Simulations of Boundary Turbulence in Tokamak Experiments*

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Abstract. Comparisons between the boundary plasma turbulence observed in the BOUT code and experiments on C-Mod, NSTX, and DIII-D are presented. BOUT is a 3D non-local electromagnetic turbulence simulation code which models boundary-plasma turbulence in a realistic divertor geometry using the modified Braginskii equations for plasma vorticity, density, the electron and ion temperatures and parallel momenta. Many features of the Quasi-Coherent (QC) mode, observed at high densities during enhanced D-alpha (EDA) H-Mode in Alcator C-Mod, are reproduced in BOUT simulations. The spatial structure of boundary plasma turbulence as observed by gas puff imaging (GPI) from discharges on NSTX and C-Mod are in general (NSTX) to good (C-Mod) agreement with BOUT simulations. Finally, BOUT simulations of DIII-D L-mode experiments near the H-mode transition threshold are in broad agreement with the experimental results.

1. Introduction

Direct numerical simulation provides a new means of studying the strong boundary turbulence observed in tokamaks and other magnetic confinement devices. Numerical simulations are more easily diagnosed, and provide greater scope for parameter variations than the corresponding experiment. However, such simulations are most interesting insofar as they are able to reproduce the phenomena observed in magnetic confinement devices. Hence, the critical first task is to demonstrate that this is the case by benchmarking numerical simulation models against experiment. In this paper we present comparisons between the boundary plasma turbulence observed in the BOUT code and experiments on C-Mod, NSTX, and DIII-D.

BOUT is a 3D non-local electromagnetic turbulence simulation code [1] which models boundary-plasma turbulence in a realistic divertor geometry using the modified Braginskii equations for plasma vorticity, density (n_i), the electron and ion temperatures (T_e, T_i) and parallel momenta. The BOUT code evolves these nonlinear plasma fluid equations in a 3D toroidal segment which includes a region inside the separatrix (the edge plasma); the neighboring region outside the separatrix and extending down to the divertor plate (the plasma scrape-off layer, or SOL); and the private flux region between the divertor strike points and the x-point. Data from BOUT simulations are saved and later analyzed with the

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*This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48 at LLNL, by MIT under Contract No. DE-FC02-99ER54512, by General Atomics under Contract No. DE-AC03-99ER54463, by PPPL under Contract No. DE-AC02-76CH03073, by LANL under contract NO. W-7405-ENG-36, and grants DE-FG03-01ER54615 at UCLA, DE-FG03-95ER54294 at UCSD, and DE-FG03-96ER54373 at the University of

GKV post-processor to obtain fluctuation spectra, two-point correlation functions (including correlation times and lengths), bispectra, etc.

2. The Quasi-Coherent Mode in C-Mod

Many features of the Quasi-Coherent (QC) mode, observed at high densities during enhanced D-alpha (EDA) H-Mode in the Alcator C-Mod tokamak, are reproduced in BOUT simulations, where the QC mode is identified as a form of resistive ballooning mode known as the resistive X-point mode [2]. The QC mode frequency in BOUT depends on the rate of plasma rotation at the boundary between BOUT's edge plasma and the plasma core (a boundary condition for the BOUT simulations). The experimentally observed QC mode frequency is obtained with a reasonable choice for this boundary condition (E_r=22 kV/m at the BOUT/plasma core boundary about 1cm inside the separatrix at C-Mod's outboard midplane). The dependence of the QC mode frequency on the plasma rotation rate at the BOUT/plasma core boundary suggests that the experimentally observed evolution of the QC mode frequency (over times much longer than the BOUT simulations) reflects changes in the plasma rotation rate on the momentum confinement time-scale. The BOUT simulations reproduce the wavenumber of the QC mode (as observed by PCI, wall-mounted magnetic coils, Langmuir probes and scanning magnetic probes) as well as the generally coherent nature of the mode, the *rms* fluctuation levels of the density (as observed by Langmuir probes and reflectometry) and magnetic field (as observed by magnetic probes) [2].

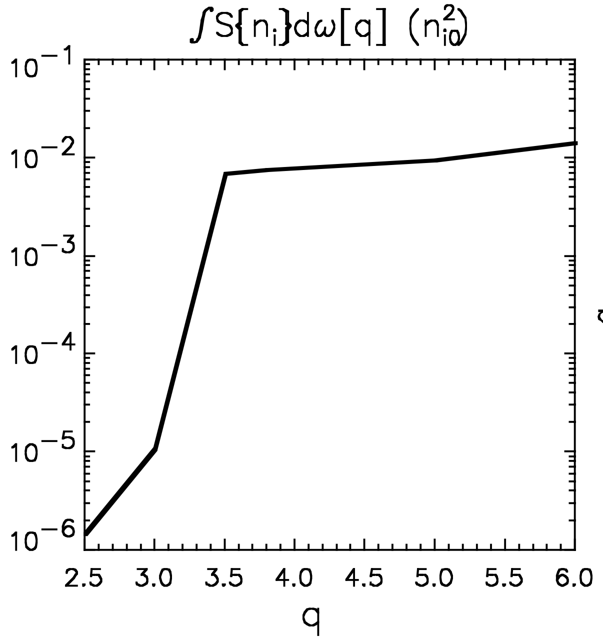

Figure 1a. *Intensity of low frequency (f < 320 kHz) density fluctuations from BOUT simulations of QC-mode. Note cut-off for* $q_{95}<3.5$.

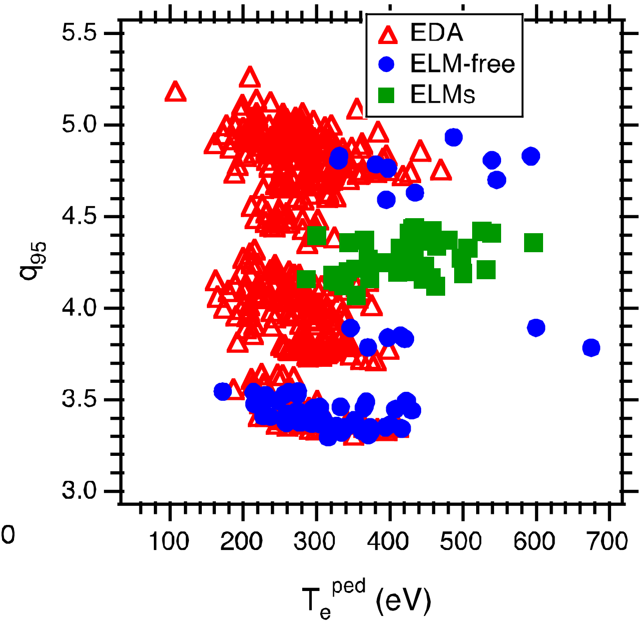

Figure 1b. q_{95} *vs.* T_{ped} *for C-Mod shots with QC-mode (open triangles) and without QC-mode (solid circles and squares).*

A sequence of BOUT simulations was performed for $2.5 \le q_{95} \le 6.0$ while holding the pedestal density and temperature fixed at $4\text{x}10^{14}/\text{cm}^3$ and 280 eV respectively. In these simulations the amplitude of the QC-mode (seen as density fluctuations at $f < 320$ kHz) drops precipitously as the safety-factor at the plasma edge drops below $q_{95}\approx3.5$ (see Figs. 1a) without any marked change in the mode coherence. Similar behavior is seen in C-Mod experiments (see Fig. 1b).

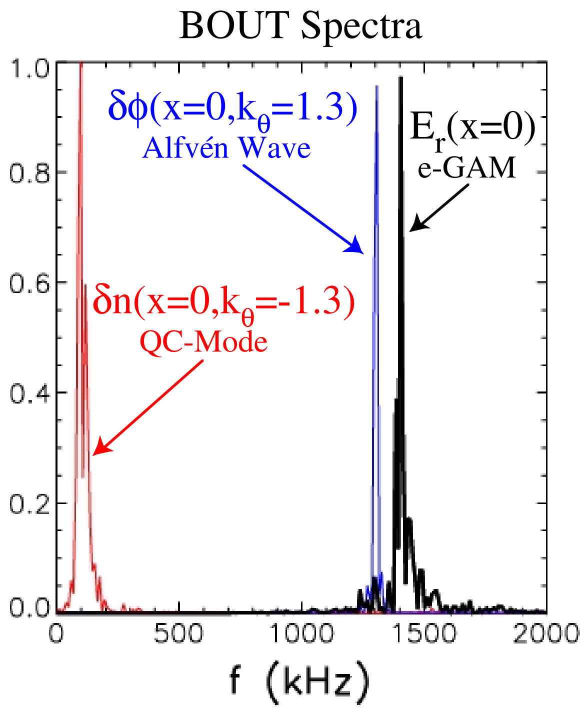

Figure 2a. *Fluctuation spectra from BOUT simulations of the QC-mode. The QC-mode is the most prominent feature in* δn*, the drift-Alfvén wave in* $\delta\phi$*, and the electron geodesic-acoustic mode in* E_r*.*

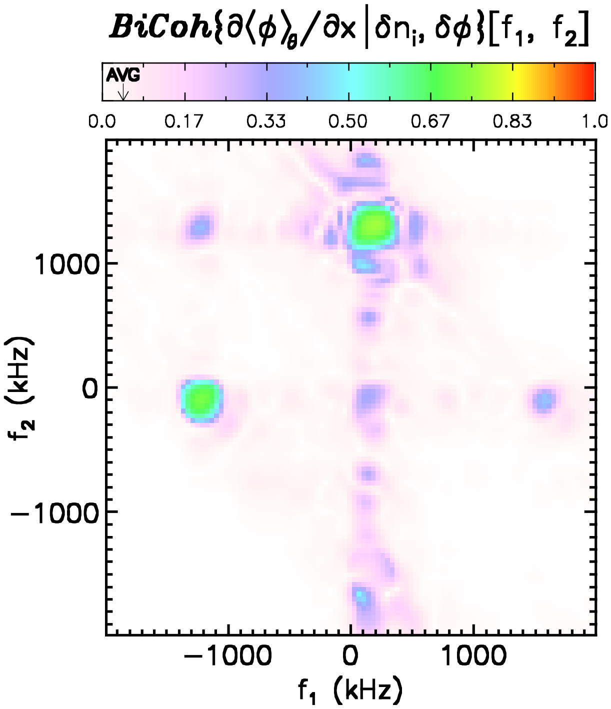

Figure 2b. *Bicoherence of an electron geodesic-acoustic mode at ~1.5 MHz, a drift-Alfvén mode at ~1.4 MHz, and the quasi-coherent mode at ~100 kHz.*

The quasi-coherent mode seen in the BOUT simulations is not linearly unstable. It appears as the linearly unstable modes saturate, suggesting that it results from non-linear mode coupling. We investigate this by computing the bicoherence, a measure of the phase coherence between modes. High (near unity) values of the bicoherence is evidence of strong mode coupling. The three strongest modes in these BOUT simulations are the QC-mode (seen most prominently as a density fluctuation), a drift-Alfvén mode (seen as a potential fluctuation) which is responsible for much of the particle flux observed in these BOUT simulations, and an electron geodesic-acoustic mode (seen as a fluctuation in $E_r=-\partial<\phi>_\theta/\partial x$), which is strongly damped. The bicoherence between these modes is 0.8 (see Fig. 2), demonstrating that that these modes are strongly coupled, and suggesting that the quasi-coherent mode saturates due to nonlinear coupling with the drift-Alfvén mode.

3. Gas Puff Imaging

The spatial structure of boundary plasma turbulence observed by gas puff imaging (GPI) [3] from Ohmic discharges on C-Mod is in good agreement with BOUT simulations. Figure 3a slices was imported into GKV and analyzed in the same manner as data from BOUT modeling of a similar C-Mod discharge. Figure 3b shows a comparison between the k-spectrum of the gas puff image and the density fluctuations from the BOUT simulations. The k-spectra from both the GPI diagnostic and the BOUT simulations show a characteristic exponential fall off with wave number (corresponding to a scale-length of 6.5 mm). This is in contrast to efforts to model the edge turbulence in C-Mod (also with a two-fluid Bragniskii model) which ignore the magnetic separatrix and scrape-off layer [4]. These later models produce power-law like fluctuation spectra [3].

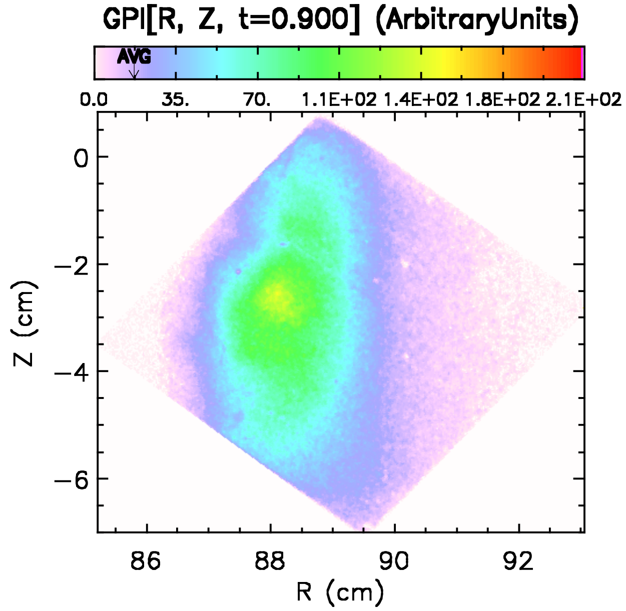

Figure 3a.. Image of light emitted from the edge of C-Mod shot #1010622006 in response to puffing gas at the plasma edge.

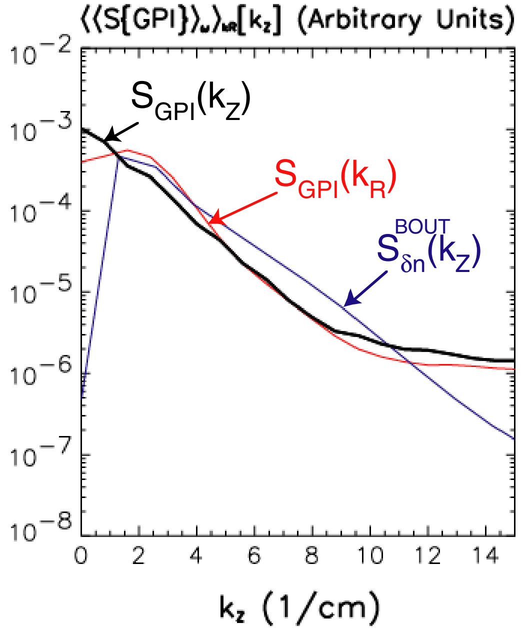

***Figure 3b.** Spectrum of the GPI data is compared with that of the BOUT simulation.*

The poloidal propagation of the fluctuations seen by the GPI is generally slower than is observed in BOUT simulations, indicating that BOUT is overstating the ExB velocity in scrape-off layer. Work is currently underway to update BOUT to include the influence of neutrals and improved the radial boundary conditions the open field-line physics in modeling the radial electric field in the scrape-off layer. Matching the propagation velocity observed in the experimental data will provide a means of benchmarking these improvements to BOUT's algorithms.

4. NSTX Modeling

BOUT simulations of boundary plasma turbulence in NSTX have been carried out. The main results specific to NSTX are: (1) The X-point geometry affects the poloidal mode structures and drift-Alfvén mode becomes robustly unstable due to low magnetic field [5]. (2) A strong poloidal asymmetry of particle flux is observed in BOUT near the separatrix. (3) The observation of radial 'streamers' at the separatrix. The spatial and temporal spectra of the turbulence in the BOUT model are in general agreement with the edge density fluctuations observed by Gas Puff Imaging in NSTX experiments [6]. Detailed comparison with results from dedicated NSTX experiments are in progress.

5. DIII-D Modeling

Finally, results from paired shots from DIII-D in which the ∇B drift is toward/away from the x-point are compared with BOUT simulations. The power threshold for L-H transition increases experimentally from 1-2 MW when the ion ∇B drift is toward the X-point to over 5 MW when it is away from the X-point. Using edge profiles from DIII-D shots with the heating power just below the H-mode transition threshold, BOUT predicts the formation of a well in the poloidal flow field when the ion ∇B drift is towards the X-point (see Fig. 4a) in SN diverted discharges. This flow-well is absent when the ∇B is directed away from the X-point, in broad agreement with the experimental results [7] (see Fig. 4b). The tendency to form a well in the poloidal flow field when the ion ∇B drift is towards the X-point may be responsible to for the lower H-Mode transition threshold in this configuration.

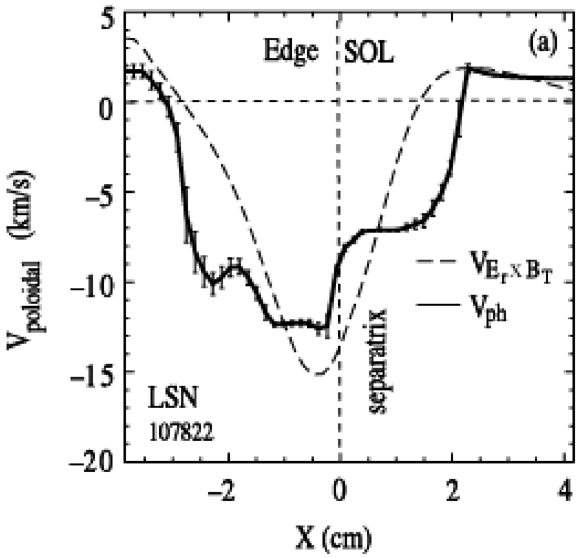

Figure 4a. *Poloidal phase velocity of fluctuations (solid line) and ExB velocity from BOUT simulation with ∇B drift directed toward the x-point.*

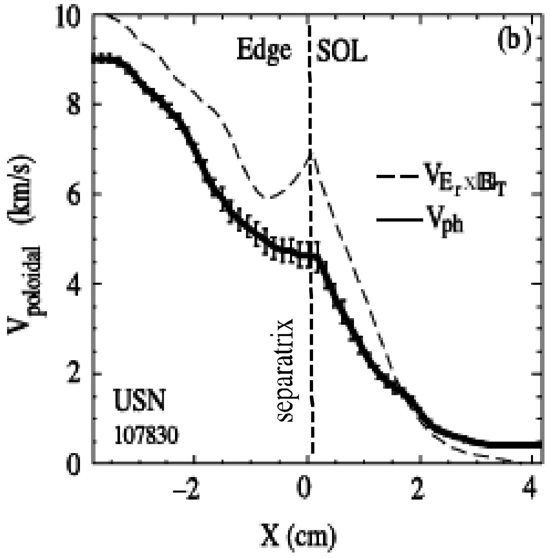

Figure 4b. *Poloidal phase velocity of fluctuations (solid line) and ExB velocity from BOUT simulation with ∇B drift directed away from the x-point.*

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