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REVIEW ARTICLE

Boundary Plasma Turbulence Simulations for Tokamaks[†]

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Abstract. The boundary plasma turbulence code BOUT models tokamak boundary-plasma turbulence in a realistic divertor geometry using modified Braginskii equations for plasma vorticity, density (n_i), electron and ion temperature (T_e, T_i) and parallel momenta. The BOUT code solves for the plasma fluid equations in a three dimensional (3D) toroidal segment (or a toroidal wedge), including the region somewhat inside the separatrix and extending into the scrape-off layer; the private flux region is also included. In this paper, a description is given of the sophisticated physical models, innovative numerical algorithms, and modern software design used to simulate edge-plasmas in magnetic fusion energy devices. The BOUT code's unique capabilities and functionality are exemplified via simulations of the impact of plasma density on tokamak edge turbulence and blob dynamics.

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Key words: Plasma turbulence simulation, plasma two-fluids equation, field-aligned coordinates, plasma blobs.

Contents

[†] Dedicated to Professor Xiantu He on the occasion of his 70th birthday.

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1 Introduction

The performance of tokamaks and other toroidal magnetic fusion devices depends crucially on the dynamics of the boundary region, i.e., the transition region from the hot core plasma through the separatrix to the material surface of the first wall, as shown in Fig. 1. Plasma turbulence, and the resulting anomalous cross-field plasma transport, are physical processes in the boundary region, affecting both core plasma confinement [e.g. high confinement mode (H-mode) and Edge Localized Modes (ELMs)], the density limit, and plasma-wall interactions [1]. The plasma boundary region has a number of physics attributes which make it quite distinct from the core: relatively low temperature, large radial gradients, and high neutral-gas and impurity densities, *proximity of open and closed flux surfaces, presence of X-point and sheath physics in the Scrape-Off-Layer (SOL).* The large radial gradients tend to drive turbulent fluctuations which are a larger percentage of background values than in the core plasma.

Strong boundary turbulence has been observed in nearly all magnetic confinement devices [2, 3]. There exist many experimental turbulence measurements in the pedestal region and in the SOL. Common diagnostics include electrostatic probes, reflectometry, phase contrast imaging (PCI), Beam Emission Spectroscopy (BES), and Gas Puff Imaging (GPI) [2]. Observed boundary turbulence has many common features, and a great deal of experimental data has been obtained over the past 20 years on e.g. fluctuation levels, spectra, correlation lengths, and scalings, but until recently this data could not be understood from first principles. The reason is simple. The diagnostics typically are limited either to local measurements in space or to particular turbulence quantities with certain working assumptions [2]. Predictive simulation of boundary turbulence from fundamental physics models is therefore an important but daunting challenge owing to the special properties of the boundary plasma, its importance to an overall understanding of fusion plasmas, and the vast range of relevant spatial and temporal scales. A critical task is to demonstrate that simulations are able to reproduce the phenomena observed in real magnetic confinement devices. With the recent development of three dimensional (3D) non-linear codes, such as BOUT, it has become possible to make a direct computation of boundary turbulence, and validating these codes with experiments has since begun [4–11]. Using well benchmarked codes at the location of a particular measurement, boundary turbulence simulations are able to validate diagnostic tools and