CORE DENSITY FLUCTUATIONS IN REVERSE MAGNETIC SHEAR PLASMAS WITH INTERNAL TRANSPORT BARRIER ON JT-60U

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Abstract

First measurements of the radial correlation length of density fluctuations in JT-60U plasmas with internal transport barrier (ITB) is reported. The measurements are obtained using a newly installed correlation reflectometer operating in the upper X-mode. Before transport barrier formation in the low beam power current ramp-up phase of the discharge, reflectometer measurements indicate density fluctuation levels ñ/n~0.1-0.2% and radial correlation lengths 2-3 cm ($k_r\rho_i \leq 0.5$) in the central plasma region (r/a<0.3). A rapid increase (ñ/n~0.5%) in the density fluctuation level is observed within 50 ms of the turn on of high power neutral beam injection during formation phase of the internal transport barrier (ITB). Inside the ITB, the radial correlation length of density fluctuations is short (~0.5cm at r/a~0.57) corresponding to $k_r\rho_i$~3. However, fluctuation levels are considerably higher than measured near the magnetic axis. Reflectometer measurements obtained at the foot of the ITB also indicate high fluctuation levels compared to measurements in the central region of the discharge.

1. INTRODUCTION

Stabilization of long wavelength microinstabilities through ExB velocity shear is thought to be a key element of most regimes of improved confinement in fusion plasmas. [1] As these regimes typically exhibit strong pressure gradients in the region of reduced transport, it is natural to ask whether the corresponding large ExB shearing rates play a decisive role in maintaining the transport barrier. This question has been central to much of the work in plasma transport over the last decade, and many elegant experiments have been performed to assess the causal or central role of ExB velocity shear in transport barrier dynamics [2] and other enhanced confinement regimes. The recent discovery of rapid transitions to enhanced core confinement with intense auxiliary heating on large tokamaks has strongly reinforced the idea that ExB velocity shear is crucial to achieving improved plasma confinement. Given the central importance of this physically intuitive picture of transport reduction, it is essential that we confirm the details of the model by direct measurement of the local correlation function of turbulence in regimes of improved confinement. It is also important to determine whether fluctuation suppression (if observed) is a natural consequence of the stabilization of long wavelengths modes. Here, most theoretical and experimental investigations suggest that the dominant drift type modes considered responsible for anomalous transport occur in the range $0.1<k_r\rho_i<0.5$ in the absence of ExB velocity shear. [3-5]

Previous studies have shown local fluctuation suppression and turbulence decorrelation in the edge region of H-mode discharges on DIII-D [6,7], JFT-2M [8] and elsewhere. Obtaining the same level of spatial resolution is more challenging for internal transport barriers and thus far there has been no direct measurement of correlation lengths inside a core transport barrier. However, single channel reflectometer measurements in TFTR indicate strong fluctuation suppression in the transition to the enhanced reverse shear regime. [9] A similar result has been obtained using the larger scattering volume of FIR measurements on DIII-D. [10] The advantage of the latter technique is its ability to survey the volume integral fluctuation behavior of the discharge.

A new initiative has been started on JT-60U aimed at measuring the local turbulence characteristics in the core region of internal transport barriers. The first step in this initiative was the installation and successful operation of a core reflectometer diagnostic as part of the PPPL/JAERI collaboration program. The key question this measurement aims to address is whether the scale length of fluctuations in the ITB region decreases as expected based on simple arguments of ExB velocity shear and whether there is a wide region of turbulence suppression extending out from the plasma center.

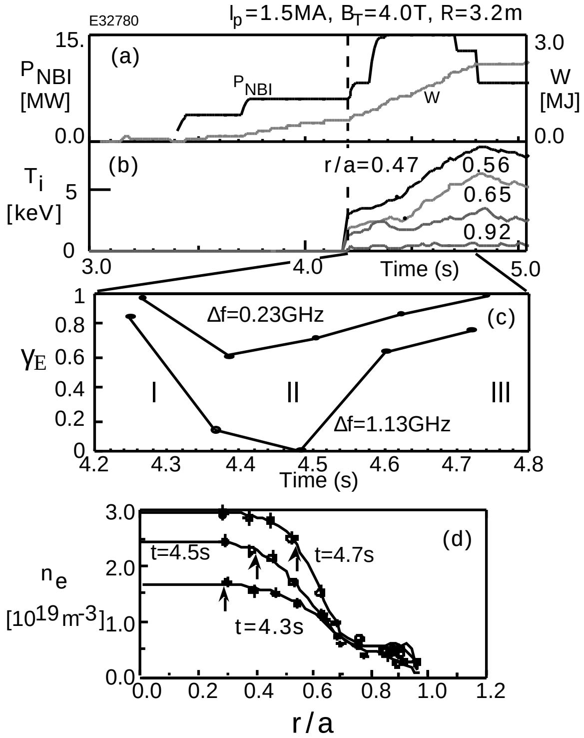

FIG. 1. Time evolution of (a) beam power and stored energy, (b) ion temperature in region of ITB, (c) evolution of reflectometer coherence for two frequency separations and (d) electron density profiles during ITB formation. Vertical arrows mark location of 115 GHz reflecting layer.

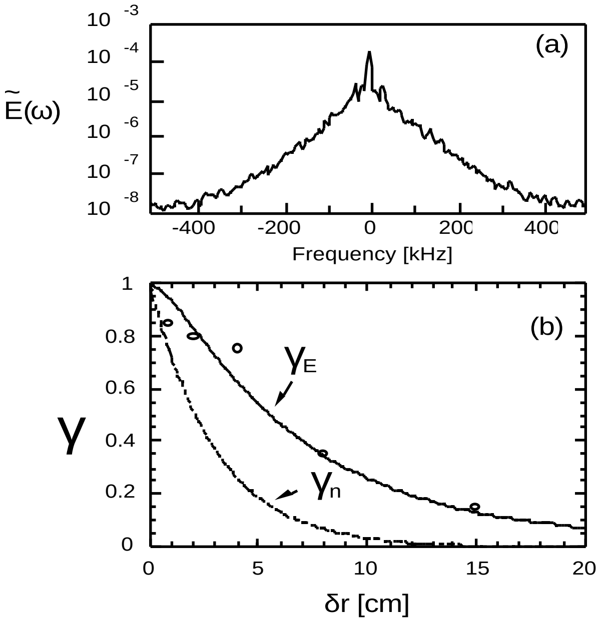

Fig. 2. Signal spectrum in phase I (t≈4.2s) before high power beam injection (a) and radial correlation of signals (b). Fitting to the signal correlation gives: ñ/n≈0.1% and Δr≈3.

The instrument uses the frequency dependence of the X-mode cutoff to measure correlations in the reflected field from two positions in the plasma. The relative spacing of these layers is easily tuned by varying the microwave frequency, thus enabling the measurement of the radial correlation of turbulent fluctuations. The relationship between the reflected microwave field and plasma density fluctuations is straight forward in the case when the amplitude of fluctuations on the reflected waves is sufficiently weak and a clear specular reflection is observed. [11] This is generally the case relating to measurements made in the central region of the discharge and in the ITB region of JT-60U plasmas. The reflectometer system operates between 105-140 GHz and takes radial correlations every 60 ms by continuously switching microwave frequencies.

2. CORE FLUCTUATION MEASUREMENTS

Figure 1 shows the evolution of the reflectometer coherence (for two different frequency separations) together with the evolution of the core density profile and ion temperature near the radius of the ITB. High power neutral beam injection starts at 4.3 s, with the following discharge condition: B=4.0 T, I_p~1 MA (current ramp-up), R=3.25 m, P_{NBI}=8-15 MW. Beam injection in the current ramp-up phase allows strong reverse shear profiles to be generated, with large radius internal transport barrier following high power beam injection. A unique feature of reverse shear plasmas on JT-60U is the large radius of q_{min} (r/a~0.7), large radius of internal transport barrier and flat pressure profiles extending from the plasma center to the shoulder of the transport barrier. [12]

The loss of coherence between reflectometer channels within 50 ms of high power beam injection (Fig. 1c) is a characteristic feature of reverse shear discharges during ITB formation. The loss of coherence is accompanied by a rapid increase in the fluctuation level (as inferred from reflectometer measurements in the plasma core). However, a high level of coherence is again recovered in the ITB, partly because of the smaller separation of the cutoff layers with the increasing density gradient. The changing position of the reflecting layer from the center to the ITB region is marked by vertical arrows in Fig. 1d. The period of interest is divided into three segments: part I refers to pre ITB formation, phase II to the formation phase and phase III to the sustainment phase which extends into the low beam power postlude of the discharge.

Figure 2 shows the measured radial correlation between two reflectometer channels as a function of the spatial separation of reflecting layers. The correlation is taken in the early phase of the discharge before high beam power injection at r/a≈0.3 in phase I. This forms our baseline case which we compare with measurements taken in the ITB in the reduced beam power postlude of the discharge. The symmetry of the signal spectrum in Fig. 2a indicates good alignment to the reflecting layer, and the presence of a coherent reflection at zero frequency indicates that the reflectometer measurement is not saturating. The radial correlation scan in Fig. 2b is taken in a 60 ms interval and the signal coherence (γ_E) is fit by assuming an exponential function for the density correlation ($\gamma_n \sim \exp(-|r|/\Delta r)$). [11] The fit to the data is extremely good, suggesting that the exponential correlation function is a very good approximation for core turbulence. The resulting estimate of the radial correlation length of the density is ≈4.5 cm so that $k_r\rho_i \sim 0.35$ for Ti≈5 keV at the point of measurement assuming the correlation length $L_r = \langle r^2 \rangle^{1/2} = (2\Delta r^2)^{1/2}$ ($k_r = 2\pi/L_r$) for an exponential function. The range of $k_r\rho_i$ is similar to measurements taken in the core region of hot ion mode and L-mode discharges in TFTR [3,4] and is consistent with theoretical estimates of the spectrum of the most unstable modes. [5]

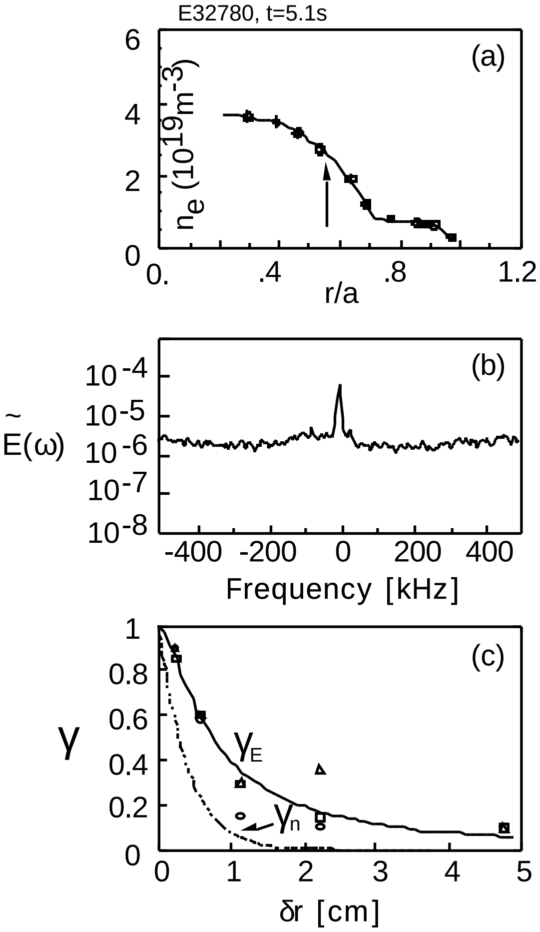

Fig. 3. Density profile and cutoff layer position in phase III (t≈5.1s) marked by arrow (a), frequency spectrum of signal showing good coherent reflection (b) and radial signal correlation (c). Fitted signal correlation gives: ñ/n≈0.5% and Δr≈0.5 cm.

After the initial burst of fluctuations with degraded signal coherence in phase II, the coherence level again rises as the correlation channels enter the region of the ITB. A unique feature of the ITB in JT-60U is the rapid dip of the effective thermal diffusivity and its strong increase outside of the pressure gradient region. From local transport analysis, improved confinement extends throughout the sharp gradient region of the profile (r/a~0.5-0.7). [13] Figure 3a shows the density profile after ITB formation in phase III along with the location of the reflecting layer marked by an arrow. The signal spectrum in Fig. 3b indicates a coherent reflection and no saturation of the reflected signal. From the radial coherence data in Fig. 3c the reflectometer signal correlation is again very well fit by an exponential function for the density. The inferred density correlation function is given by the dashed curve with a correlation length ≈0.5 cm. This value is considerably shorted that the one obtained outside the ITB early in the discharge evolution and corresponds to $k_r\rho_i \approx 3$. The corresponding fluctuation level is ñ/n≈0.5% which is considerably higher than the value measured near the center of the discharge. The high wavenumber of the fluctuations (≈12 cm^{-1}) is well above values measured on other devices in the L-mode and hot ion regimes, and is considerably higher than expected from theoretical estimates of the most unstable modes in the abscence of ExB shear. Figure 4 shown the radial profile of the density fluctuation level after ITB formation. The fluctuation levels were estimated assuming $0.5 \le k_r\rho_i \le 5$, as correlation measurements are not available at all radii. The shaded region indicates the typical radial extent of the ITB. From this data it is apparent that a low uniform level of fluctuations does not extend from the center of the plasma to the ITB. The data suggests that there is a fluctuation profile in the core of large radius ITB plasmas on JT-60U, with no clear reduction to central values in the ITB region. However, correlation lengths have been measured in the ITB and are found to be very short - essentially at the resolution limit of the reflectometer (approximately 2x the free space wavelength to avoid Bragg reflection: ≈4mm). Measurements at the foot of the barrier also indicate a high level of scattering of microwaves which is suggestive of large fluctuation levels. However, correlation measurements at the foot of the barrier near r/a=0.7 are not currently available.

III. DISCUSSION

Radial correlation lengths near the limit of the resolution of the reflectometer diagnostic have been measured in the ITB region of JT-60U. These measurements also indicate that the absolute fluctuation level in the ITB is not particularly small (ñ/n~0.5%) compared to the level observed in the central region of the discharge (~0.1-0.2%). Is this picture consistent with the standard model of **ExB** suppression of turbulence? Linear stability analysis using the FULL code [13] indicates that the maximum linear growth rate actually occurs in the ITB of JT-60U with very weak growth rate outside the ITB, presumably due to the weak pressure gradients in the central region of the discharge. The calculated ExB shearing rate is of the order expected to affect the dominant micro-instabilities, so that some ExB shear stabilization should be expected. A second issue is whether the fluctuation profile inside the radius of the ITB can be responsible for the very flat pressure profiles which extend to the shoulder of the ITB. The correlation length of the fluctuations in the shoulder region immediately outside of the ITB needs to be measured in future experiments. Finally, the rapid decorrelation of reflectometer signals immediately after high power beam injection during ITB formation (phase II) needs to be studied more carefully. We can only speculate that fluctuation induced flows may play a role in the decorrelation of the signal [14] and possibly trigger the transition to enhanced confinement going from phase II to phase III.

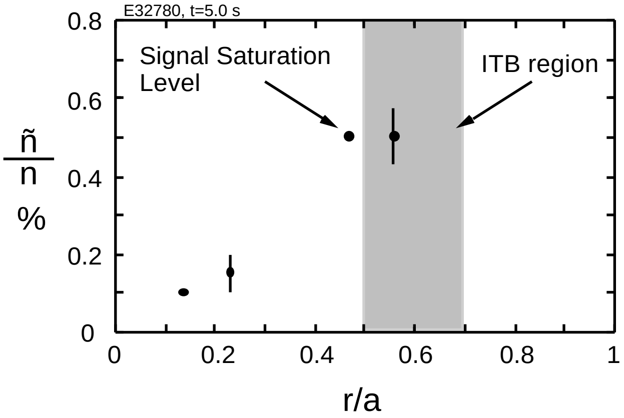

Fig. 4. Inferred local fluctuation level in the central region of the discharge which indicates that the level increases out from the center of the plasma into the ITB. Correlation length in ITB region is very short (≈0.5 cm).

Acknowledgment

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