Partnership for Edge Physics Simulation

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Institutional PI: Arnold H. Kritz
Institutional Co-PI: Tariq Rafiq

Prepared by

Tariq Rafiq and Arnold H. Kritz

Department of Physics
Lehigh University
16 Memorial Drive East
Bethlehem, PA 18015

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Technical Final Report: Partnership for Edge Physics Simulation (EPSI)

Department of Physics, Lehigh University

Institutional PI: Arnold H. Kritz
Institutional Co-PI: Tariq Rafiq

The research carried out by the Lehigh University fusion group has included: (1) Analysis of core and edge gyrokinetic simulations of ion temperature gradient (ITG) turbulence carried out using the XGC1 code for a plasma with circular geometry[1]; (2) Analysis of ITG XGC1 simulations with impurity effects included in DIII-D geometry[2]; (3) Self-organization of tokamak turbulence fluctuations[3]; (4) Analysis of statistical properties associated with potential fluctuations, turbulence intensity, radial flow velocity, turbulence intensity flux and ion heat flux[4-6]; (5) Kinetic modeling of divertor heat load fluxes in the Alcator C-Mod and DIII-D tokamaks[7]; (6) Anomalous transport in the H-mode pedestal of Alcator C-Mod discharges[8-14]; and (7) Investigation of the plasma shaping effects on the H-mode pedestal structure using coupled kinetic neoclassical/MHD stability simulations[15-17].

The Lehigh University fusion research group has been led by Prof. Arnold Kritz. The research team included Dr. Tariq Rafiq and Dr. Varun Tangri.

(1) Analysis of ITG Turbulence Data in Circular Geometry[1]

The statistical properties of ITG turbulence data provide evidence for Self-Organized Criticality. The following quantities were computed using turbulence intensity data and ion heat flux data: (a) Speed of inward and outward propagating fronts (see Fig.1); (b) Distribution count; (c) Fraction of total ion heat flux carried by events; (d) Power spectrum; (e) Hurst parameter using both R/S and Aggregate Variance methods; (f) Skewness and kurtosis**.** The fluctuations in the deep core region were found to be self-organized, but do not possess non-Gaussian characteristics.

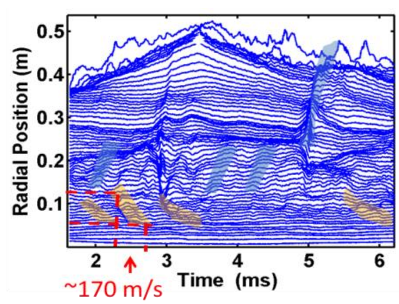

Fig.1: Propagating fronts of speed of a few hundred m/s observed in ion temperature fluctuations. Highlighted light blue bands indicate outward propagating fronts and brown bands indicate inward propagating fronts.

(2) Analysis of ITG Turbulence Data in DIII-D Geometry with Impurity Effects Included[2]

The XGC1 simulation utilized included turbulence intensity, temperature fluctuation data and ion heat flux data. The following quantities were computed for the DIII-D discharge: (a) Speed of inward and outward propagating fronts; (b) Distribution count; (c) Fraction of total ion heat flux carried by events; (d) Power spectrum; (e) Hurst parameter using both R/S and Aggregate Variance methods; (f) Skewness and kurtosis**;** and (g) Potential fluctuation characteristics for smaller scale structures in space-time (poloidal angle, radius, time).

The power spectrum $P(k)$ was found to be of the form $P(k) \sim k^{-a}$, where $a \sim 2$, and k is the wavenumber observed in the potential fluctuation data. The turbulent intensity distribution count was computed by combining data from 32 poloidal cuts thereby improving the statistical treatment. Distributions were then classified into four major types: Peaked, Gaussian, Non-Gaussian and Double-Humped. In all four types, small variations of intensity fluctuations from the mean value, as well as different inboard and outboard skewness and kurtosis of normalized potential fluctuations, were found. In order to gain further insight into the turbulent fluctuations of the radial electric field, the flux surface averaged potential and the averaged $E \times B$ flow shear were computed. The radial location of high skewness is found to coincide with the radial location of high kurtosis. It is suspected that high skewness and high kurtosis at specific radial locations may be consistent with previous observations in simulations of a meso-scale $\boldsymbol{E} \times \boldsymbol{B}$ flow 'staircase' which regulates the non-local avalanche transport [Dif-Pradalier *et. al.*, Phys. Rev. E **82,** 025401 (2010)]. The meso-scale $\boldsymbol{E} \times \boldsymbol{B}$ flow structures may open up from time to time and promote avalanche events that have a length scale that is larger than the meso-scale. The opening up of the $\boldsymbol{E} \times \boldsymbol{B}$ flow 'staircase' structures is found to occur at the normalized flux locations of 0.50 and 0.85. (The normalized flux ranges from 0 at the plasma center to 1.0 at the separatrix). It is observed that in the vicinity of the 0.50 and 0.85 radial locations, there is large skewness and kurtosis.

Prof. Kritz and Dr. Tangri attended the EPSI All Hands Meeting at Austin, TX in January 2013. Dr. Tangri also examined the XGC0 source code, compiled and ran XGC0, and developed an understanding of the algorithms used in the XGC0 code. Several trips were made to PPPL to present and discuss results with members of the PPPL EPSI Team.

(3) Self-organization of Tokamak Turbulence Fluctuations[3]

The focus of this work was on the self-organization of tokamak turbulence fluctuations to form a staircase structure in ion temperature and to demonstrate how small scale turbulence in plasmas self-organizes with dynamically driven quasi-stationary $\boldsymbol{E} \times \boldsymbol{B}$ flow shear. The study leads to a better understanding of self-organization in the core and edge turbulence in tokamak discharges.

The following features, which are not found in a local ITG model of ion thermal transport, were observed in the analysis of the XGC1 simulation data: (i) Staircase structures, *i.e.*, step-like

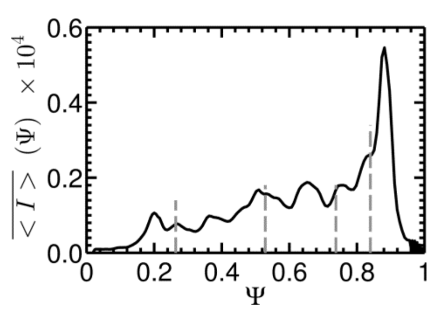

Figure 2: Time and surface averaged turbulence intensity plotted as a function of Ψ. Peaks in turbulence intensity appear in the vicinity of the dips in $\boldsymbol{R_0/L_{T_i}}$, indicated by vertical dashed lines.

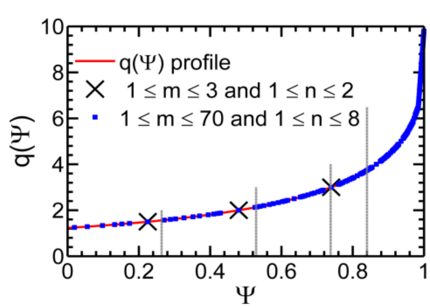

Figure 3: The $\boldsymbol{q}$-profile as a function of $\boldsymbol{\Psi}$ is plotted. Low-order rational surfaces are indicated by crosses. The vertical lines indicate $\boldsymbol{R_0/L_{T_i}}$ minima.

structures in the ion temperature profile correlated with quasi-stationary $\boldsymbol{E} \times \boldsymbol{B}$ poloidal flows, are characterized by minima in $R_0/L_{\mathrm{T_i}}$; (ii) The staircase structures lead to the emergence of a mesoscale; (iii) The electrostatic potential at staircase locations is three-dimensional, poloidally elongated, nonlocal, and is not compatible with the flux-tube paradigm; (iv) Turbulence intensity accumulates with a large amplitude in the vicinity of the local minima in R_0/L_{T_i} (indicated by vertical dashed lines in Fig. 2) in contrast to the expectation that with minima in $R_0/L_{\mathrm{T_i}}$ the linear growth rate of ITG instability is expected to be lower resulting in a decrease in turbulence; (v) Staircase structures are found to occur in the vicinity of low-order rational surfaces corresponding to the vicinity of local minima in $R_0/L_{\mathrm{T_i}}$ (indicated by vertical lines in Fig. 3); (vi) Turbulence intensity events can propagate both inward and outward between rational surfaces and; (vii) Local heat avalanches between rational surfaces may propagate up or down the mean ion temperature gradient inside the staircase structure.

Data for electrostatic potential fluctuations, turbulence intensity, radial $\boldsymbol{E} \times \boldsymbol{B}$ flow, and turbulence intensity flux versus radius was analyzed. The distribution function of turbulence intensity, turbulence intensity flux and their low and higher order moments were estimated analytically. Various statistical measures were computed: (a) Distribution count; (b) Fraction of total ion heat flux carried by events; and (c) Mean, standard deviation, skewness and kurtosis. It was observed that the potential fluctuations have a non-Gaussian distribution at staircase locations. Consequently, skewness and kurtosis of the potential fluctuations, in the vicinity of the staircase structures of the ion temperature profile, deviate from the skewness and kurtosis that one would observe if the potential fluctuations were Gaussian.

An experiment was proposed by the Lehigh group. The goal of the proposed experimental campaign is to measure quantities associated with the staircase structures. It was shown that the proposed experiment would be useful in understanding turbulence, its global self-organization, its non-local nature, and its statistical properties. Specifically, the following physical phenomena in the Alcator C-Mod (or in other existing tokamaks) can be explored: (i) Existence of the ion temperature staircase structures and its relation to dynamically driven quasi-stationary $\boldsymbol{E} \times \boldsymbol{B}$ flow shear in the vicinity of the rational surfaces; (ii) Reduction of heat transport as a result of the formation of the staircase; (iii) Inward/outward propagation of turbulence intensity; (iv) Non-local heat flux; and (v) Non-Gaussian statistics including probability distribution function, skewness and kurtosis in the scrape-off-layer region. Another consequence of the proposed experiment is to understand the relevance of flux tube simulations, the contribution of microinstabilites in electron and ion thermal transport, and the role of rational surfaces in regulating heat transport. Because of limited operating time in tokamaks, it is uncertain when the proposed experiment can be carried out.

Drs. Tangri and Rafiq attended the EPSI All Hands Meeting, Oak Ridge, TN Jan 9-10, (2014) where Dr. Tangri presented *Further Developments in the Statistical Data Analysis* [2]. Dr. Tangri also presented EPSI supported research on *Statistical Analysis of XGC1 Turbulence Data* at the APS DPP annual meeting in Denver, CO [4]. A number of visits were made to the Princeton Plasma Physics Laboratory to present and discuss results of research carried out at Lehigh with members of the Princeton EPSI Team. Dr. Tangri examined the structure of the

XGC0 code so that the Multi-Mode anomalous transport module can be combined with neoclassical transport.

(4) Analysis of Statistical Properties Associated with Potential Fluctuations, Turbulence Intensity, Radial flow velocity, Turbulence Intensity flux and Ion Heat Flux[6]

Statistical properties associated with potential fluctuations, turbulence intensity, radial flow velocity, turbulence intensity flux and ion heat flux were analyzed. The data was obtained from an XGC1 electrostatic ion-temperature-gradient (ITG) gyrokinetic simulation carried out employing DIII-D geometry. Self-organization of ITG turbulence fluctuations results in the formation of an **E**×**B** corrugated pattern and an R/L_{Ti} staircase pattern. The standard deviation, skewness and kurtosis for turbulence quantities were computed and found to be large in the vicinity of the "staircase-steps." Large values of skewness and kurtosis can be explained by a temporary opening and closing of the structure which allows turbulence intensity events to propagate. In Fig. 4, dips and peaks in R/L_{Ti} are generally found in the locations where the poloidal shear flow changes its sign. The variation of shearing rate with Ψ is much greater than the variation with time (shown in the vertical direction). Since the temporal change in the shearing rate is small, the flows may be considered quasi-stationary during the simulation (5ms). Thus, variations of surface and time averaged R/L_{Ti} are found to be correlated with the non-linearly self-organized, dynamically driven, steady-standing **E**×**B** poloidally flows– the "**E**×**B** staircase." The staircase shear layers stop the heat avalanches therefore acts as weak transport barriers.

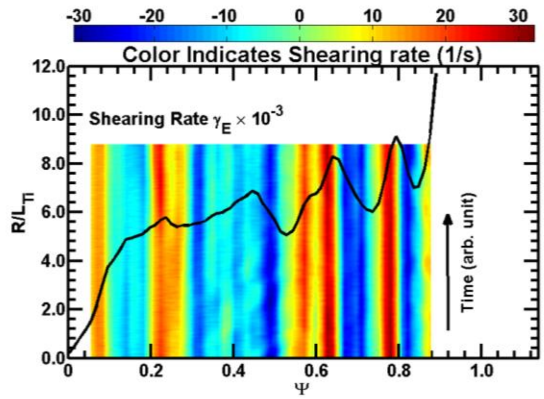

Figure 4: The time and flux surface averaged R/L_{TI} (solid line) and time dependent flux surface averaged E×B poloidal flow shearing rate (indicated by color bars) are plotted at various radial locations Ψ. Variation of color in the vertical direction indicates variation of shear with time. The limited variation in the vertical direction indicates that the shear is nearly constant in time.

In order to understand the nature of turbulence intensity at steplike locations, a fraction of events that propagate turbulence intensity inward f ($\Gamma_I < 0$) is plotted in Fig.5 by

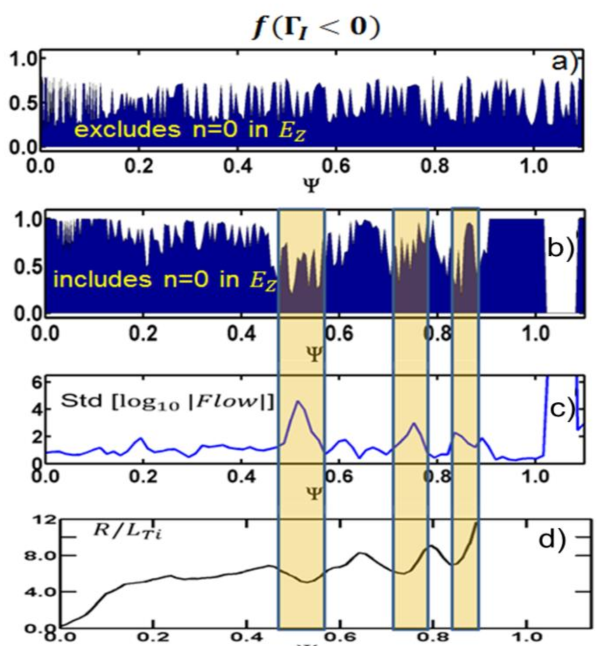

Figure 5: a) Fraction of events that propagate turbulence intensity inward f($\Gamma_I < 0$) excluding n = 0 component of potential and b) including n = 0 component of potential in the derivation of Γ_I c) standard deviation of log of flow (Std[$\log_{10}$|Flow|]) and d) R/L_{TI} are plotted as a function of radial coordinate Ψ. The fraction of events moving inward is found to be small at the staircase step locations ($\Psi \sim 0.52$, $\Psi \sim 0.73$ and $\Psi \sim 0.84$). The turbulence intensity flux is observed moving outward where flow change is large and where the local minima in R/L_{TI} are found.

excluding and including n = 0 component of potential in the derivation of Γ_I along with a standard deviation of log of flow and normalized ion temperature gradient scale length R/L_{Ti}. In the top panel in Fig.5 the value of one in the y-axis corresponds to the maximum number of events that propagate turbulence intensity inward. It is found that a fraction of the events that propagate turbulence intensity inward are small at the staircase step locations $\Psi \sim 0.52$, $\Psi \sim 0.73$, and $\Psi \sim 0.84$. The turbulence intensity flux is found to be moving outward (1- f $(\Gamma_I) < 0$) where a change in flow is large and where the local minima in R/L_{Ti} are found. It is found that n = 0 component of potential plays a major role in regulating inward propagation of turbulence intensity. In summary, the propagation of turbulence intensity flux is related to the change in poloidal flow velocity shear and to the change in the ion temperature gradient. Large values of skewness and kurtosis found in the vicinity of the staircase-steps can be due to a temporary opening and closing of the structures which allows turbulence intensity to propagate.

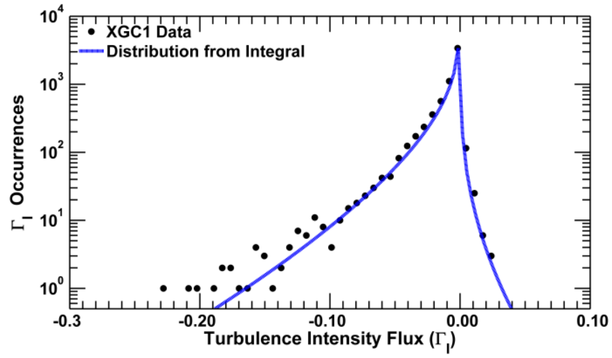

Figure 6: The number of occurrences of the normalized turbulence intensity flux, $\Gamma_I \equiv V_R\,\phi^2$ versus Γ_I at radius position $\Psi = 0.3$. The points are obtained from the analysis of the XGC1 data and the solid line represents the derived analytical distribution.

It was shown in the analysis of the XGC1 data that the distributions obtained are in good agreement with those given by the derived analytic expressions (see Fig. 6). Analytic expressions were obtained for the distributions of the turbulence intensity and turbulence intensity flux when the distributions of the potential fluctuations and radial flow velocity are Gaussian. The analysis would be useful in understanding turbulence, its global self-organization, its non-local nature, and its statistical properties. Specifically, the following physical phenomena in tokamaks can be explored: (i) Existence of $\boldsymbol{E} \times \boldsymbol{B}$ staircase and its relation to the rational surfaces; (ii) Reduction of heat transport as a result of the formation of $\boldsymbol{E} \times \boldsymbol{B}$ staircase; (iii) Inward/outward propagation of turbulence intensity; (iv) Non-local heat flux; (v) Non-Gaussian statistics including PDF, Skewness and Kurtosis in the SOL region. Another consequence of the proposed study will be to understand the relevance of flux tube simulations, and the contribution of microinstabilites in thermal ion and electron transport and the role of rational surfaces in regulating heat transport.

Dr. Rafiq attended the 2nd EPSI All Hands Meeting, Cambridge, MA August 14-15, (2014). Dr Rafiq presented the research on Statistical Properties of XGC1 ITG Turbulence Data and Staircase Structure at the Sherwood Fusion Theory Meeting, New York, NY March 16-18.. A draft of the paper, Statistical Analysis of XGC1 Tokamak Turbulence Data had been prepared and is being finalized for submission for publication [6].

(5) Kinetic Modeling of Divertor Heat Load Fluxes in the Alcator C-Mod and DIII-D Tokamaks[7]

The XGC0 code was used to compute the heat fluxes and the heat-load width in the outer divertor plates of C-Mod and DIII-D tokamaks. It was observed that the width of the XGC0 neoclassical heat-load was approximately inversely proportional to the total plasma current I_p.

The scaling of the divertor heat-load width with plasma current was found to be weaker in the Alcator C-Mod discharge compared to scaling found in the DIII-D discharges. The effect of neutral collisions on the I_p scaling of heat-load width was shown not to be significant. Although inclusion of poloidally uniform anomalous transport resulted in a deviation from the I_p scaling, the inclusion of the anomalous transport driven by ballooning-type instabilities lead to recovering the neoclassical I_p scaling. The Bohm or gyro-Bohm scalings of anomalous transport did not strongly affect the dependence of the heat-load width on plasma current. The inclusion of anomalous transport, in general, caused the width of neoclassical divertor heat-load to widen and enhanced the neoclassical heat-load fluxes on the divertor plates. Understanding heat transport in the scrape-off layer plasma strengthens the basis for predicting divertor conditions in ITER.

(6) Anomalous Transport in the H-mode Pedestal of Alcator C-Mod Discharges[8-14]

Anomalous transport in the H-mode pedestal region of five Alcator C-Mod discharges, representing a collisionality scan, was analyzed. The understanding of anomalous transport in the pedestal region is important for the development of a comprehensive model for the H-mode pedestal slope. A possible role of the DRIBM modes in the edge of Alcator C-Mod discharges was analyzed. The stability analysis, carried out using the TRANSP code, indicates that the DRIBM modes are strongly unstable in Alcator C-Mod discharges with large electron collisionality. An improved interpretive analysis of H-mode pedestal experimental data was carried out utilizing the additive flux minimization technique together with the guiding-center neoclassical kinetic XGC0 code. The neoclassical and neutral physics were simulated in the XGC0 code and the anomalous fluxes were computed using the additive flux minimization technique. The anomalous fluxes were reconstructed and compared with each other for the collisionality scan Alcator C-Mod discharges. It was found that the electron thermal anomalous diffusivities at the pedestal top increase with the electron collisionality. This dependence can also point to the DRIBM as the modes that drive the anomalous transport in the plasma edge of highly collisional discharges.

(7) Investigation of the Plasma Shaping Effects on the H-mode Pedestal Structure Using Coupled Kinetic Neoclassical/MHD Stability Simulations[15-17]

The effects of plasma shaping on the H-mode pedestal structure was investigated. High fidelity kinetic simulations of the neoclassical pedestal dynamics were combined with the MHD stability conditions for triggering ELM instabilities that limit the pedestal width and height in H-mode plasmas. The neoclassical kinetic XGC0 code was used to carry out a scan over plasma elongation and triangularity. As plasma profiles evolve, the MHD stability limits of these profiles were analyzed with the ideal MHD ELITE code. Simulations with the XGC0 code, which include coupled ion-electron dynamics, yielded predictions for both ion and electron pedestal profiles. The differences in the predicted H-mode pedestal width and height for the DIII-D discharges with different elongation and triangularities were discussed. For the discharges with higher elongation, it was found that the gradients of the plasma profiles in the H-mode pedestal reach semi-steady states. In these simulations, the pedestal slowly continued to evolve to higher pedestal pressures and bootstrap currents until the peeling ballooning stability conditions were satisfied. The discharges with lower elongation do not reach the semi-steady state, and ELM crashes were triggered at earlier times. The plasma elongation was found to have a stronger stabilizing effect than the plasma triangularity. For the discharges with lower elongation and lower triangularity, the ELM frequency was large, and the H-mode pedestal evolves rapidly. It was found that the temperature of neutrals in the scrape-off-layer region can affect the dynamics of the H-mode pedestal buildup. However, the final pedestal profiles were nearly independent of the neutral temperature. The elongation and triangularity affected the pedestal widths of plasma density and electron temperature profiles differently. This study illustrated a new mechanism for controlling the pedestal bootstrap current and the pedestal stability.

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