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Edge Turbulence Imaging on NSTX and Alcator C-Mod*

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1. Introduction:

Edge turbulence images have been made using an ultra-high speed CCD camera on both NSTX and Alcator C-Mod. In both cases the D_α or HeI (587.6 nm) line emission from localized deuterium or helium gas puffs was viewed along a local magnetic field line near the outer midplane. Fluctuations in this line emission reflect fluctuations in n_e and/or T_e through the atomic excitation rates, which can be modeled using the DEGAS-2 code. The 2-D structure of the measured turbulence can be compared with theoretical simulations based on 3-D fluid models.

2. Gas Puff Imaging Diagnostic:

The diagnostic set-up and first results from "gas puff imaging" (GPI) have been presented elsewhere [1-3]. In this paper we discuss images which were made using an ultra-high speed Princeton Scientific Instrument CCD camera with a gating time of 10 μsec per frame for NSTX and 4 μsec per frame for C-Mod. These images clearly show the effects of edge turbulence on the light emission from these neutrals. If the fluctuations in electron density and temperature are in phase, as expected theoretically [4-6] and seen with Langmuir probes [7], then these 2-D images are at least qualitative representations of the space-time structure of these fluctuating fields. Analysis of the atomic excitation rates in these edge plasmas using DEGAS-2 shows that near the peak of the D_α light emission in C-Mod, the local emissivity varies as $S \propto n^{0.6} T_e^{0.5}$ [8], and near the peak of the light emission of HeI(587.6 nm) in NSTX the local emissivity varies as $S \propto n^{0.7} T_e^{0.5}$. Details concerning the GPI diagnostic technique and its interpretation will be described in [9].

3. Images from NSTX and Alcator C-Mod:

A typical set of 28 sequential images of edge turbulence in NSTX taken with a HeI (587.6 nm) filter viewing a He gas puff near the outer midplane is shown in Fig. 1. The framing rate is 100,000 frames/sec and the exposure time for each frame is 10 µsec/frame. The viewing area is ≈ 30 cm x 15 cm in each frame, with the magnetic separatrix running approximately from the upper left to the lower right corner and the He gas puff and outer wall toward the lower left corner. This discharge (#108164) is an Ohmic plasma with I_p=0.8 MA, B_o=3.0 kG, a line averaged density of n≈3x10^{13} cm^{-3} and an aspect ratio A=1.3. Qualitatively similar images were obtained in a variety of Ohmic and L-mode discharges using either He puffs viewed with a 587.6 nm filter or D_2 puffs viewed with a D_α filter.

A typical set of 12 sequential images of edge turbulence in Alcator C-Mod taken with a D_α(656.2 nm) filter viewing a D_2 gas puff near the outer midplane is shown in Fig. 2. The framing rate is 250,000 frames/sec and the exposure time for each frame is 4 µsec. The viewing area is ≈ 6 cm x 6 cm, with the magnetic separatrix running approximately vertically through the center of the image and the D_2 gas puff and outer wall toward the left. This discharge (#1010720006) is an Ohmic plasma with I_p=0.95 MA, B_o=53 kG, and a line averaged density of n≈ 3x10^{14} cm^{-3} with an aspect ratio A=3.2. Qualitatively similar images were obtained in a variety of Ohmic and L-mode discharges using either D_2 puffs viewed at in D_α or He puffs viewed with a 587.6 nm filter.

Both Fig. 1 and Fig. 2 show show complex patterns which vary randomly in time and space. The timescale for these variations is typically ≈ 20-30 µsec in NSTX and ≈10-20 µsec in C-Mod, corresponding to the autocorrelation time of the light emission fluctuations at a point in these images. The spatial scale for these variations is ≈ 3-7 cm in NSTX and ≈ 0.6-1.2 cm are C-Mod, which are typical of density turbulence correlation lengths in such devices. The frequency spectrum of the GPI light emission fluctuations in C-Mod closely matches the frequency spectrum of ion saturation current fluctuations in a Langmuir probe at that radius [3].

The only qualitative change in these images occurs during the ELM-free H-mode in NSTX, when the GPI light emission can become highly localized within a ≈2-3 cm wide radial band just inside the separatrix. This is most likely due to edge profile steepening in H-mode, which causes the He line emission to narrow compared with its ≈ 10 cm wide radial extent in Ohmic and L-modes plasmas (as in Fig. 1). This narrowing is not seen during H-modes in C-Mod, most likely because the edge density is higher in C-Mod and the neutral gas does not penetrate into the steep gradient region, but remains largely with the SOL where the turbulence does not change significantly during H-mode.

4. Comparison with Theory and Simulation:

In principle the GPI results can be directly compared with numerical simulations of the 2-D structure of edge turbulence. However, raw images such as shown in Figs. 1 and 2 are sensitive to both electron density and temperature fluctuations (see Sec. 2), and also possibly to neutral density fluctuations due to radial "shadowing" [8]. Therefore rigorous comparisons should be made by either converting the raw images into actual density or temperature distributions, or (more easily) by converting the theoretical simulations into images of the expected GPI light emission patterns using a neutral transport and atomic physics code. The latter approach is being developed for interpreting the 2-D spatial structure using the time-independent DEGAS 2 code [8].

However, as a first approximation we can tentatively assume that the space-time structure of the raw images is similar to that of the edge turbulence itself [3]. Under this assumption, the most significant difference between the edge turbulence in NSTX and C-Mod is the spatial size of the "blobs" (i.e. localized maxima of the light emission), which appear to be $L_B \approx 5$ cm in NSTX and $L_B \approx 1$ cm in C-Mod. These scales are roughly consistent with the drift-wave-like trend seen previously as $k_\perp \rho_s \approx 0.1$[10] (within a factor-of-two), since $\rho_s \approx 0.03$ cm in C-Mod and $\rho_s \approx 0.3$ cm in NSTX, with $< k_\perp > \approx 3/L_B$.

From a theoretical perspective, the size scale of edge turbulence may be related to the resistive ballooning mode scale length [11], which for C-Mod is $L_o \approx 0.2$ cm and for NSTX roughly $L_o \approx 2$ cm, while the SOL turbulence may be driven by flute-like interchange modes [12]. However, it is difficult to explain the size scale based on linear instability theory since these structures, in particularly the "blobs" [13], are highly non-linear.

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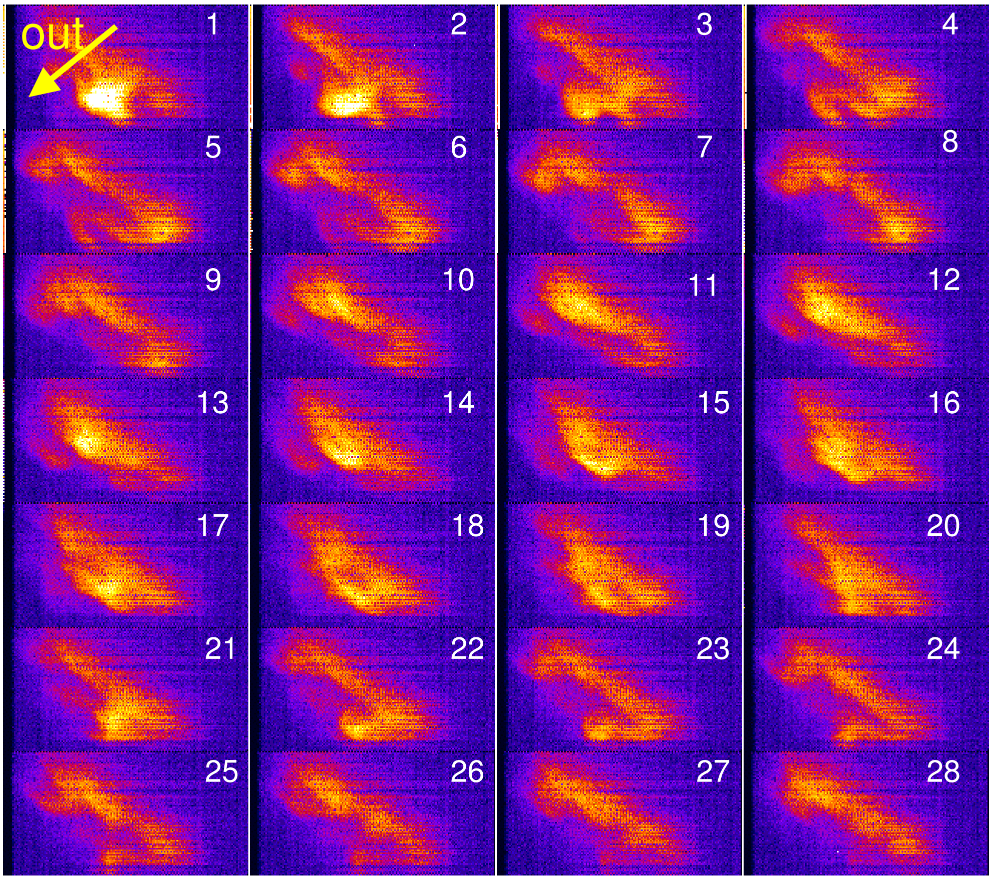

Fig. 1: Edge turbulence images from NSTX at 100,000 frames/sec showing a region ≈ 30 cm x 15 cm near the outer midplane with the outer wall toward the lower left corner.

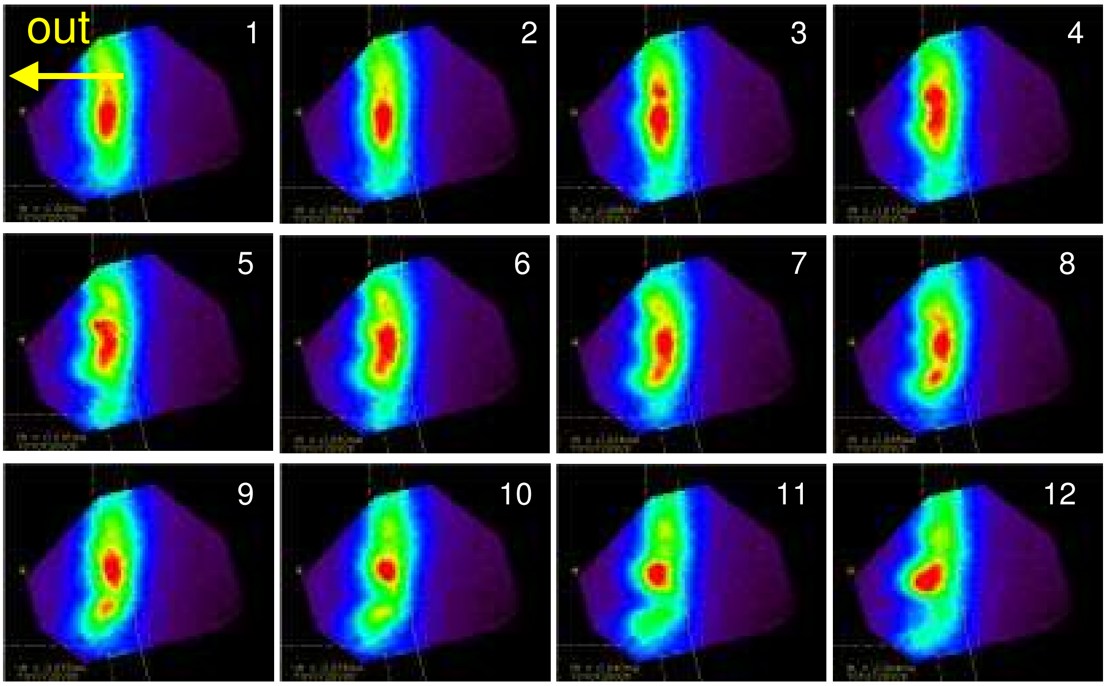

Fig. 2 – Edge turbulence images from Alcator C-Mod at 250,000 frames/sec showing a region ≈ 6 cm x 6 cm near the outer midplane with the outer wall toward the left.