Impurity-Induced Suppression of Core Turbulence and Transport in the DIII-D Tokamak

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Turbulence is significantly reduced in a tokamak plasma as a result of neon seeding of an L-mode discharge. Correspondingly, confinement is improved and cross-field ion thermal transport reduced. Fully saturated turbulence in the range $0.1 \le k_\perp \rho_s \le 0.6$ is measured at $\rho = 0.7$ and exhibits a factor of 5 reduction in total power after neon injection, with almost complete suppression for $k_\perp \rho_s > 0.35$. These observations are consistent with a reduction in the calculated linear growth rate for $k_\perp \rho_s > 0.5$ and an increase in the measured $\mathbf{E} \times \mathbf{B}$ flow shearing rate.

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Optimizing confinement of particles and energy within a magnetically contained plasma remains a central challenge to fusion energy development. Anomalous transport, believed to result primarily from turbulence arising from temperature- and density-gradient-driven drift wave microinstabilities, limits confinement. Previous experimental studies have indicated a strong correlation between long-wavelength turbulent-driven density fluctuations and the anomalously high ion thermal and particle transport typically observed [1–3]. Local fluctuation-induced turbulent transport is typically modeled with a particle flux given by $\Gamma = \langle \tilde{n} \tilde{v}_r \rangle$, and energy flux $Q = n\langle \tilde{v}_r \tilde{T} \rangle + T\langle \tilde{n} \tilde{v}_r \rangle$, indicating a dependence of anomalous fluxes on turbulent density fluctuations.

Experiments on DIII-D and other tokamaks [TEXTOR [4,5], ISX-B [6], Tokamak Fusion Test Reactor (TFTR) [7]] have demonstrated the surprising result that plasmas with reduced turbulence and transport, and thus improved confinement, can be produced by impurity seeding of the discharge. Although the physical mechanism responsible for the improved confinement has not yet been clearly identified, gyrokinetic calculations and measured density fluctuations indicate turbulence suppression from impurity seeding may be the dominant cause. Measurements obtained on the DIII-D tokamak, and presented in this Letter, demonstrate for the first time that turbulence-driven density fluctuation levels in the plasma core are dramatically reduced in response to neon injection, while the plasma transport is also markedly reduced. These correlations suggest that turbulence suppression resulting from the neon impurity species may play a key role in the observed transport reduction.

We compare two discharges with similar operational parameters, except that neon is puffed into one discharge, and no neon is puffed into the second, which serves as a reference discharge. These plasmas have an L-mode (low-confinement) edge and negative central magnetic shear core [8,9] that exhibits enhanced confinement. Comparison of the temporal evolution of these two discharges (plasma current, injected neutral beam power, radiated power, confinement time, neutron rate) is shown in Fig. 1. The beam emission spectroscopy (BES) fluctuation measurements discussed here were available from 0.7–1.2 s,

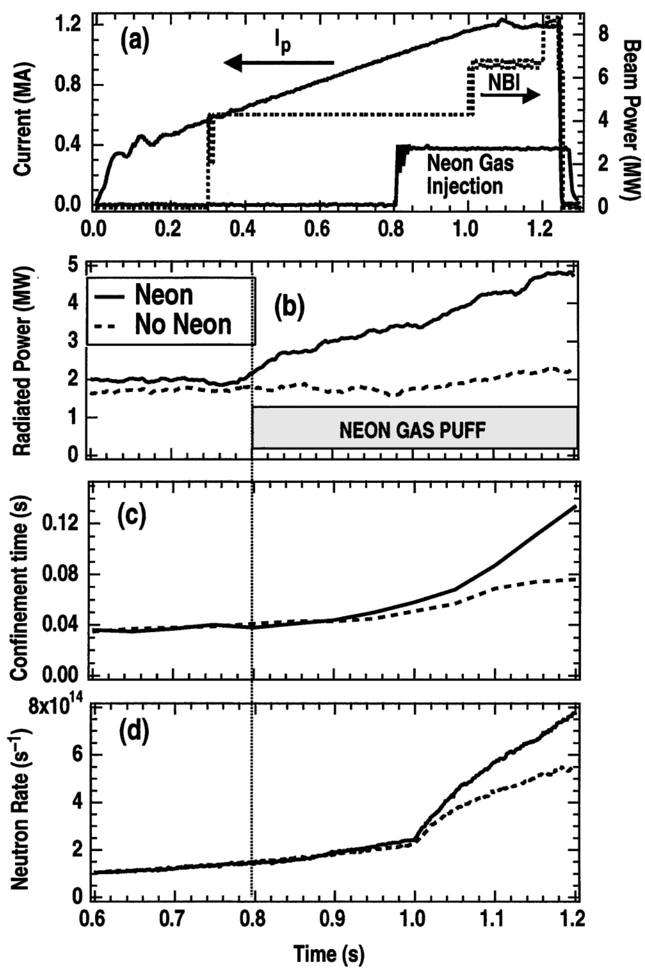

FIG. 1. Discharge parameters for the radiative and reference shots: (a) beam power, plasma current, and neon puff, (b) radiated power, (c) confinement time, (d) neutron rate, showing the relative improvement in performance after the neon puff. Note the different time scales for (a) and (b) through (d).

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so the present analysis is limited to that period. These plasmas are evolving in time and do not reach a steady-state condition, though there is no practical reason why steady state should not be possible. Neon is puffed in at 0.8 s in one discharge at a rate of 2.9 Torr ℓ/s. The neon density approached 1.5% of the electron density in the seeded discharge as indicated by ultraviolet and charge exchange recombination spectroscopy measurements of the core plasma.

Both discharges are very similar during the first 0.8 s, until the neon is injected. The plasma current is ramped to 1.2 MA, with 4.3 MW of neutral beam injection during the ramp, and the toroidal field is 1.6 T. The radiated power increases dramatically in the shot with neon injection at 0.8 s [Fig. 1(b)], due to partially ionized neon states near the edge. The confinement time and neutron rate increase more rapidly in the neon-injected shot, indicating reduced transport in the plasma with neon injection. Confinement time is defined here as $\tau_E = W_{\mathrm{Plasma}}/[P_{\mathrm{tot}} - (dW/dt)]$, where P_{tot} is the total absorbed power and W_{plasma} is the stored energy. It is noted that the plasma stored energy and confinement time increase despite the additional radiated power loss. It is interesting to note that, despite the addition of the impurity, the higher neutron rate indicates greater reactivity in the neon discharge, indicating that the confinement increase more than offsets the relatively small dilution of core fuel ions.

Measured density and temperature profiles are compared for the two discharges in Figs. 2(a)–2(d) at $t = 1.2$ s. Significant increases are observed in the central electron density [Fig. 2(a)] and ion temperature measurements [Fig. 2(c)]. The electron temperature profile [Fig. 2(d)] is slightly broadened and increased. The neon density [Fig. 2(b)], measured with charge exchange recombination spectroscopy [10,11], is seen to be roughly 1.5% of the electron density. Ion heat transport is reduced in the neon-seeded discharge by a factor of 3–5 across most of the profile relative to the reference discharge [Fig. 2(e)], while heat transport in the electron channel is slightly reduced [Fig. 2(f)], as determined by TRANSP analysis [12] using these measured plasma profiles. This suggests that neon is acting in some way, directly or indirectly, to significantly reduce ion energy transport. Coincident with the reduced transport is a reduction in the density fluctuations.

The density fluctuation measurements reported here were obtained with the beam emission spectroscopy diagnostic on DIII-D [13]. BES measures radially and poloidally localized density fluctuations by observing the Doppler-shifted D_α emission from the heating neutral beams. This emission arises from collisionally induced excitation of the beam and is proportional to the local plasma density. High time-resolution (1 MHz) digitization and high spatial resolution ($\Delta r \approx 1.0$ cm) allows for measurement of fluctuations arising from long-wavelength ($k_\perp < 3$ cm^{-1}) turbulence. For this experiment, 32 spatial channels were deployed to sample density fluctuations in the outer third of the plasma minor radius ($0.68 \le \rho \le 1.0$), with one 16-channel radial array covering about 16 cm ($\Delta r \approx 1$ cm channel separation), and two eight-channel poloidal arrays at $\rho = 0.7$ and $\rho = 1.0$ (again, $\Delta z \approx 1.0$ cm).

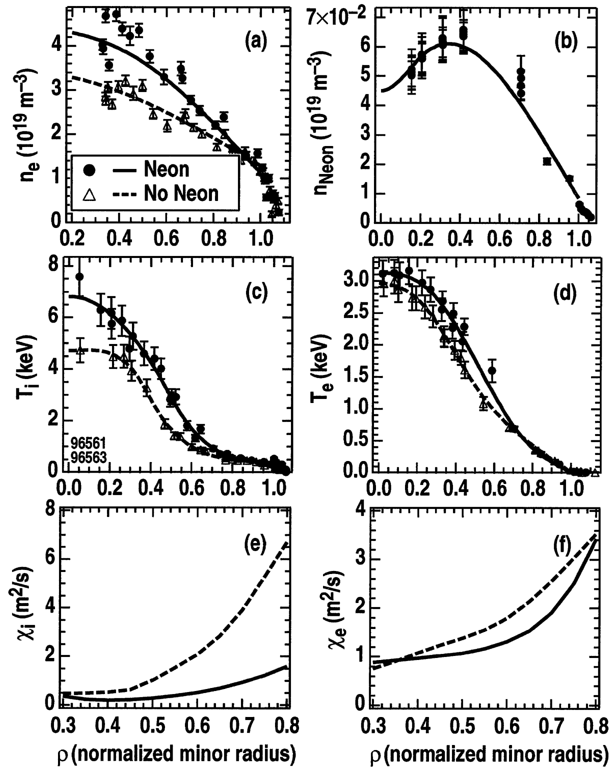

FIG. 2. Comparison of measured profiles of (a) electron density, (b) neon density, (c) ion temperature, and (d) electron temperature at 1.2 s in the neon and reference discharge. Calculated ion (e) and electron (f) thermal diffusivity showing substantial reduction in χ_i with neon and a smaller reduction in χ_e.

The density fluctuation power spectra for this pair of discharges, obtained with BES measurements at a normalized minor radius near $\rho = 0.7$, are compared at two time intervals in Fig. 3. The first spectra [Fig. 3(a)] are integrated over 0.7–0.8 s, prior to the neon injection, while the second [Fig. 3(b)] are integrated over 1.0–1.1 s, 200–300 ms after neon injection. In each case, cross power signals from seven pairs of channels at $\rho = 0.7$, arrayed poloidally, are averaged to improve signal-to-noise. Broadband turbulent density fluctuations, commonly thought to be electrostatic drift-wave-like turbulence, dominate the spectrum up to about 200 kHz in Fig. 3(a), and up to 350 kHz in Fig. 3(b). The observed lab-frame frequency spectrum is determined by the sum of the fluctuation frequency in the plasma frame and the Doppler shift arising from the radial electric field as $\omega_{\mathrm{lab}} = \omega_{\mathrm{plasma}} + \vec{k} \cdot \vec{v}_{\mathbf{E}\times\mathbf{B}}$ [14]. For these plasmas, the Doppler shift term dominates the plasma frequency ($\vec{k} \cdot \vec{v} \gg \omega_{\mathrm{plasma}}$). Therefore the frequency is nearly proportional to the poloidal wave number of the fluctuations,

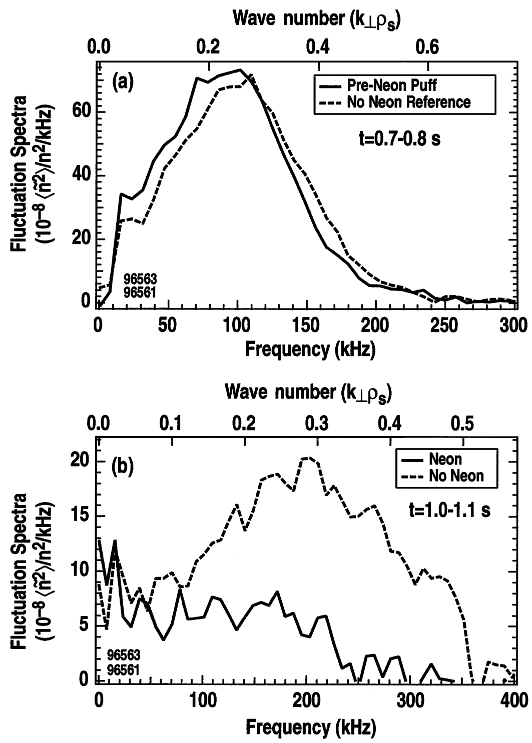

FIG. 3. Density fluctuation spectra comparison at $\rho = 0.7$ (a) before the neon puff ($t = 0.7-0.8$ s), and (b) 200–300 ms after the neon puff ($t = 1.0-1.1$ s) showing the substantial reduction in overall fluctuation power in neon discharge.

and so the $S(k_\theta)$ wave number spectrum is essentially proportional to the observed frequency spectrum. References [14–16] describe how this condition was observed and utilized in BES measurements on the TFTR.

The poloidal group velocity of the fluctuations in measured directly with BES by applying time-delay correlation analysis [16] to the poloidally separated channels. Here, the measured group velocity is about 5.7 km/s in the neon-injected discharge, and 6.3 km/s in the reference discharge at 0.7–0.8 s. This difference results in a slightly higher Doppler shift in the reference discharge which is apparent as the slightly higher average frequency. The group velocities increase to 11.4 km/s (neon) and 13.9 km/s (reference) averaged over 1.0–1.1 s. These are in close agreement with the $\mathbf{E} \times \mathbf{B}$ velocity, determined by local measurements of the radial electric field using charge exchange recombination spectroscopy [17], which yield velocities of 12 (neon) and 14 km/s (reference) at $t = 1.05$ s. This velocity increase results in an overall shift of the spectra to higher frequency at the later time.

The resulting approximate wave number scale is obtained as $k = 2\pi f/v$, with v obtained by averaging the measured group velocity over the two shots and associated time window. This scale is accurate to roughly 10% or better and is shown on the upper axis of the graphs. This range corresponds to absolute wave numbers $k_\perp \leq 2$ cm^{-1}. Here, $\rho_s = c_s/\Omega_i$; $c_s = \sqrt{T_e/m_i}$ is the sound speed, and $\Omega_i = eB/m_i$ is the ion gyrofrequency. We note that the raw spectra contain significant nonlocal features below 70 kHz that include strong edge turbulence imprinted on the neutral beam density and a quasicoherent feature inherent in the beam sources near 50 kHz. These signals are not pertinent to the local plasma turbulence and have been removed utilizing standard common-mode subtraction methods [16]. In Fig. 3(b), these nonlocal features have a much higher amplitude in the lower frequency range ($<$70 kHz) than the local fluctuation level, and less-than-perfect subtraction results in lower signal-to-noise in this spectral region.

At the pre-neon injection time (0.7–0.8 s), the fluctuation spectra in the two shots are very similar in shape and magnitude, aside from the small difference in Doppler shift [Fig. 3(a)], as expected since the discharges are nearly identical to this point. The spectra obtained from 1.0 to 1.1 s [Fig. 3(b)], in contrast, differ in two distinct characteristics: First, the overall power of the fluctuation spectrum in the neon plasma is significantly lower in magnitude; and second, while the entire spectrum is suppressed in the neon case, the higher frequencies are preferentially reduced with almost complete suppression of fluctuations above about 250 kHz ($k_\perp \rho_s \approx 0.35$). The integrated power ($0.1 \leq k_\perp \rho_s \leq 0.5$) shows a factor of 5 reduction in the neon shot. It appears that the higher k modes at $k_\perp \rho_s > 0.3$ are most strongly suppressed, while the lower k modes exhibit a more modest though still significant reduction. The fluctuation suppression occurs over 0.2–0.3 s, similar to the time scale over which the global confinement increase takes place, as shown in Fig. 1.

A physical mechanism which may cause the observed reduction in turbulence and transport is suggested from effects of neon on both the linear stability of drift-wave turbulence and the radial electric field shear. First, suppression of ion temperature gradient driven turbulence by impurities has been predicted by several simulations [5,18–22]. Gyrokinetic modeling indicates that impurities alter electrostatic drift-wave turbulence and may give rise to the observed turbulence suppression. To explore such possibilities, the GKS (gyrokinetic simulation) code [23,24] is used here to estimate the linear stability growth rates in the discharges under consideration. The growth rate at a given radial location and time is calculated as a function of wave number using measured plasma temperature and density profiles, and includes the full kinetic response for both ions and electrons in the real geometry. Second, it has been predicted theoretically and demonstrated experimentally that fluctuations are suppressed in plasmas as the local $\mathbf{E} \times \mathbf{B}$ shearing rate, $\omega_{\mathbf{E}\times\mathbf{B}}$ [25], increases above the local maximum linear growth rate, $\gamma_{\text{lin,max}}$, of unstable turbulent modes [17,26–28]. To examine the possibility of this mechanism causing the observed behavior, the growth and shearing rates are compared for these discharges at $t = 1.05$ s.

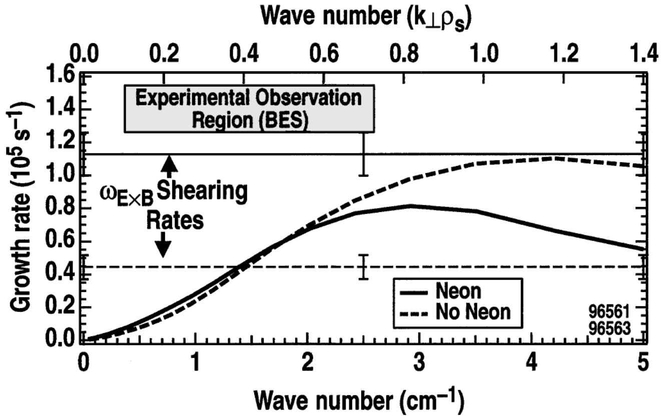

FIG. 4. Comparison of turbulence linear growth rates (curves) and $\omega_{\mathbf{E}\times\mathbf{B}}$ shearing rates (horizontal lines) as a function of wave number for the neon discharge (solid curve and line) and reference discharge (dashed curve and line) using measured profiles at the location of fluctuation measurements in Fig. 3 ($\rho = 0.7$) at $t = 1.05$ s.

The calculated growth rates near the region of k space measured with BES are shown in Fig. 4. Also shown are the $\mathbf{E} \times \mathbf{B}$ shearing rates arising from shear in the radial electric field profile [17]. In the reference shot, the growth rate is seen to be above the local shearing rate for much of the observed region of k space. In the neon shot, two effects take place relative to the reference shot. First, the linear growth rate is reduced for $k \geq 2$ cm^{-1} ($k_\perp \rho_s \geq 0.5$), and second, the shearing rate more than doubles so that it is now larger than the growth rate for this region of k space. While the dominant linear growth rate reduction occurs at and above the upper end of the k space region sampled by BES, it is qualitatively consistent with the trends seen in the data. In addition, nonlinear wave-wave coupling processes provide a possible mechanism whereby changes in growth rates in one region of the k spectrum can affect fully saturated turbulence amplitude measurements in a nearby region of k space [14].

The increased $\mathbf{E} \times \mathbf{B}$ shearing rate arises primarily from an increase in the measured core toroidal rotation, which likely results from a reduction in momentum transport, as indicated by TRANSP analysis. The reduction in momentum transport is a possible consequence of the turbulence reduction and would thus be acting in a positive feedback loop since increased $\mathbf{E} \times \mathbf{B}$ shear further suppresses turbulence. It appears, then, that impurity reduction of growth rates could be acting synergistically with $\mathbf{E} \times \mathbf{B}$ shear to reduce turbulence and, hence, transport. These results indicate that improved energy confinement in a tokamak plasma can be compatible with a highly radiative mantle to more evenly disperse the heat flux over the first wall surface.

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