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GENERAL ATOMICS

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ABSTRACT

A series of experiments on the DIII-D tokamak show peaked (non-flat) density profiles which are invariant as a function of collisionality, with experimental measurements in agreement with theory-based predictions. The experiments were designed to test the key collisionality (ν^*) scaling of particle transport, with measurements of perturbative transport and complete turbulence data sets. The experiments were also specifically designed to compare measured particle diffusion coefficients (D) and particle pinch velocities (v), as well as turbulence characteristics, with TGLF theory-based modeling and GYRO predictions. In both L- and H-mode experiments, similarity scan techniques were employed to vary ν^* by a factor of 3–5, while holding other dimensionless parameters constant. No change was observed in either case in the measured density profiles and density profile peaking, in contrast to published H-mode database results in which density peaking clearly scales with ν^*. With changes to the analysis code we have also developed a significant new capability to directly compare experimental particle transport measurements with the predictions of TGLF modeling; a first such comparison, presented here, shows good agreement for perturbative particle transport rates. Significant new particle transport results have also been obtained with resonant magnetic perturbations (RMPs), which can have the effect of reducing the operating plasma density. We have obtained the first direct confirmation of an increase in particle diffusion coefficient, D, and reduction in inward pinch velocity, v, with RMP application, in both L- and H-mode plasmas, changes which extend beyond the pedestal into the plasma core.

1. INTRODUCTION

The absence of an experimentally validated particle transport model arguably has a more substantial impact on burning plasma projections than the absence of a validated energy transport scaling. To improve this situation, the scaling of particle transport with collisionality and its response to resonant magnetic perturbations (RMPs) has been studied in experiments on the DIII-D tokamak. Previously, multiple experimental studies have shown that density peaking decreases, and particle transport increases, with increasing collisionality [1,2]. However, many of these studies were performed using data from database collections or experiments in which multiple plasma parameters varied in addition to collisionality. More recently, GYRO [3] simulations have predicted a somewhat different behavior, that the particle flux, as a function of collisionality only, should show a strong increase at low collisionality, but with little change above a critical value [4]. To investigate this issue we have performed a series of L- and H-mode experiments in which the collisionality scaling of particle transport and turbulence was studied using similarity techniques [5]. Such experiments utilize a dimensionless parameter scaling approach, holding ρ^*, β, q, plasma shape, and other dimensionless quantities fixed, while varying collisionality.

Separately, we have developed a new capability to directly compare experimental perturbative particle transport measurements with TGLF [6] modeling; a first such comparison, presented here, shows good agreement. This work significantly contributes to and expands the U.S. effort at transport model validation in the area of particle transport physics. In addition, we have obtained the first direct confirmation of an increase in particle diffusion coefficient, D, and reduction in inward pinch velocity, v, with Resonant Magnetic Perturbation (RMP [7]) application, in both L- and H-mode plasmas, changes which extend beyond the pedestal into the plasma core [8]. This increase in core transport is consistent with an increase in measured turbulence levels and decreased **ExB** shear, and also with increased linear growth rates, calculated by the TGLF transport model.

The results presented here are directly relevant to ITER and future burning plasmas in several ways. In particular, while density peaking is a key parameter for ITER performance, and peaking is both predicted by models and observed in present experiments [1,2], ITER at present *assumes* a flat density profile in their reference baseline scenario [9]. Changing this assumption would impact many aspects of ITER performance. For example, increased density peaking could significantly improve ITER performance by increasing fusion power density and fusion gain, and help circumvent constraints on the H-mode pedestal density, such as stability and the Greenwald density limit [10]. The density profile gradient is also a key determinant of the bootstrap current profile evolution, e.g. [11], and thus of the ability to sustain a large non-inductive current fraction essential for practical steady-state operation – a non-flat density profile would significantly improve the prospects for steady-state plasma operation on ITER. At the same time, however, there are also significant potential drawbacks for ITER – peaked profiles can result in undesirable impurity accumulation, fuel dilution and core radiation losses. In addition, particle transport is frequently (but not invariably) increased by proposed ELM-control techniques such as the use of RMPs, which could lower fusion gain on ITER [7,8].

2. PARTICLE TRANSPORT SCALING IN L- AND H-MODE PLASMAS

Particle transport governs the peaking of plasma density profiles and impurity accumulation, both of which will ultimately affect the performance of burning plasma devices like ITER. Recent GYRO [3] simulations predict that the particle flux, as a function purely of collisionality, should show a strong increase at low collisionality, but with little change above a critical value, ν^*~0.01 [4]. To investigate this prediction, both L- and H-mode experiments have been performed employing similarity techniques [5] to vary collisionality, i.e. the magnetic field strength and heating power were varied, while matching parameters such as the line average density, relative gyroradius, beta and safety factor. In both experiments, B_T was varied from 2.1 to 1.65 T, resulting in a change in ν^* by a factor of 3–5, e.g. from ~0.04 to ~0.09 in H-mode. Here, we use the definition of ν^* from [12], with quoted values evaluated at ρ~0.5. The relatively modest change in magnetic field employed in the experiments was determined by the desire to obtain high resolution electron density profile data from a profile reflectometer system at both ends of the scan. The L-mode experiment was performed in an upper single-null plasma shape, and some of the matched and varying plasma parameters are shown in Fig. 1. Heating was NBI only in the high ν^* case, and a combination of NBI and ECH in the low ν^* case. By contrast, the H-mode experiment was performed in a lower single null plasma, using only NBI heating, and with higher line average density (~$5\text{x}10^{19}$ m^{-3}) and normalized beta (~2).

The results of these experiments with regard to density profile peaking and non-dimensional parameter matching are summarized in Fig. 2, for both L- and H-mode. As can be seen from Fig. 2(a) and 2(c), the density profile shape, and hence density peaking, are identical, within error bars, for both values of ν^*, in both L- and H-mode. This is a significant result, in agreement with the GYRO predictions made prior to the experiments, but differing from the result obtained in database studies, in which density profile peaking increases strongly with reducing collisionality [1,2]. The multi-machine H-mode database results presented in reference [1] indicate that the density peaking factor, defined as the ratio of the local density at ψ_N=0.2 to the volume averaged density, would be expected to change by ~0.2 over the range of the DIII-D experimental variation in collisionality. Such a change should be visible in the DIII-D experimental data, but is not observed, though as the data presented here cover only a moderate range in ν^* it is hard to draw definitive conclusions. TGLF modeling of the L-mode discharges is also in agreement with experimental measurements, as discussed in the following section. The results presented here do support the database studies in that the density profile is significantly peaked, in contrast to the flat density profile assumed in the ITER baseline scenario [9].

That both the L- and H-mode plasmas were well matched with regard to non-dimensional parameters is shown by the plots of ρ^* in Fig. 2(b,d), though it should be mentioned that T_e/T_i and Z_{eff} are not as well matched as ρ^*. However, all relevant plasma parameters, no matter the

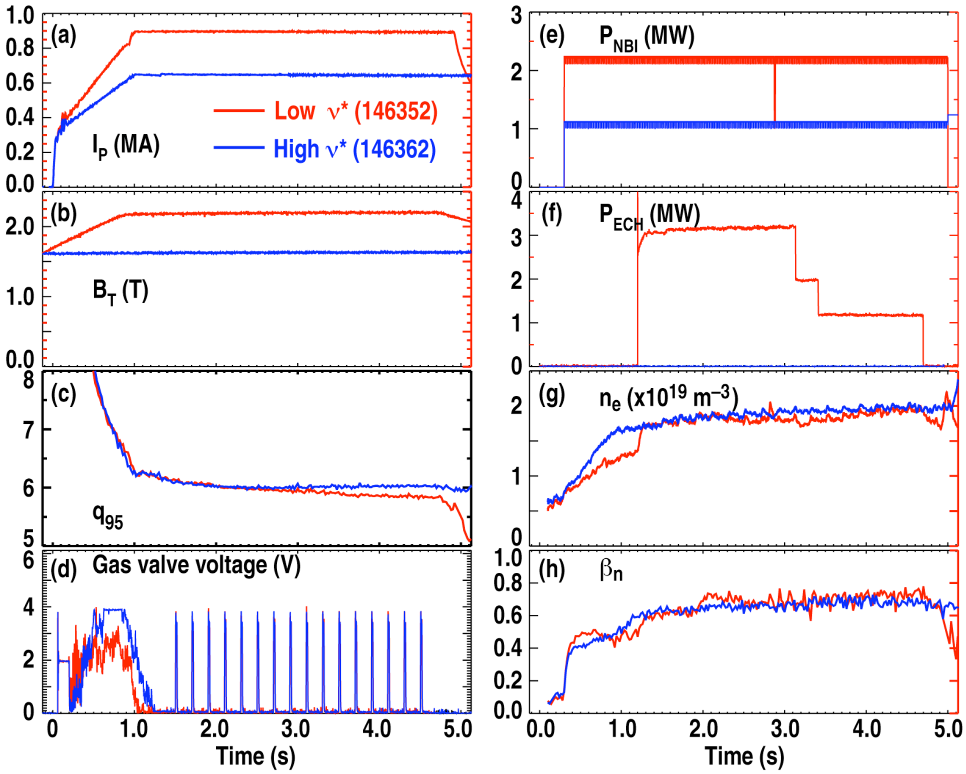

FIG. 1. Showing: (a) Plasma current, (b) toroidal magnetic field, (c) safety factor, q_{95}, (d) gas valve voltage, (e) NBI power, (f) ECH power, (g) line average density, and (h) normalized beta. The data are for two L-mode discharges, a low collisionality case shown in red (146352), and a high collisionality case shown in blue (146362).

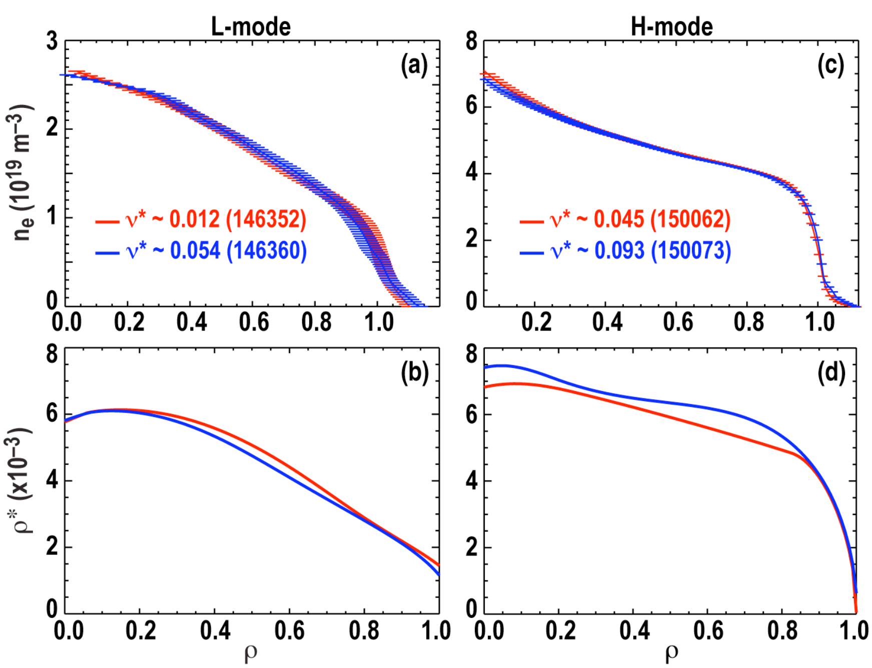

FIG. 2. Showing: (a) and (c), measured density profiles, with error bars, and (b) and (d), normalized gyroradius ρ, for both L-mode (left hand side) and H-mode (right hand side) plasmas, as a function of collisionality.*

quality of the match, are accounted for in TGLF modeling. The non-perfect matches in T_e/T_i and Z_{eff} are probably the cause of small but measurable changes in turbulence levels, shown in Fig. 3, even though the measured density profiles are invariant as a function of ν*. This interpretation is supported by the fact that the observed turbulence changes are consistent with TGLF modeling for this location, which predict a modest increase in linear turbulence growth rates for the higher collisionality case, for wavenumbers in the BES measurement range.

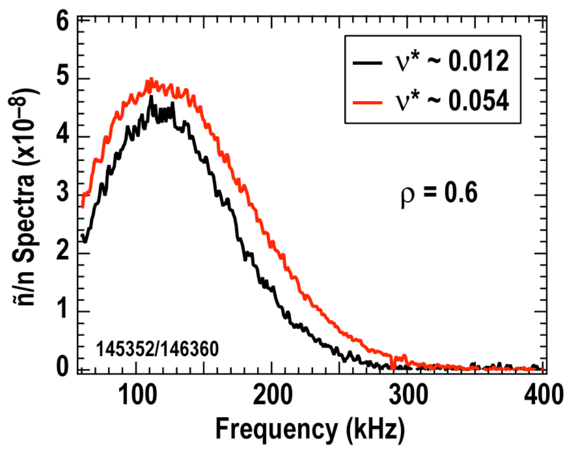

FIG. 3. Measured density fluctuation amplitudes at ρ=0.6, as measured by the DIII-D BES system, showing a small increase in turbulence amplitude with collisionality.

3. COMPARISON OF PERTURBATIVE PARTICLE TRANSPORT MEASUREMENTS WITH TGLF MODELING

Perturbative techniques have been in use for many years as a powerful tool by which to probe plasma transport processes, e.g. see review articles [13,14]; perturbed measurements are related to the local profile stiffness. As explained below, we have developed a new capability to directly compare experimentally determined values for perturbative particle diffusivities and pinch velocities with equivalent values predicted by the state-of-the-art, Trapped Gyro-Landau-Fluid (TGLF) transport model [6]. This new capability to directly compare measured and model derived particle transport results represents both an important extension of the ways in which the TGLF transport model can be tested and validated, to include perturbative particle transport, and is simultaneously a powerful new way to connect perturbative transport results to theory. Previous validation studies with TGLF tended to concentrate on ion and electron thermal transport, as opposed to particle transport.

A key requirement for performing perturbative transport experiments is the availability of diagnostic systems capable of resolving transient perturbations as a function of both time and space. On DIII-D, perturbative particle transport experiments are enabled by a profile reflectometer system, which has a combined (simultaneous) spatial and temporal resolution of ~ 4 mm spatial, and 25 μs time resolution [15,16]. Data from this system, combined with use of gas puff modulation techniques, has enabled us to determine perturbative particle transport rates in a number of regimes. An example of an oscillating gas puff waveform used to generate a periodic plasma density modulation was shown in Fig. 1(d) earlier. Our analysis of such perturbative data utilizes the approach developed in reference [17]; subject to simple assumptions, such as that the region of analysis is outside the location of the narrow edge particle source, it is possible to analytically determine both the particle diffusion coefficient (D) and the particle pinch velocity (v). [SOLPS5 analysis confirms that neutral densities inside the separatrix are low, except in the vicinity of the divertor X-point]. The analysis process starts with a set of modulated density data as a function of time and space. An example of high resolution 2-D density data for edge gas puffs into a DIII-D L-mode plasma is shown in Fig. 4; the propagation of the gas-puff-induced density perturbations from the edge into the plasma core can be clearly seen. The modulated density data are then Fourier transformed as a function of time for multiple spatial locations to obtain the amplitude and phase of the fundamental frequency of the density perturbation as a function of plasma radius. The modulated amplitude and phase data obtained in this way are illustrated in Fig. 5, for the same data set as show in Fig. 4. With these two experimentally determined quantities (modulated amplitude and phase), it is then possible to solve analytically for the two unknowns, D and v, as a function of radius [17]. This is in contrast with equilibrium particle transport measurements, where only the ratio v/D is obtained, i.e. for equilibrium measurements D and v are usually inseparable [18]. This is one manifestation of the fact that modulated and equilibrium transport rates are not identical [13,14].

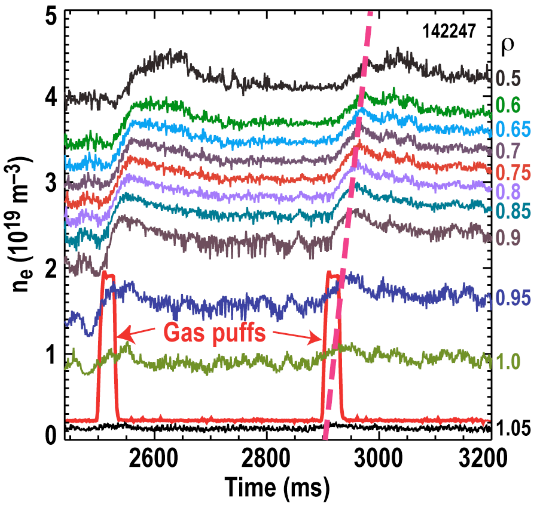

FIG. 4. Showing density data from the DIII-D profile reflectometer system, as a function of time and space, through two edge gas puffs (red overlay). The propagation of the gas-puff-induced density perturbations from the edge into the plasma core can be clearly seen. The dashed line is to guide the eye, and is not a fit to the data.

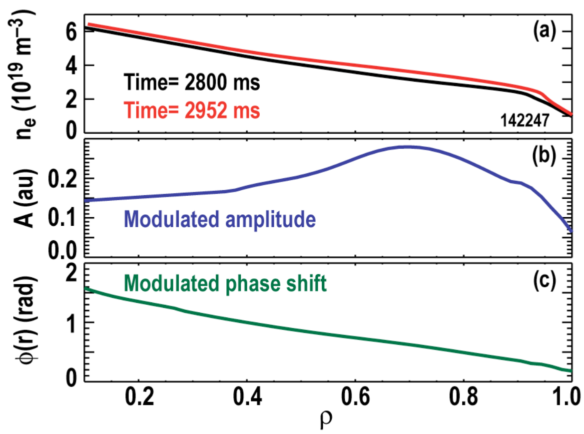

FIG. 5. Illustration of: (a) Density profiles at two times, (b) density modulation amplitude, and (c) density modulation phase shift, as a function of ρ, for the same gas puff modulation data set shown in Fig. 4.

A new capability to determine equivalent perturbative D's and v's from TGLF was also developed. The particle flux computed by TGLF is local to a flux surface, but depends on all of the local profile gradients, not just the density gradient. Since the flux depends non-linearly on the density gradient, the change in the flux with a local change in density gradient can be much larger than expected from a diffusive model. In fact, since density gradients stabilize some instabilities, an increase in density gradient can lower the particle flux, or change its direction to inward instead of outward. Thus, even though the particle transport is inherently non-diffusive, the TGLF model can still be used to compute effective transport coefficients using the data from modulated gas puff experiments. This is done in the following way. The Fourier transform of the particle balance equation is $-i\omega n+(1/V')(d/dr)[V'\Gamma]=S$, with $V'=(dV/dr)$. Each term (density n, flux Γ and particle source S) represents the Fourier transform of the deviation from the time averaged values. The radial derivative of the volume V gives the surface area of the flux surface. Integrating this equation from the axis to a flux surface r determines the measured flux $\Gamma=(1/V')\int_0^r dV[S+i\omega n]$. The effective diffusion D and convection v at the flux surface are defined through an assumed model of the standard form $\Gamma=-D\partial n/\partial r+nv$. Defining the amplitude A and phase ϕ of the density perturbation by $n=A(r)\sin[\omega t-\varphi(r)]$, the real coefficients (D, v) at each radius can be determined as functions of (A, ϕ), using the measured flux and the model. The TGLF transport model is completely local, so it can compute the local particle flux at each radius and time using the measured density and temperature profiles. This time series of particle fluxes are then Fourier transformed in time to determine a perturbed amplitude and phase. This TGLF flux can be used directly in the model to determine a set of transport coefficients ($D^{TGLF}v^{TGLF}$) to compare with the empirical ones found via experiment. It should be noted that both the analytic and TGLF modeling assume that any coupled transport driven by associated temperature perturbations is negligible.

Using the above procedures, we have determined both experimental and TGLF derived estimates for the L-mode particle transport experiment described in Section 2, above. Both sets of D, v data are presented in Fig. 6, with the analytically derived values on the left hand side, and the TGLF estimates on the right hand side. Both the experimental and TGLF estimates indicate little change in particle transport with collisionality. In addition, the quantitative agreement between the two estimates is remarkably good for what is a first test of this new technique. The most significant disagreement is with regard to the value of D in the plasma center (ρ≤0.25), where TGLF in general predicts turbulence to be stable.

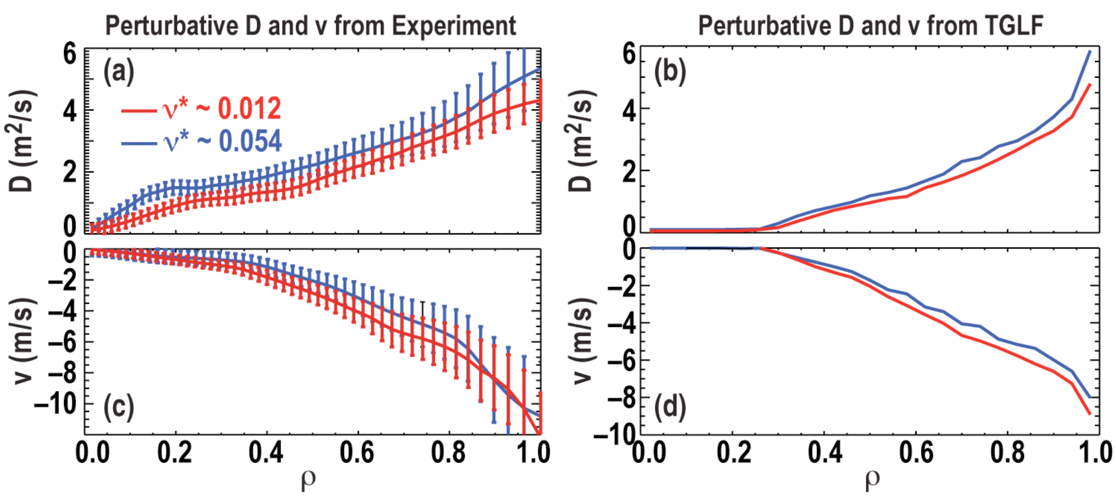

FIG. 6. Illustration of: (a,b) perturbative particle diffusion coefficient, D, and (c,d) particle pinch velocity, v, as a function of ρ and collisionality, for the same L-mode plasmas as in Fig. 1. Experimental estimates for D and v are on the left hand side, while the TGLF modeling estimates for the same quantities are on the right hand side. Both data sets show little change in D and v as a function of collisionality. The quantitative agreement between experimental and TGLF estimates is good.

4. MEASUREMENTS OF PARTICLE TRANSPORT IN H-MODE ELM-SUPPRESSED REGIMES

In a separate set of experiments to those described in the preceding sections, perturbative transport techniques using oscillating gas puffs were also utilized to measure D and v in conventional ELMing H-mode and RMP ELM-suppressed regimes. ELM-suppressed H-mode operation is a critical need on ITER, as ELM-induced energy and particle fluxes to the first wall can potentially generate unacceptable wall erosion [19]. RMP application is a leading candidate for ELM-suppressed H-mode operation on ITER [7]. However, a decrease in density (density "pump-out") is often, though not invariably, observed with RMP application, independent of whether ELM-suppressed operation is obtained, which could reduce fusion performance on ITER [7,8]. Consequently, it is important to understand if RMP application affects particle transport through changes in D and v, and over what spatial region. To this end, a series of perturbative particle transport experiments were performed with varying levels of RMP applied. As described in detail in [8], these experiments provide the first direct measurements confirming an increase in D and decrease in v with RMP application. Figure 7 provides a direct comparison of D and v for two comparable discharges, with and without RMP application, and also for a QH-mode discharge under somewhat different conditions. An important feature of the results is that they indicate the changes in D and v with RMP application extend deep into the plasma core, well past the edge region where the applied RMP fields are expected to directly impact the magnetic field topology. In the plasma core, clear increases in plasma turbulence levels with increasing levels of RMP application are observed, see Fig. 8. The observed increase in turbulence is consistent with the observed increase in particle transport, and also with TGLF modeling, which indicates that the transport increase is due to a decrease in **ExB** shear to a level below the linear growth rate – for details of these results, see reference [8]. Note that the TGLF analysis does not include any changes in magnetic topology associated with RMP application.

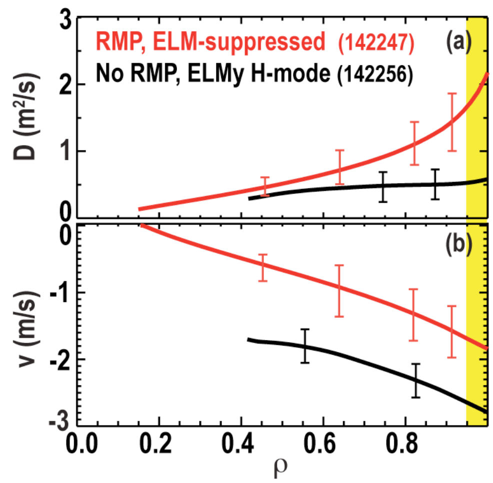

FIG. 7. Radial profiles of: (a) Measured perturbative diffusion coefficient D, and (b), inward particle pinch velocity v, for two conditions; a conventional ELMing H-mode discharge (black), and an equivalent ELM-suppressed discharge with RMP applied (red).

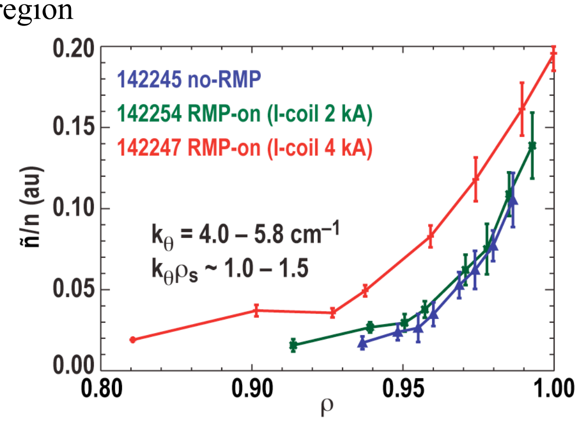

FIG. 8. Measured intermediate-k turbulence levels as a function of radius from a Doppler backscattering system, showing a clear increase in turbulence levels with RMP amplitude.

5. SUMMARY

Recent particle transport experiments on DIII-D have addressed a range of important issues: They contribute to the development of a predictive capability for electron particle transport, through validation (or not) of the capabilities of state-of-the-art transport models and simulations such as TGLF and GYRO. The experimental data presented here are in fact in good agreement with GYRO and TGLF. In particular, the L- and H-mode collisionality scaling data presented in Section 2 are consistent with GYRO predictions made prior to the experiments for little variation in particle transport with collisionality, in the collisionality range probed. In addition, as discussed in Section 3, a new capability to directly compare TGLF and experimental measurements was developed and tested for the first time, with good quantitative agreement obtained. The experiments also address key issues for ITER, such as the collisionality scaling of particle transport and density peaking, which will directly impact fusion power production and impurity accumulation. The experiments also addressed, Section 4, the key ITER issue of the causes and nature of the core density pump-out associated with RMP application, which occurs independent of ELM suppression, with new results confirming that D and v are modified by RMP application over a wide spatial range, not just the plasma edge, and with changes in **ExB** shear playing a significant role.

Taken together, the results presented here represent a significant step towards developing a validated predictive capability for particle transport on ITER. The apparent discrepancy between the similarity scaling results presented here (no change in density profile peaking with collisionality) and previous database studies (clear change with collisionality), argues for further studies to resolve this important ITER issue, e.g. via similarity scans over a broader range of collisionality, and matching experiments on other devices.

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