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Reflectometer Measurements of Density Fluctuations in Tokamak Plasmas

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Abstract

We show that many anomalous features observed in reflectometer measurements of turbulent fluctuations in tokamak plasmas, such as loss of coherent reflection, large amplitude fluctuations, large angular divergence of the reflected waves and correlation lengths of the order of the free space wavelength of the probe beam, can be explained by modeling the plasma fluctuations as a poloidally varying random phase grating located at the cutoff with a phase magnitude given by 1D geometric optics. A key result of our analysis is that the turbulence spectrum cannot be inferred from phase measurements when large amplitude fluctuations are observed at the receiver. However, the turbulence spectrum may still be recovered from phase measurements by use of imaging optics and wide angle phase sensitive receivers.

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amplitude fluctuations. This requires that the cutoff layer be imaged onto wide angle receivers.

II. The Random Phase Screen Model

Based on the success of the phase screen model in describing the spectrum of waves reflected from the cutoff in the presence of large amplitude sinusoidal density fluctuations,¹⁸ we developed a model of reflectometry in which the plasma fluctuations behave as a corrugated random phase screen located at the cutoff, with a magnitude given by 1D geometric optics. To an external observer the phase screen will in fact appear to be located further than the actual distance to the cutoff due to the wave group delay. The model to date has been successful in predicting many of the characteristics of reflectometer data taken on tokamak plasmas such as loss of a coherent reflection, broad frequency and angular spread of the reflected waves, strong frequency shifts and correlation lengths of the order of the free space wavelength of the probe beam. However, the analytic results do not readily extend to a description of the amplitude and phase of the scattered field. At issue is whether the measured phase at the receiver can be interpreted as the phase of geometric optics in the presence of large amplitude fluctuations. The correct interpretation of the phase is a particularly important issue for further progress in understanding this diagnostic. We develop a numerical model to investigate such issues in fluctuation reflectometry. In this section, we briefly overview important analytic results and then present a numerical analysis of the phase and amplitude of waves scattered from corrugated random phase screens.

A. Analytic results

Assuming that the plasma turbulence behaves as a random phase screen with a magnitude given by 1-D geometric optics, the field E (also known as the complex amplitude) immediately beyond the phase screen becomes $E=e^{i\phi}$ where

$$\phi \approx k_0 \int_0^{z_c} \frac{\tilde{\epsilon}}{\sqrt{\epsilon_0}} dz, \quad (1)$$

$\tilde{\epsilon} \approx 2\tilde{n}/n$ is the fluctuating part of the permittivity in the X-mode near the region of maximum contribution around the cutoff, z represents the radial direction of wave propagation on the equatorial plane of the plasma, z_c is the location of the cutoff layer and

phase measured at the receiver is to be interpreted as the phase of geometric optics, then it must pass the simple self consistency check $\gamma_\phi > \gamma_E$. Other random contributions to the measured complex amplitude E should only enhance this inequality for large σ_ϕ . An estimate of σ_ϕ from $\tilde{n}$ at the cutoff can be obtained from Eq. (1) by linearizing ϵ_0 near the cutoff $\epsilon_0 \approx (z_c - z)/L_\epsilon$, which leads to the previously derived expression,

$$\Gamma_\phi(k_z) \approx 4\pi \frac{k_0^2 L_\epsilon}{k_z n_0^2} \Gamma_n(k_z) \quad ; \quad k_z > 1/L_\epsilon, \quad (6)$$

where L_ϵ is the X-mode permittivity scale length at the cutoff, $\Gamma_\phi(k_z)$ is the radial Fourier transform of the phase correlation $\rho_\phi(z_1 - z_2) = \langle \phi(z_1) \phi(z_2) \rangle$ and $\Gamma_n(k_z)$ is the Fourier transform of the density correlation $\rho_n(z_1 - z_2) = \langle \tilde{n}(z_1) \tilde{n}(z_2) \rangle$, where z_1 and z_2 are the locations of two cutoff layers. If we assume for convenience a radial density fluctuation spectrum of the form

$$\Gamma_n = \sigma_n^2 \frac{k_z}{w_z^2} \exp(-k_z^2 / \Delta k_z^2) \quad (7)$$

where $\sigma_n^2 = \langle \tilde{n}^2 \rangle$ then for the case where the radial density correlation length is much shorter than the permittivity scale length, we obtain

$$\Gamma_\phi(k_z) \approx 4\pi k_0^2 L_\epsilon \frac{\sigma_n^2}{n_0^2 \Delta k_z^2} \exp(-k_z^2 / \Delta k_z^2) \quad (8)$$

Integrating over k_z , taking $\Delta k_z \approx 1 \text{ cm}^{-1}$, and for typical TFTR plasma parameters such as $k_0 = 25 \text{ cm}^{-1}$, $k_x, k_z \approx 1 \text{ cm}^{-1}$, central plasma density $5 \times 10^{13} \text{ cm}^{-3}$ and magnetic field 42.5 kGauss, we obtain $\sigma_\phi \approx 3.5 \times 10^2 (\tilde{n}/n_0)$. Thus, for a density fluctuation level of 0.01 in the plasma core we expect ≈ 3.5 radians for the magnitude of the phase screen. For such a fluctuation level we expect strong harmonic generation in the scattered field as the first Born approximation no longer holds. Note that all the difficulties in the interpretation of the complex amplitude would disappear if the phase of geometric optics could be measured directly. However, as is now known from the solution to the 2D wave equation, the phase of the wave well away from the screen bears little resemblance to the phase at the screen.¹⁹

B. Numerical simulations

For simulating the propagation of waves scattered from two partially correlated phase screens, we begin by producing two independent phase screens $\hat{\phi}_1$ and $\hat{\phi}_2$ with identical frequency spectra as shown in Fig. 1 and with a poloidal spectrum of the same form but peaked at $k_x \approx 1$. The shifted spectra were chosen to conform with recent measurements of the poloidal spectrum of turbulent fluctuations in TFTR.^{18,21} However, we observe that the numerical results are almost independent of the precise form of the initial phase spectrum apart from determining the amplitude and the diffraction scale length of the phase screen. By a linear combination of the two independent phase screens $\phi_1 = \hat{\phi}_1$ and $\phi_2 = \alpha \hat{\phi}_1 + \beta \hat{\phi}_2$ where $\alpha^2 + \beta^2 = 1$, we obtain two new phase screens with a normalized correlation $\gamma_\phi \equiv \rho_\phi / \sigma_\phi^2 = \alpha$ where $0 < \alpha < 1$. As in the preceding theory, these two phase screens are used to represent the phase of geometric optics for two slightly different cutoff layers. We then compute the complex amplitude $E = e^{i\phi}$ for each of these screens and propagate them in free space to a distance of 100cm, corresponding to the effective distance of the cutoff from the receiver for typical TFTR experimental conditions. Essentially we assume that the only effect of the intervening plasma is to introduce a group delay in the propagation. We propagate the waves by first taking the spatial Fourier transform of the complex amplitude and then phase shifting each plane wave component by an amount $e^{ik_z z}$, where $k_z = \sqrt{k_0^2 - k_x^2}$ is the parallel wave number of the scattered field for each spectral component of the phase screen and z is the propagation distance. We then take the inverse Fourier transform after the phase shift in order to obtain the field at the observer plane. The phase and amplitude of the two fields are then recovered and correlations or other spectral information are evaluated. The correlation properties of the wave field are then investigated for many pairs of phase screens corresponding to different cutoff layer separations. The numerical model has been successfully tested against 2D solutions to the wave equation and analytic results based on the RPSM. Fig. 2 shows two frequency spectra of the complex amplitude at the observer plane for different fluctuation levels. The levels chosen are $\sigma_\phi = 0.35$ and $\sigma_\phi = 3.5$, corresponding to $\tilde{n}/n = 0.001$ and $\tilde{n}/n = 0.01$ for typical TFTR plasma conditions in quiescent ohmic and neutral beam heated plasmas, respectively. In the case of weak fluctuations, the spectrum shows a strong coherent reflection and retains the original shape of the phase screen spectrum with a clear shifted peak. However, for $\sigma_\phi = 3.5$ the coherent reflection disappears and the spectrum broadens considerably over the weak fluctuation spectrum. These results are consistent with Eq. 3 and Eq. 4 where the

correlation length and correlation time of the complex amplitude contracts with increasing σ_ϕ .¹⁸ The amplitude fluctuations at the observer plane are shown in Fig. 3 for the two cases. Importantly, the loss of coherent reflection coincides with the development of strong amplitude fluctuations, while only weak amplitude fluctuations are observed for $\sigma_\phi < 1$ consistent with the weak scattering or first Born approximation for poloidally varying fluctuations. Note that by definition the amplitude fluctuations are zero at the phase screen (dashed line) and only develop as a result of the propagation and dispersion of waves away from the phase screen. For a phase grating it can be shown that the diffraction scale length D_f over which significant amplitude fluctuations occur is of the order $2k_0/\sigma_\phi^2 k_x^2$ for $\sigma_\phi > 2$, which for the strong phase screen gives $D_f \approx 5\text{cm}$ while for the weak phase screen $D_f \approx 2k_0/k_x^2 \approx 50\text{cm}$. In both cases the observer plane is well beyond the near field or image zone of the phase screen. To see how the phase spectrum is affected after propagation, Fig. 4 displays the spectrum of the phase for the two cases. The most surprising result is that the phase spectrum for strong fluctuations looks completely different to the original spectrum of the phase screen whereas the phase spectrum for the case of weak fluctuations conforms closely in magnitude and form to the phase screen spectrum. The phase spectrum for the case of strong fluctuations is precisely $1/f^2$, and this result is independent of the original form of the phase screen. The $1/f^2$ spectrum always arises when the field is measured beyond the diffraction scale length for strong phase screens and is always accompanied by strong amplitude fluctuations at the observer plane. The $1/f^2$ behavior of the spectrum extends down to the lowest resolved frequency, determined by the sample window. This suggests that for strong fluctuations the phase beyond the diffraction scale length is diffusive, with a non stationary rms fluctuation level and a characteristic frequency which is a function of the time window of the measurement. The spectrum in the poloidal dimension is also found to go like $1/k_x^2$ so that the phase appears diffusive in both space and time. The actual variance or local rms magnitude of the phase at the observer plane for the case of strong fluctuations is close to 10 radians, however, this figure is very sensitive to where the spectrum is truncated and how large a time window is chosen. Finally, Fig. 5 shows the normalized correlation of the field E and phase at the observer plane as a function of the separation of the cutoff layers for the strong and weak phase screens. The solid line indicates the correlation of the phase screens. Importantly, in the limit of weak fluctuations we obtain that the correlation length of the complex amplitude and the correlation length of the phase at the receiver are identical (solid triangles) and coincide with the correlation length of the phase screens. This is consistent with Eq. 4 for small σ_ϕ where $\gamma_E \approx \gamma_\phi$. For $\sigma_\phi = 3.5$ we observe that the $1/e$ width of γ_E (open triangles) is down by more than a factor of 3 over

the $1/e$ width of the phase screen correlation, as is consistent with Eq. 5. But the most important result is that for large σ_ϕ , and for measurements performed away from the image plane, the coherence of the phase at the receiver (open squares) falls well below the coherence of the complex amplitude. This violates the necessary criteria that $\gamma_E < \gamma_\phi$ for the phase at the receiver to correspond to the phase of geometric optics. Note that the only assumption which goes into this criteria is that the phase represents a stationary statistical process. This condition must obviously be violated if the phase begins to resemble a diffusive process. The conclusion is that the phase cannot be interpreted as the phase of geometric optics when large amplitude fluctuations are observed at the receiver. These results suggest a very simple method for identifying the scattering regime in reflectometer experiments and hence to determine whether a particular phase measurement conveys useful information on the turbulence spectrum. The first regime is characterized by a strong coherent reflection, weak amplitude fluctuations and $\gamma_E \approx \gamma_\phi$. This regime corresponds to the weak scattering or Born approximation which has been extensively studied elsewhere for poloidally varying fluctuations.¹⁶ However, it appears that the dominant regime for current reflectometer experiments corresponds to the case of strong amplitude fluctuations and $\gamma_\phi < \gamma_E$. In this case the receiver is located well away from the image zone and the phase measurements cannot be used to infer the turbulence spectrum in the plasma. This limit is almost always associated with a $1/f^2$ spectrum for the phase. Note that from Fig. 5, the correlation length of the phase at the receiver is of the order of 1-3mm compared with the 2mm wavelength of the probe beam and the 2cm correlation length of the phase screen. Importantly, in large plasma devices such as TFTR, this regime is reached for a fluctuation level as small as $\tilde{n}/n \approx 0.01$ and poloidal wavelengths of 1cm^{-1} . Finally, in order to recover useful information from the strong phase screen regime, one must do imaging, in which case the phase at the receiver is the phase of geometric optics. At the image plane the complex amplitude is given by the simple form $E = e^{i\phi}$. This regime can be identified experimentally by weak amplitude fluctuations $|E| \approx 1$ and $\gamma_\phi > \gamma_E$ as given by Eq. 5.

III. Experimental Results

In the following we show data from the X-mode reflectometer system on TFTR. The data was obtained during Ohmic and high neutral beam power operation. Typical plasma parameters are $B_T = 45\text{ kG}$, $I_p = 1.6\text{ MA}$, $n_e(0) = 6.5 \times 10^{13}\text{ cm}^{-3}$, and major radius of 260 cm . The correlation measurements were obtained using a fixed frequency 122 GHz channel and a tunable 110-123 GHz channel which was stepped in frequency every 32ms. A scan

of the tunable channel over ~ 4 GHz was obtained in ~ 240 ms for both the ohmic and beam phase of the discharge. By use of quadrature detectors, we measure a signal proportional to the complex amplitude E . Fig. 6 shows the frequency spectra for the ohmic and beam phase of the discharge. The ohmic data are taken in the central region of the plasma where the fluctuations are very small while the neutral beam data are taken in the outer region of the plasma where the fluctuations are known to be very large. The coherent reflection clearly observed in the ohmic phase is no longer present in the beam phase. The frequency spectrum has also dramatically broadened over that of the ohmic spectrum, but this can partially be attributed to strong plasma rotation. The loss of coherent reflection is also accompanied by strong amplitude fluctuations as shown in Fig. 7 where the complex signal $E(t)$ is plotted over a 10ms time window for the ohmic and beam heated cases. While the amplitude fluctuations during the ohmic phase are small compared to the mean amplitude, during the beam phase the amplitude fluctuations greatly increase and the central region of the plot completely fills up. From the preceding section the loss of a coherent reflection is evidence for a transition from weak to strong scattering while the large amplitude fluctuations indicate that the detector is far from the image plane. The spectrum of the phase during ohmic and beam operation are shown in Fig. 8. For the ohmic spectrum we obtain an rms phase fluctuation level of 0.25, corresponding to a density fluctuation level at the cutoff of $\approx 0.1\%$. The fluctuation level inferred from these measurements is consistent with the weak scattering limit. On the other hand, we obtain a clear $1/f^2$ spectrum for the phase during high beam power operation, as predicted by the numerical model for large fluctuation levels and distances greater than the diffraction scale length of the phase screen. The $1/f^2$ spectrum extends down to the lowest resolved frequencies, indicating that the phase does not possess a stationary well defined magnitude and that the characteristic frequency of the phase fluctuations is determined by the size of the time window. From Fig. 9, for the ohmic case we obtain $\gamma_E \approx \gamma_\phi$ and correlation lengths of order 4-5cm. The long correlation length compared to the free space wavelength of ≈ 2 mm is consistent with the assumption of geometric optics and the equivalence of the phase correlation and complex amplitude correlation is consistent with the weak scattering limit or Born approximation for the phase screen. In contrast, Fig. 10 shows that the correlation length of the complex amplitude during neutral beam operation is now much shorter than in the ohmic case. Also, we obtain a phase correlation at the receiver which is of the order of the free space wavelength of the probe beam and much shorter than the correlation length of the complex amplitude. These results are in conformity with numerical predictions based on the random phase screen model for strong fluctuations measurements far from the image

plane. In this limit phase measurements are not consistent with the phase of geometric optics and cannot be used to infer the spectral characteristics of turbulent density fluctuations in the plasma. Note that from a simple consideration of plasma turbulence, given the experimental data available from other diagnostics, it is highly unlikely that very large amplitude low frequency modes can exist in a rapidly rotating plasma with correlation lengths of the order of 2-3mm.

Finally, we show that even in the case of strong turbulent fluctuations, reflectometry is still capable of measuring very long wavelength coherent mode activity in tokamak plasmas. In Fig. 11 the phase spectrum for reflectometer measurements taken during high power Deuterium-Tritium operation on TFTR is shown together with the spectrum of the complex amplitude. As is usual during high beam power operation on TFTR, we observe strong amplitude fluctuations, large frequency shifts due to plasma rotation and antenna misalignment, loss of a coherent reflection and a strong $1/f^2$ phase spectrum which extends down to the lowest resolved frequency in the data record. However, we are still able to measure with excellent spatial resolution and phase sensitivity the fluctuations associated with long wavelength coherent mode activity on TFTR. Note that the coherent mode which is clearly observed on the phase spectrum at $\approx 20\text{kHz}$ is not at all observed on the spectrum of the complex amplitude. These results have been confirmed numerically for model calculations of coherent long wavelength modes superimposed on a background of random poloidally varying fluctuations. Comparison with coherent mode measurements taken using the far infrared interferometer on TFTR indicates that reflectometer phase measurements are generally consistent with 1D geometric optics for very long wavelength modes. This result is fully consistent with the phase screen model, as for very long wavelength modes the receiver is always located in the near field of the fluctuations and so the phase at the receiver is given by 1D geometric optics.

IV. Conclusion

We have shown that microwave reflectometry on tokamak plasmas can be used to infer the correlation length of turbulent fluctuations when the fluctuation level is sufficiently small or when the receiver is located at the image plane for strong fluctuations. Simulations of the random phase screen model have predicted a wide range characteristics of reflectometer measurements on tokamak plasmas such as loss of coherent reflection, large amplitude fluctuations, and very short correlation lengths. In particular we have shown that when large amplitude fluctuations are observed at the receiver, then the phase cannot be interpreted as the phase of geometric optics and cannot

be used to infer the characteristics of the turbulent fluctuations in the plasma. Finally, even in the case of strong scattering and large amplitude fluctuations at the receiver, long wavelength coherent mode activity can still be observed from phase measurements. Further progress in the development of fluctuation reflectometry will require large aperture optics and wide angle phase sensitive detectors in order to image the cutoff.

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Figure Captions

Fig. 1

Shifted Gaussian frequency spectrum of randomly generated phase screens.

Fig. 2

Simulation results of spectrum of complex amplitude in the case of weak fluctuations $\sigma_\phi=0.35$ (top) and strong fluctuations $\sigma_\phi=3.5$ (bottom).

Fig. 3

Simulation results of amplitude fluctuations $|E(t)|$ at the observer plane for the case of weak fluctuations $\sigma_\phi = 0.35$ (top) and strong fluctuations $\sigma_\phi = 3.5$ (bottom).

Fig. 4

Simulation results of the spectrum of phase fluctuations at the observer plane for the case of strong fluctuations $\sigma_\phi = 3.5$ (top curve) and for weak fluctuations $\sigma_\phi = 0.35$ (bottom curve). Strong fluctuations lead to a $1/f^2$ phase spectrum for measurements performed away from the phase screen.

Fig. 5

Simulation results of the phase screen correlation (solid line) compared to the correlation of complex amplitude γ_E and the correlation of the phase γ_ϕ at the observer plane for weak and strong fluctuations. For small fluctuations $\sigma_\phi=0.35$, γ_E and γ_ϕ are identical (solid triangles) and equivalent to the phase screen correlation (solid line) with a $1/e$ point of ≈ 2 cm. However, for strong fluctuations $\sigma_\phi=3.5$, the $1/e$ point of γ_E (open triangles) is 0.6 cm while the $1/e$ point of γ_ϕ (open squares) is ≈ 0.2 cm, close to the free space wavelength of the probe beam at $\lambda_0 \approx 0.25$ cm.

Fig. 6

Spectrum of complex amplitude in the case of weak fluctuations (top) and strong fluctuations (bottom). The case of weak fluctuations corresponds to the core of an ohmic plasma with $\sigma_\phi=0.25$ corresponding to $\approx 0.1\%$ density fluctuations. Spectrum of complex amplitude in high power neutral beam plasma (bottom), shows effects of strong fluctuations such as loss of a coherent reflection and spectral broadening.

Fig. 7

Plot of complex amplitude in ohmic (left) and neutral beam plasma (right) over a 10 ms time window, showing transition from small to large amplitude fluctuations at the receiver. Large amplitude fluctuations on the right are indicated by the filling up of the central region of the plot around $E \approx 0$.

Fig. 8

Phase spectrum in ohmic plasma (lower curve) and phase spectrum in neutral beam plasma (top curve). The $1/f^2$ phase spectrum for the neutral beam case extends down to the lowest resolved frequency in the data, consistent with measurement performed beyond the image zone of a strong phase screen.

Fig. 9

Coherence of complex amplitude γ_E (black dots) coincides with the phase coherence γ_ϕ (white dots) plotted as a function of the cutoff layer separation taken in the core region of an ohmic plasma. The l/e point is ≈ 4 cm, which is much longer than the free space wavelength of the probe beam with $\lambda_0 \approx 0.26$ cm.

Fig. 10

Coherence of complex amplitude γ_E (open triangles) and phase γ_ϕ (open squares) as a function of the cutoff layer separation in the case of strong fluctuations in high neutral beam power plasmas. $\gamma_\phi < \gamma_E$ is inconsistent with the assumption of 1D geometric optics for the phase.

Fig. 11

Coherent long wavelength modes in a strong turbulent background observed in the phase spectrum (top) during DT experiments on TFTR. The phase spectrum shows a clear $1/f^2$ behavior, with a coherent mode peaking two orders of magnitude above the background. The spectrum of the complex amplitude (bottom) shows no sign of coherent mode activity, consistent with the RPSM for a uniform coherent mode superimposed on a background of strong random poloidally varying fluctuations.

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