fluctuations is[21]

$$q^{\tilde{E}}_{{\rm cond},j} = \frac{3}{2}\frac{n_j}{B_\phi}\langle k_B\tilde{T}_j\tilde{E}_\theta\rangle - k_BT_j\Gamma_j^{\tilde{E}}\,. \qquad (4)$$

The electron temperature fluctuation measurements in the SOL show that $\tilde{T}_e$ and $\tilde{E}_\theta$ are highly correlated and in phase[16] unlike $\tilde{n}$ and $\tilde{E}_\theta$ which are more weakly correlated. The temperature fluctuation level is, however, relatively small compared to the density fluctuation level, as shown in Fig. 1. The resulting conducted energy flux $q^{\tilde{E}}_{{\rm cond},e}$ thus contributes only about 20% to the total electron energy flux in the SOL.[28] In the interior plasma, on the other hand, $q^{\tilde{E}}_{{\rm cond},e}$ could possibly account for the remaining part of the energy flux if $\tilde{T}_e/T_e$ were only a few times $\tilde{n}/n$ and were well correlated and nearly in phase with $\tilde{E}_\theta$.

Several experiments[29] indicate that magnetic field fluctuations are linked to electron confinement, since the energy confinement time decreases with increasing magnetic fluctuation level. We therefore consider the contribution of stochastic magnetic fluctuations to the energy flux,

$$q^{\tilde{B}}_{{\rm cond},j} = -\chi_{j\perp}(\tilde{B}_r)n_j\,\partial T_j/\partial r\,,$$

where the thermal diffusivity $\chi_{j\perp}(\tilde{B}_r)$ can be estimated using theoretical models.[2] In the applicable regimes, these quasilinear models can predict, within a factor of 2–3, the changes in the energy flux caused by magnetic field perturbations of an ergodic magnetic limiter.[23] However, when applied to the magnetic turbulence, the Rechester-Rosenbluth model,[2] $\chi_{e\perp}(\tilde{B}_r)=qRv_{{\rm th},e}(\tilde{B}_r/B_\phi)^2$, for example, gives $q^{\tilde{B}}_{{\rm cond},e}(r/a=1.02)=6\times10^{-5}$ W/cm^{-2}. The magnetic fluctuations therefore cannot account for the measured energy fluxes in the SOL and in the outer edge plasma. The results allow two interpretations of the scaling of magnetic field fluctuations with the global energy confinement time: Because of the correlation between density or potential fluctuations, and magnetic fluctuations,[17] the scaling may be an indirect manifestation of the energy loss by electrostatic processes in the edge region affecting the global confinement time. Alternatively, the observed $\tilde{B}_r$ may be symptomatic of interior magnetic turbulence which causes transport. However, the $\tilde{B}_r$ with large k_θ (high m) actually observed is correlated with $\tilde{E}_\theta$ in the edge region and therefore must arise there. In addition, a spectrum of $\tilde{B}_r$ with large k_θ inside $r=0.8$ would produce no observable signal outside $r=1$. Therefore one cannot draw any inferences to the interior.

In summary, the following conclusions can be made: (i) The total convected energy flux by electric field fluctuations, $q^{\tilde{E}}_{\rm conv}$, dominates for all but the lowest densities the total plasma energy loss in the plasma *edge* region where the plasma source is large. For radial locations where $q^{\tilde{E}}_{\rm conv}\simeq q$, the fluctuation-induced convected energy flux by each individual species, $q^{\tilde{E}}_{{\rm conv},j}$, must dominate q_j as well. (ii) Conduction of energy by electrons through electrostatic fluctuations, $q^{\tilde{E}}_{{\rm cond},e}$, is at most 20% of the total electron flux q_e in the edge region.[28] (iii) Magnetic fluctuations, interpreted with quasilinear models, do not contribute significantly to the energy loss in the cool plasma edge. While $\tilde{B}_r$ rises rapidly toward the center it does not indicate a dominant role in the transport process in the interior since the source for these fluctuations lies in the edge region. (iv) Electrostatic fluctuations may explain the convected energy flux in the *interior*, and if $\tilde{T}_j/T_j$ were only a few times $\tilde{n}_j/n_j$, also the conducted energy flux. The observed similarity in the scaling of particle and energy confinement times with density is then possibly a result of the electrostatic fluctuations.

In view of the current ability to measure the spectra, correlations, and phase relationships of fluctuations, we encourage theoretical predictions of these quantities to identify the turbulence mechanisms responsible for the transport. Anomalous fluxes may then be determined *directly* through equations such as (2)–(4). This offers an alternative to the use of transport coefficients (D, χ_e, etc.) which can hide the cause of the transport. Further, the transport coefficients can themselves be a function of the fluctuations and plasma parameters and thus obscure the physics process.

The authors wish to thank D. L. Brower, P. H. Diamond, D. W. Ross, and P. W. Terry for useful discussions and the TEXT staff for technical support. This work was supported by the U.S. Department of Energy, Office of Fusion Energy, under Contract No. DE-FG05-88ER-53267.

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