Physics of Confinement Improvement of Plasmas with Impurity Injection in DIII–D* **EX**

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Clear increases in confinement (from $H_{89P}\approx 1$ to $H_{89P}\leq 2$) and simultaneous reducions of (long-wavelength as well as short-wavelength) turbulence have been observed in L–mode edge discharges in DIII–D which are directly correlated with external impurity injection [1]. These observations provide an opportunity to test theory-based understanding of mechanisms for confinement improvement with impurity seeding observed in a number of tokamaks, including in ISX-B (Z–mode), TEXTOR-94 (RI–mode), TFTR and ASDEX-U. Reduction of both ion and electron thermal transport is attributed to reduction of turbulence due to both impurity-induced growth rate reduction and increased E×B shear. These experimental observations allow comparisons of measured turbulent characteristics with gyrokinetic and gyrofluid code predictions, and quantitative tests of predictions of theory-based transport models. Impurity seeding can be used to produce a radiating mantle to reduce heat fluxes to the material surfaces [2], and control MHD stability in the reduced core transport region and/or the edge pedestal region by broadening pressure profiles.

Significant confinement improvements are observed with injection of recycling impurity gas (Ne, Ar, and Kr) into L–mode edge, negative central shear (sawtooth-free) plasmas in DIII–D. Compared to similar reference discharges without impurity injection, the confinement enhancement factor and the neutron emission in neon-injected discharges are nearly doubled [Fig. 1 (a) and (b)]. The ion and electron temperature with neon injection exhibit increased central values and profile broadening while the electron density profile becomes more peaked ($n_{e0}/\langle n_e \rangle = 1.2 \rightarrow 1.5$). A similar discharge in which the neon puff was replaced with a D_2 puff exhibits neither density profile peaking nor confinement improvement. Transport analyses using the TRANSP code show that reduction of transport coefficients with neon injection are observed in all transport channels, with a reduction of up to a factor of 5 in the ion thermal diffusivity [Fig. 1(d)], substantial reduction in toroidal momentum diffusivity, and modest (≤1.5) reduction in electron thermal diffusivity [Fig. 1(e)] and particle diffusivity. The impurity species scan (Ne, Ar, and Kr) with a fixed radiative loss fraction ($P_{rad}/P_{in} \approx 0.75$) show that the improvement of confinement and reduction of transport coefficients are largest with lower Z for which the impurity charge fraction (Zn_Z/n_e) is the largest.

Observed reductions of both long and short wavelength fluctuations are correlated with reductions of ion and electron thermal transport, respectively, triggered by impurity injection.

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Long-wavelength ($0 < k_\theta < 3$ cm^{-1}) density fluctuations measured with Beam Emission Spectroscopy (BES) [Fig. 1(c)] and Far Infrared (FIR) scattering show long-wavelength ($k_\theta \rho_s \leq 0.6$ where ρ_s is the ion sound gyroradius) turbulence is dramatically reduced in the core (at normalized radii, $\rho \leq 0.7$). Reduced edge turbulent particle flux is observed with edge Langmuir probes, which also correlates well with the confinement improvement. Preliminary analysis of short-wavelength ($k_\theta = 13$ cm^{-1}) fluctuations measured with FIR scattering shows that the RMS amplitude of short-wavelength fluctuations ($k_\theta \rho_s \approx 3.5$) at $\rho = 0.65 \pm 0.15$ decrease in bursting fashion during impurity injection. The average fluctuation level is correlated with electron thermal diffusivity as impurity quantities and species are varied.

Both the reduction of growth rates of toroidal drift waves and E×B shearing suppression are believed to be responsible for the confinement improvement mechanism. Gyrokinetic linear stability simulations (using GKS and FULL codes) show a reduction in the growth rates of ion temperature gradient (ITG) and trapped electron modes (TEM) due to impurity density gradients and dilution effects on the main fuel ion turbulence. The measured E×B shearing rate increases with neon injection, suggesting that the impurity induced reduction of growth rates is acting synergistically with E×B shearing suppression to decrease long-wavelength turbulence and ion transport. Predictions of saturated turbulent levels calculated with a nonlinear 3-D gyrokinetic particle simulation code are consistent with measured long-wavelength fluctuation amplitudes. Simulations with a nonlinear gyrofluid code also show similar results. Reduction of short wavelength fluctuations is believed to be due to reduced electron temperature gradient (ETG) modes, independent of E×B shearing. Predictions of toroidal rotation, ion and electron temperature with a comprehensive gyro-Landau-fluid (GLF23) model compare favorably with experimental profiles with a fixed (experimental) density profile and boundary conditions (at $\rho = 0.8$). The GLF23 model includes the effects of toroidal drift wave turbulence (ITG, TEM and ETG mode) and E×B shearing on transport coefficients.

Impurity injection is a useful tool to control profiles in both L–mode and H–mode edge advanced tokamak operations. Impurity injection can be used to form and expand the internal transport barrier. Broad pressure profiles obtained with impurity injection are a distinct advantage for MHD stability, while higher radiation power allows a diverted L–mode edge at higher power. The edge stability problem in H–mode plasmas can be mitigated with impurity injection by reducing the edge pressure gradient and edge bootstrap current. The paper will review these experimental results from DIII–D, and some implications for future devices.

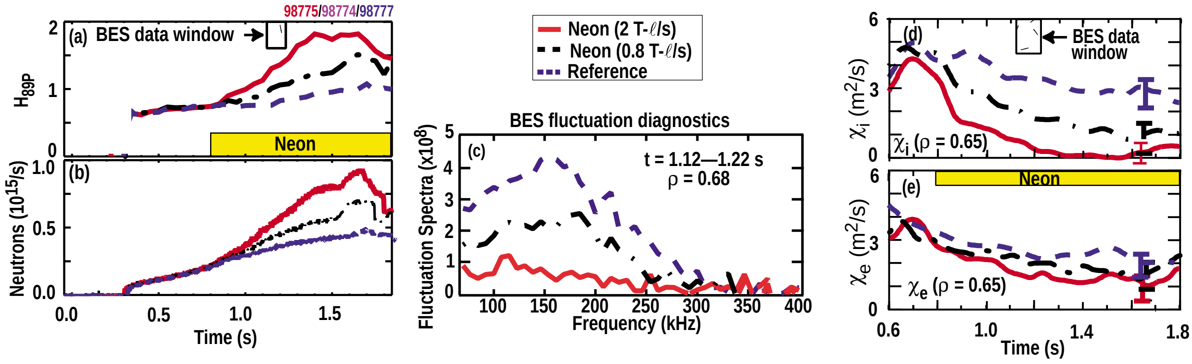

Fig. 1. Results of neon quantity scan [largest (solid), medium (chain), and no-neon injection (dash)]: (a) time evolution of confinement time enhancement factor (H_{89P}); and (b) neutron emission; (c) BES density fluctuation frequency spectra at $t \approx 1.17$ s and $\rho = 0.68$; (d) time evolution of ion thermal diffusivity; and (e) electron thermal diffusivity, both at $\rho = 0.65$.

References

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