Turbulence and Transport Suppression Scaling with Flow Shear on the Large Plasma Device

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Continuous control over azimuthal flow and shear in the edge of the Large Plasma Device (LAPD) [W. Gekelman, *et. al*, Rev. Sci. Instr. **62**, 2875 (1991)] has been achieved using a biasable limiter. This flow control has allowed a careful study of the effect of flow shear on pressure-gradient-driven turbulence and particle transport in LAPD. The combination of externally-controllable shear in a turbulent plasma along with the detailed spatial diagnostic capabilities on LAPD makes the experiment a useful testbed for validation of shear suppression models. Motivated by these models, power-law fits are made to the density and radial velocity fluctuation amplitudes, particle flux, density-potential crossphase and radial correlation length. The data show a break in the scaling these quantities with shearing at around a normalized shearing rate of one (shearing rate (γ_s) equal to the turbulent decorrelation rate ($1/\tau_{\rm ac}$). No one model captures the trends in the data across all values of shearing, but some models successfully match the trend in either the weak ($\gamma_s\tau_{\rm ac} < 1$)or strong shearing limits ($\gamma_s\tau_{\rm ac} > 1$).

I. INTRODUCTION

Suppression of turbulence and turbulent transport by flow shear has been observed on a multitude of different magnetized plasma experiments[1–5,11]. While the importance of cross-field flow shear for the successful high confinement operation of fusion devices is well recognized (add another cite here?), we still lack a fully first-principles understanding of how sheared flow regulates turbulence and transport. The development of this understanding is essential in the development of a predictive capability for transport for current and future devices such as ITER. Experimental validation of shear suppression models is a critical part of this development process, providing motivation for experiments in which the response of turbulence to shear flow is carefully documented. External control of flow shear in a magnetized plasma has been previously achieved in a number of torodial devices using biased electrodes to drive cross-field currents and torque to drive plasma rotation[6,7]. Transport reduction and confinement transitions have been observed and this response has been compared to models for shear suppression, in particular from TEXTOR[8–10].

Biasing has been used to induce rotation and transitions in particle confinement in the Large Plasma Device (LAPD)[? ?] . Recently,

Using a recent dataset on LAPD[11] where a detailed scan of sheared flow in a turbulent, linear field line plasma was made using a biased limiter, we hope to extend such shear suppression model verification studies. The recent data set demonstrated the suppression and modification of a number of turbulent quantities with increased shearing rate including cross-field particle flux, density and radial $E \times B$ velocity fluctuations, the relative crossphase between said fluctuations, and radial correlation length. Moreover, the scan included data points in both the weak and strong shearing regime, as defined by the ratio of shearing rate to inverse autocorrelation time providing the ability for comparison to models which make separate predictions for each regime.

Models based on radial decorrelation of turbulent structures by shear are prominent Shear suppression models based on the spatial decorrelation of turbulent structures have been the most common approach to describing both the physical mechanism underlying suppression as well as for making scaling predictions[5]. The basic premise underlying these models is the effect of shearing to break apart or shrink turbulent eddies and consequently decrease both fluctuation amplitude and transport step size. Variation in the model predictions arise from differences in shearing regime, source of turbulent drive (i.e. Ion Temperature Gradient, Interchange Drive or Pressure-Gradient Drive), as well as consideration of passive versus dynamic scalars. Recently, other approaches to explaining shear suppression have been made including the enhancement of coupling to damped eigenmodes by sheared flow[12] and by nonlinear shifts in the wavenumber spectrum of the turbulence by shearing(Staebler, APS 2012). However, this paper will focus on the varying decorrelation models which include scaling predictions.

This paper presents experimental fits of density fluctuation amplitude, radial velocity fluctuation amplitude, particle flux, crossphase, diffusivity and radial correlation length as functions of flow shear and compares them to a number of model predictions for this shear suppression. No one model predicts how all the quantities scale though some models do make favorable comparisons for some quantities, but unfavorable comparisons to others. The fits generally show a stronger decrease in turbulent fluctuations than crossphase as a contributer to reduction of particle flux. Fits to the suppression of measured radial diffusion—which incorporates the changes in density gradient—compare well to numerical simulation predictions. The ability to make favorable predictions for some quantities while not other perhaps suggests a dependence on turbulent conditions for determining shear suppression and call for specific calculations for LAPD plasmas to be made.

The remainder of this paper will first look at the various models of shear suppression in Section II, then move on to a brief review of the limiter biased rotation studies on LAPD in Section III. In Section IV, the approach for model fitting of the experimental data is discussed and the results of these fits are presented in Section V. Finally a discussion of how these fits compare to analytic and simulation model predictions is given in Section VI.

II. MODELS OF SHEAR SUPPRESSION

Two of the earliest models of shear suppression were decorrelation models developed by Biglari, Diamond, Terry[13] (hereafter BDT) and Shaing[14]. The BDT theory presents a generalized analysis of the transport of a passive scalar in a mean sheared flow in the strong-shear regime with constant turbulent drive (pressure gradient). The BDT model predicts that normalized fluctuation amplitude scales directly with shear to the -2/3 power:

$$\frac{\langle|\tilde{\xi}|^2\rangle}{\langle|\tilde{\xi}|^2\rangle_{\gamma_s=0}} \sim (\gamma_s \tau_{ac})^{-2/3} \tag{1}$$

where η can be any quantity such as density or temperature. Conversely, the Shaing model focuses on the weak shearing limit and predicts a scaling of the form:

$$\frac{\langle|\tilde{\xi}|^2\rangle}{\langle|\tilde{\xi}|^2\rangle_{\gamma_s=0}} \sim 1 - \alpha(\gamma_s \tau_{ac})^2 \tag{2}$$

Where α is a constant containing mode number information. An attempt to consolidate the BDT and Shaing models was made by Zhang and Mahajan[15,16]by expanding the model to incorporate the self-consistent modification of the diffusion coefficient and fluctuation spectrum by the flow shear (allowing for a distinction between weak and strong turbulence regimes in the shearing model). The resulting model shows correspondence to the Shaing model in the weak shearing regime while the BDT model is recovered in the strong shearing regime but only for the case where diffusion is unchanged by fluctuation amplitude changes. Furthermore, they extend the model to incorporate the effect of changes in gradient scale-length, showing that shear suppression of fluctuation amplitude is enhanced by a steeper equilibrium gradient.

Work by Ware and Terry[17,18] made predictions for the effect of shearing on particle transport specifically in resistive pressure-gradient driven turbulence. Their work predicted a decrease in flux as $\Gamma_p \sim 1 - \gamma_s^2$ in the weak shear limit. Additionally, the model predicted a decrease in the cosine of the crossphase between density and radial velocity fluctuations of the form $1-\omega_s^2$. They too incorporated the modification of the pressure gradient, formulating an expression for shearing suppression of radial particle diffusivity of the form:

$$\frac{D}{D(\gamma_s = 0)} \sim 1 - \beta(\gamma_s)^2 \tag{3}$$

where β is a constant containing the linear growth rate and radial mode width.

Further work by Terry, Newman and Ware[19] examined the modification of flux in the strong shearing regime for a non-mode-specific turbulence system, predicting a direct scaling of $\Gamma_p \sim \gamma_s^{-4}$ overall, with fluctuation amplitude reduction contributing one power while crossphase reduction contributed three powers of γ_s, suggesting both a strong dependence of flux on shear as well as an implication that the crossphase can be the dominant flux suppression mechanism rather than the fluctuation amplitude. However, Kim and Diamond[20] recast the decorrelation model to include resonance absorption between the shear flow and fluctuations leading to a much weaker dependence of flux on shear, $\Gamma_p \sim \gamma_s^{-1}$, and even weaker dependence of crossphase, $\cos(\theta_{nv_r}) \sim \gamma_s^{-1/6}$, while fluctuations decreased as $|\tilde{n}|^2 \sim \gamma_s^{-5/3}$. Additional work[21] added the effect of treating the fluctuating flows dynamically in an interchange driven turbulent plasma which allowed for a prediction for the decrease in fluctuating radial velocity as a function of shear scaling as $|\tilde{v_r}|^2 \sim \gamma_s^{-3}$ in weak shear, and $|\tilde{v_r}|^2 \sim \gamma_s^{-4}$ in strong shearing.

Most recently, Leconte et al.[22] found different scalings for flux, fluctuations and crossphase in the strong shear regime depending on relative shearing strength relative to a characteristic time and shearing spatial gradient relative to the inhomogeneity gradient. Work by Newton and Kim has utilized numerical simulations to determine shearing scalings in a generic model[23,24].

III. SHEAR SUPPRESSION EXPERIMENTS

The Large Plasma Device[25] (LAPD) is a 17m long, ∼60cm diameter cylindrical plasma produced by a barium-oxide coated nickel cathode. In the experiments reported here, a plasma of density $\sim 2 \times 10^{12}$ cm^{-3} and peak temperature of 8eV is produced in a uniform solenoidal magnetic field of 1000G. All measurements reported here were collecting using Langmuir probes recording floating potential, V_f, or ion saturation current, I_{sat}. Azimuthal electric field fluctuations, $\tilde{E}_\theta$, are found by taking the simultaneous difference in two V_f signals separated a small azimuthal distance apart. Turbulent particle flux $\Gamma \propto \left\langle \tilde{n}_e \tilde{E}_\theta \right\rangle$ is determined through correlating density fluctuations with $\tilde{E}_\theta$ where it assumed that E_θ produces radial $E \times B$ flow. The relative crossphase between fluctuation time-series is determined through the cross-spectrum of the quantities. That is,

$$\theta = \tan^{-1} \frac{\langle Q(f,r)\rangle_{f,r}}{\langle C(f,r)\rangle_{f,r}} \tag{4}$$

where Q and C are the imaginary and real parts of the cross-spectrum, calculated from product of the complex FFTs of the two time-series in question as in,

$$G(f,r) = \hat{x}^*(f,r)\hat{y}(f,r) \tag{5}$$

where the cross-spectrum is first averaged over frequencies to power-weight the crossphase signal, and then averaged radially, before the phase is determined. Finally, steady-state azimuthal flow, V_θ is determined through the radial derivative of plasma potential profiles measured using a swept-Langmuir probe technique again assuming only $E \times B$ flow. The shearing rate is computed as $\gamma_s = d/dr(V_\theta)$.

A large annular aluminum limiter was installed in LAPD to provide a parallel boundary condition for the edge plasma and is biased relative to the cathode of the plasma source to control plasma potential and cross-field flow. A diagram of the limiter arrangement and biasing circuit is shown in Fig. 1.

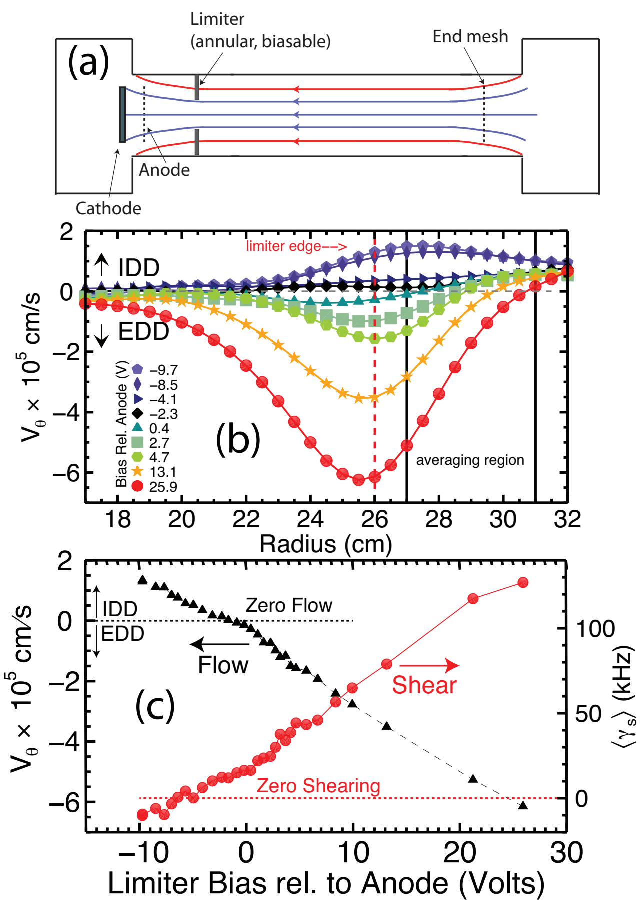

FIG. 1. (a) Diagram of the LAPD device showing annular limiter. (b) Velocity profiles using plasma potential from swept measurements. (c) Flow at the limiter edge (black, triangles) and mean shearing rate, averaged over $27 < r < 31$cm (red, circles).

A recent experiment on the LAPD demonstrated the ability to achieve continuous control of steady-state azimuthal flow and flow shear through the use of these biasable limiters[11]. Spontaneous rotation is observed in LAPD in the ion diamagnetic direction. This spontaneous flow can be reduced and reversed into the electron diamagnetic direction as the limiter bias is increased. This results in a continuous variation of edge flow and flow shear including zero flow and flow shear states. Shearing rates are acheived up to about five times the turbulent inverse autocorrelation time τ_{ac}^{-1} as measured in the unsheared state. Radial particle flux and fluctuation amplitude are reduced as shearing rate is increased and the resulting transport changes cause observable steepening of the density gradient. Figure 2 shows the experimental results for measurements of density fluctuation amplitude, radial velocity amplitude and density-radial velocity crossphase as functions of normalized shearing rates. The shearing rates achieved span two regimes: a weak-shear regime where $\gamma_s \tau_{ac} < 1$ and a strong-shear regime where $\gamma_s \tau_{ac} > 1$. The blue solid lines correspond to the best fits for the strong-shear cases while the green are the best fits for the weak-shear case. Similar plots for particle flux and diffusivity $D = \Gamma/|\nabla n|$ are shown in Fig. 3.

Measurements of the radial correlation length were recorded as a function of shearing rate (applied bias) using a two-probe correlation technique. A reference probe collecting I_{cmrsat} is kept stationary at a particular axial and radial location within LAPD. A second Langmuir probe situated at an axial point closer to the cathode is moved shot-to-shot in a rectangular grid around the radial location of the reference probe. The cross-field cross-correlation function of these two measurements is computed shot-to-shot for a delay time τ as $C(x, y, \tau) = \langle I_{ref}(x, y, t) I_{mot}(x, y, t + \tau)\rangle$. Fig. 4(a) shows the normalized correlation function $C(x, y)/C_{max}$ for the unbiased state (flow in the IDD), a minimum shear state, and a high bias state (large EDD flow) with a reference probe located at $x = 29.5$cm, $y = 0$cm (right in the middle of the shear layer). The black curve represents the contour line where $C(x, y)/C_{max} = 0.5$. The radial correlation length Δr_c is defined here as the radial width of this black curve through the reference probe location. The variation of the correlation length versus shearing rate is shown in Fig. 4 (normalized to the maximum radial correlation length calculated for all biases). The correlation length is found to decrease substantially with shearing. A break in the trend of decreasing correlation length is observed for larger shearing rates where the correlation function appears to be dominated by a coherent mode (which also appears in the temporal power spectrum).

Some acheived parameters regimes for the shearing rat and density gradient length scales are presented in Fig. 5. The shearing scale length is calculated as in $L_\gamma = |\nabla \ln(v_{E\times B}|^{-1}$. This value is compared to the density gradient scale length, $L_n = |\nabla \ln n|^{-1}$ for each bias and mapped to a normalized shearing value. This plot shows that for the all of the strong shearing regime, and nearly half of the weak shearing regime, $L_n > L_\gamma$. The reverse is true only for the weakest shearing points. This quantity L_γ/L_n can be utilized in asymptotic limits similar to the γ_s/τ_{ac}^{-1} ratio for models[22].

IV. EXPERIMENTAL SHEAR SUPPRESSION SCALING

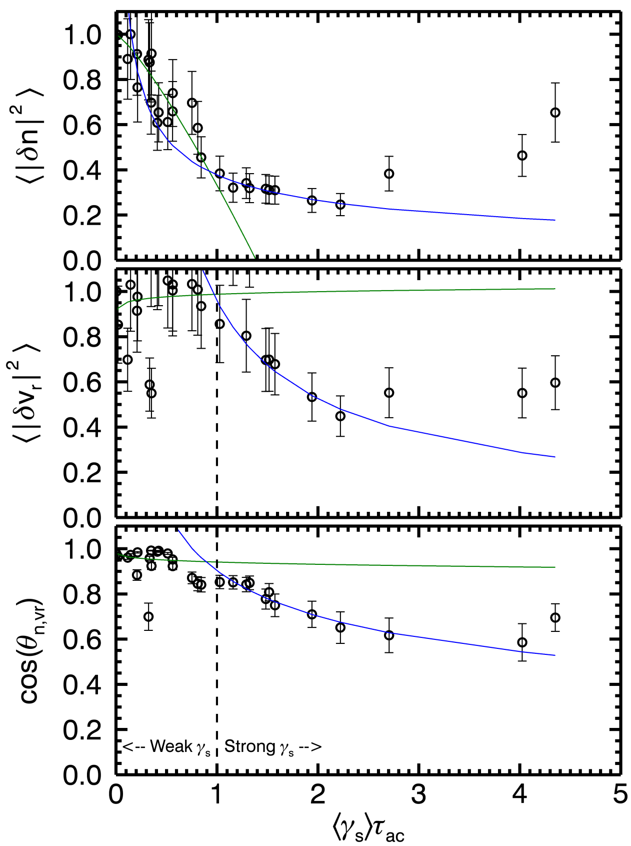

FIG. 2. Scaling of (a)density fluctuation amplitude, (b)radial velocity fluctuation amplitude, and (c)relative crossphase between denisty and radial velocity fluctuations. Density and velocity fluctuation are each normalized to the value at minimum shear. The green curves correspond to $1-\gamma_s^\nu$ fits of the weak shear regime with $\nu = 0.501$ for flux and $\nu = 0.418$ for D. The blue curves correspond to γ_s^ν fits with $\nu = -1.719$ for flux and $\nu = -1.646$ for D.

The variation of the experimentally measured quantities with normalized shearing rate was fit to functions motivated by models discussed above: functions of the form $1 - \gamma_s^\nu$ (hereafter M1 or model type 1) and of γ_s^ν (hereafter M2). For model type 1, the measured quantity, y, was normalized to the value at zero shear, then transformed as $-(1-y)$. Then,

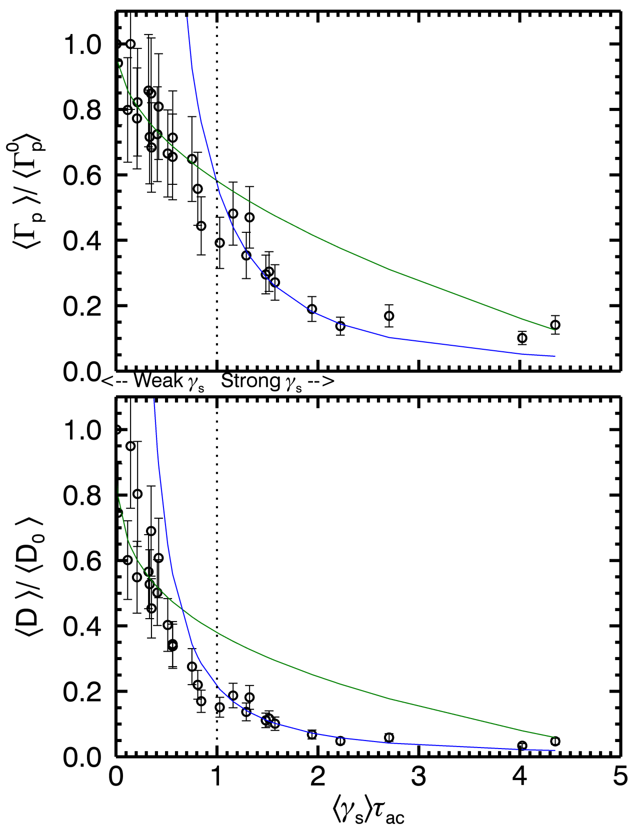

FIG. 3. Scaling of (a)radial particle flux and (b)diffusion coefficient each normalized to the value at minimum shear, $\Gamma_p^0 = 1.7 \times 10^{16} cm^{-2}$ and $D_0 = 36.7 m^2/s$. The green curves correspond to $1 - \gamma_s^\nu$ fits of the weak shear regime with $\nu = 0.501$ for flux and $\nu = 0.418$ for D. The blue curves correspond to γ_s^ν fits with $\nu = -1.719$ for flux and $\nu = -1.646$ for D.

TABLE I. Power-law fits for $|\tilde{n}^2|$ scaling with shear for frequencies in 350Hz to 100kHz. Model form refers to how the shearing relates to the quantity in question, with C a constant and ν the power exponent.

Model form	γ_s regime	ν	χ^2	χ^2/ndf
$\sim 1 - C\gamma_s^\nu$	$\gamma_s \tau_{ac} < 1$	1.228	1.091	0.0642
$\sim C\gamma_s^\nu$	$\gamma_s \tau_{ac} < 1$	-0.116	0.1791	0.0094
$\sim C\gamma_s^\nu$	$\gamma_s \tau_{ac} > 1$	-0.512	0.0024	0.0003

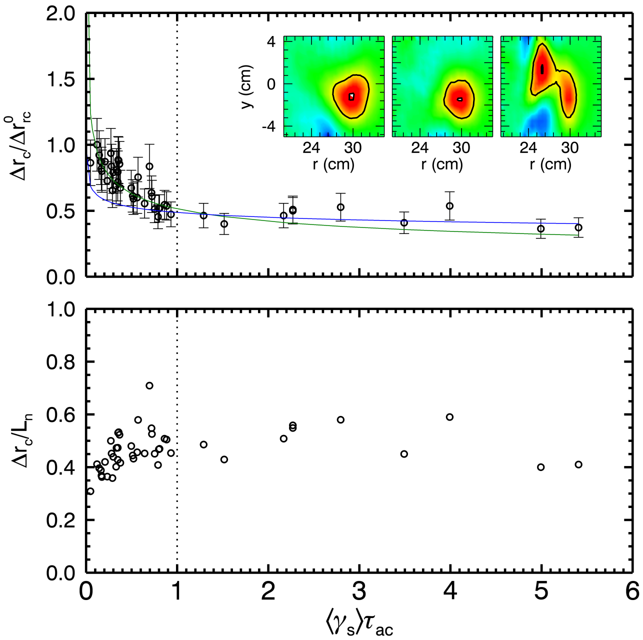

FIG. 4. (a)Radial correlation length normalized to maximum correlation length versus normalized shearing rate with correlation planes of unbiased, zero shear, and high bias states in the inset. (b)Ratio of radial correlation length to density gradient scale length.

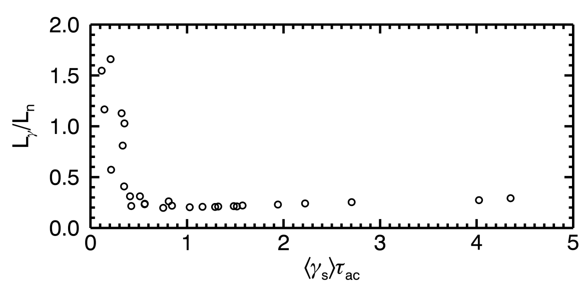

FIG. 5. Ratio of shearing length scale to density gradient length scale versus normalized shearing in the radial region of 27 to 31cm.

TABLE II. Power-law fits for $|\tilde{v}_r^2|$ scaling with shear for frequencies in 350Hz to 100kHz. Model form refers to how the shearing relates to the quantity in question, with C a constant and ν the power exponent.

Model form	γ_s regime	ν	χ^2	χ^2/ndf
$\sim C\gamma_s^\nu$	$\gamma_s\tau_{ac} < 1$	0.016	0.2121	0.0117
$\sim C\gamma_s^\nu$	$\gamma_s\tau_{ac} > 1$	-0.866	0.0037	0.0005

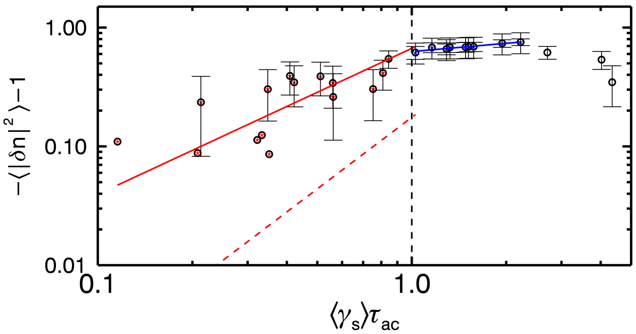

FIG. 6. Log-Log plot of -(density fluctuation amplitude)-1 versus shearing with fit function for weak shear in solid red, Shaing scaling of 2 indicated by dashed red line. Blue line is fit for strong shearing

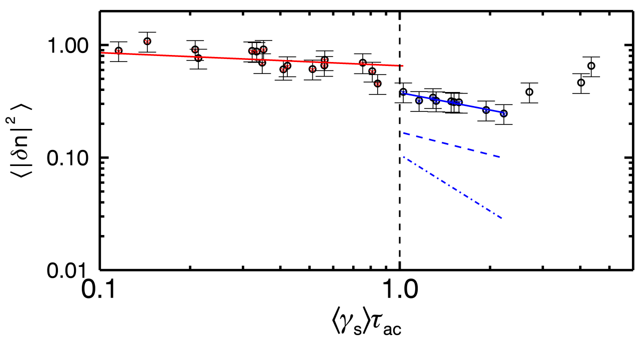

FIG. 7. Log-Log plot of density fluctuation amplitude versus shearing with fit function for strong shear in solid blue, BDT scaling of -2/3 indicated by dashed blue line and Kim and Diamond scaling of -5/3 indicated by steeper dashed-dotted line.

TABLE III. Power-law fits for Γ_p scaling with shear for frequencies in 350Hz to 100kHz. Model form refers to how the shearing relates to the quantity in question, with C a constant and ν the power exponent.

Model form	γ_s regime	ν	χ^2	χ^2/ndf
$\sim 1 - C\gamma_s^\nu$	$\gamma_s\tau_{ac} < 1$	0.501	0.332	0.0189
$\sim C\gamma_s^\nu$	$\gamma_s\tau_{ac} < 1$	-0.111	0.146	0.0077
$\sim C\gamma_s^\nu$	$\gamma_s\tau_{ac} > 1$	-1.719	62.49	5.2000

TABLE IV. Power-law fits for $cos(\theta_{nv_r})$ scaling with shear for frequencies in 350Hz to 100kHz. Model form refers to how the shearing relates to the quantity in question, with C a constant and ν the power exponent.

Model form	γ_s regime	ν	χ^2	χ^2/ndf
$\sim 1 - C\gamma_s^\nu$	$\gamma_s\tau_{ac} < 1$	0.226	6.1140	0.3320
$\sim C\gamma_s^\nu$	$\gamma_s\tau_{ac} < 1$	-0.020	0.0369	0.0019
$\sim C\gamma_s^\nu$	$\gamma_s\tau_{ac} > 1$	-0.365	0.0023	0.0003

taking the logarithm of both sides, a linear fit was made for points in the weak shear and in the strong shear separately. The resulting slope of the fit is taken as the power ν. For M2, no transformation of the quanitity y to $-(1-y)$ is made before taking the logarithm and fitting. For a complete comparison to the wide range of model predictions made, fits were made for density fluctuation amplitude, radial particle flux, density-radial velocity fluctuation crossphase, radial velocity (ExB) fluctuation amplitude, radial correlation length, and experimentally determined diffusivity ($\Gamma/|\nabla n|$). The best fits are summarized in Table I-VI for each model type and for both weak and strong shearing. The χ^2 and χ^2/ndf (where ndf is the number of degrees of freedom) is also indicated in the tables. Error bars of +/-20% for each quanitity are shown on the plots and used in the fits, reflecting a statistical error from the number of shots used to average the quanity ($\sigma \sim 1/\sqrt{nshots}$). For weak shear fits, all points less than the weak shear cutoff $\gamma_s\tau_{ac}$¡1 are used in the fit. For strong shear, all but the last three points are used. The last points appear to be strongly influenced by the presence of a coherent mode that develops in the highest shear and flow cases and is thought to be a break from the scaling observed in the strong shear regime. For quantities determined by averaging over frequency (e.g. density and velocity fluctuation amplitudes, flux and diffusivity) the frequenquency band used was 350Hz to 100kHz.

V. RESULTS

The best fits for scaling of density fluctuation amplitude are shown in Table I. For the weak shear regime, fitting to M2 has a slighty better χ^2 than for M1. Both fits suggest a slightly weaker dependance on shearing with $\nu = 1.228 < 2$ for M1, and $\nu = -0.116 < -2/3$ for M2. In the strong shear regime, a best fit of $\nu = -0.512$ for M2 is not far from

TABLE V. Power-law fits for $D = \Gamma_p/\nabla n$ scaling with shear for frequencies in 350Hz to 100kHz. Model form refers to how the shearing relates to the quantity in question, with C a constant and ν the power exponent.

Model form	γ_s regime	ν	χ^2	χ^2/ndf
$\sim 1 - C\gamma_s^\nu$	$\gamma_s\tau_{ac} < 1$	0.418	1.4710	0.0817
$\sim C\gamma_s^\nu$	$\gamma_s\tau_{ac} < 1$	-0.217	0.4200	0.0221
$\sim C\gamma_s^\nu$	$\gamma_s\tau_{ac} > 1$	-1.646	0.0187	0.0021

TABLE VI. Power-law fits for Δr_c scaling with shear for frequencies in 350Hz to 100kHz. Model form refers to how the shearing relates to the quantity in question, with C a constant and ν the power exponent.

Model form	γ_s regime	ν	χ^2	χ^2/ndf
$\sim C\gamma_s^\nu$	$\gamma_s\tau_{ac} < 1$	-0.290	5.8730	0.1630
$\sim C\gamma_s^\nu$	$\gamma_s\tau_{ac} > 1$	-0.113	3.7040	0.3370

predictions of $\nu = -2/3$ as made by BDT for example. However, it should be noted that BDT assumes a fixed turbulence drive and that in this dataset, the gradient scale length decreases substantially as shearing is increased, resulting in an increase in turbulent drive. This implies a stronger than BDT scaling of fluctuation amplitude suppression.

(This is a bit confusing – the focus should be on comparing to the models, not comparing the ν values between M1 and M2)

Particle flux scaling in Table III shows a much weaker scaling in the weak shear limit than predicted by ???? with $\nu = 0.501 < 2$. Meanwhile for strong shear, the direct scaling fit of $\nu = -1.719$ suggest stronger scaling then predicted by Kim and Diamond in the passive scalar model[20], but less than that predicted by Terry[19] and by Kim and Diamond in the dynamic model[21]. Diffusivity in Table V shows a similar weak shear scaling for $1-\gamma$ models with $\nu = 0.418$ while for strong direct scaling a similar fit of $\nu = -1.646$ is found. Since $D = \Gamma_p/\nabla n$, this suggest that the effect of changing gradient tends to decrease the strength of scaling. Numerically, the direct scaling strong shear fit of $\nu = -1.646$ is close to the prediction made by Newton and Kim[24] of $\nu = -1.75$ for evolved turbulence with a finite correlation time.

Cosine of the the crossphase scaling in Table IV again shows much weaker scaling in the weak shear regime with $\nu = 0.226 << 2$. Direct scaling fits in the strong shearing regime are more consistent with weak scaling as predicted by Kim and Diamond[20,21], $\nu = -0.365 \sim -1/6$ compared to the strong scaling predicted by Terry[19], $\nu = -0.365 << -3$.

A prediction for the scaling of radial velocity fluctuation amplitude is only made by Kim and Diamond[21] in the dynamically evolved case. Fits however for both weak and strong shear suggest a much weaker scaling than predicted. The weak shear fit actually shows a slight increase in fluctuation amplitude rather than a $\nu = -3$ scaling while in the strong shear regime a fit of $\nu = -0.866 << -4$ is found.

Finally, a fit to radial correlation length is made and compared to the only explicit prediction made by BDT[13]. Neither the weak shear fit of $\nu = -0.290$ nor the strong shear of $\nu = -0.113$ is unreasonably far from the predicted value of $\nu = -1/3$. However, it should again be noted that the gradient scale length is decreasing with increasing shear, a variation that is inconsistent with assumptions in BDT. In Figure 4(b) the ratio of the radial correlation length to the density gradient scale length is shown, with this quantity remaining nearly constant with shearing. This suggests that the correlation length could be adjusting to the gradient scale length and that a scaling with shearing rate could be indirect.

VI. DISCUSSION

While the large variation in fits of shear suppression for six turbulent quantities makes careful model validation difficult, there an a number of conclusions that can be drawn from this analysis. First both analytic predictions and the experimental results from this dataset show a distinct difference in scaling between the weak and strong shear regimes. Moreover, in the weak shear regime the trends are better fit by M2 than by M1. [[generally compare more favorably to values made by the direct scaling γ_s^ν model form then to the $1 - \gamma_s^\nu$ form as the closest fit to the frequently predicted $1 - \gamma_s^2$ curve comes from the density fluctuation amplitude scaling while fits for flux, crossphase, diffusivity are all much less than 2. Not sure what is less than 2 here?]] These results also shed some light on the mechanisms involved in the reduction of flux due to shearing showing density fluctuation amplitude reduction being a more significant contributer compared to crossphase change. The fits show a much more favorable comparison to weak crossphase scaling predictions then to strong, and while density amplitude scaling are generally weaker then predicted, they are closer to the prediction than the crossphase counterparts. Comparison of velocity fluctuation to prediction suggest that the dynamic modeling of the flow may not be as important in LAPD plasmas. Finally, as indicated by the wide range of predictions, the scaling of shear suppression may be dependent on the nature of the turbulence at hand. Many of the turbulence models are mode specific such as pressure-gradient turbulence for the Terry, Ware models or Rotational interchange for the later Kim, Diamond models. However, neither model fits the LAPD results very well which itself is likely a combination of pressure-gradient and rotational interchange turbulence. For future model development and comparison to these results, it may be worthwhile to make predictions based on specific LAPD type turbulence.

VII. CONCLUSIONS

The results of this paper present power-law fits of experimental measurements of density fluctuations, radial velocity fluctuations, particle flux, crossphase, diffusivity and radial correlation length as a function of both weak and strong shearing as found on the LAPD. These results are compared to the myriad of models for prediction of shear suppression which are based on the physical idea of shear decorrelation of turbulent eddies. While some of the model predictions approach the experimentally measured values, most are only capable of being close to only one or two of the predicted quantities while generally far off on others. The process of developing these analytic shear suppression models often must necessarily make assumptions about the type of turbulence involved (such as pressure-gradient driven turbulence or rotational interchange driven turbulence) when it is likely that experimentally many types of free-energy is available (as on the LAPD where both drift waves and rotational interchange modes may be present). Simulation work which can incorporate more complex turbulent environment, then, could in this vein have some promise for better matching to experiment as well as analytical endeavors to develop a shear suppression model specifically for LAPD plasma.

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