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Technical Progress Report

A PORTABLE AND INDEPENDENT EDGE FLUCTUATION DIAGNOSTICS

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Motivation

The consolidation of edge plasma parameters into a database allows comparisons between experiment and predictions of theoretical models over a wide range of parameters. In this way we hope to validate (or refute) various proposed driving mechanisms for the observed turbulence and transport and to derive empirical scaling laws for parameters useful in machine design, such as e-folding lengths, fluxes and effective diffusion coefficients.

Current Status

A. Data

An edge database consisting of edge equilibrium, turbulence and transport related plasma parameters has been incorporated into the Magnetic Fusion Energy Database (MFEDB). In order to provide the magnetic fusion community with access to this data, the database has been constructed as a network resource which can be accessed in several ways from the Internet.

Currently, the edge database contains Langmuir probe data acquired using a standardized probe array and analyzed using a consistent set of signal processing routines. The Langmuir probe data sets are comprised of three categories of parameters: i) edge equilibrium profiles of electron temperature, density, and potential, ii) edge fluctuation properties including characteristics of frequency, wavenumber, propagation velocity, and rms amplitude, iii) transport parameters such as fluctuation-driven particle flux and electron energy flux. At present, most of the data were obtained in limiter plasmas.

B. Analysis Tools

In order to facilitate the data analysis, a Mathematica package has been developed which provides the scientist with tools for accessing the data and bringing it into the Mathematica environment. Once there, all the power of Mathematica can be brought to bear on the problem. There are four general areas where this environment can be used effectively to analyze and visualize the data: i) Mathematica's extensive facilities for statistical analysis, especially nonlinear regression, ii) Mathematica's graphics capabilities which include 2D and 3D graphics and animation, iii) a locally implemented set of database functions that provide the same functionality as a standard database management system, a relational calculus, i. e., select, project, join, union, and complement, iv) Mathematica's powerful programming environment that allows the creation of special functions that can combine all the areas mentioned in i) - iii) above.

C. Distributed Access

In order to provide distributed access to the database we implemented the *Mathematica* Database Interface (MDI) system. The MDI system is composed of three parts: the Mdi.m package, which adds the database access functions to *Mathematica*, the RPC client/server process pair, which provide network communication between the *Mathematica* kernel and the MFEDB host computer, and the database manager software, which handles the MFEDB. Figure

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1 shows a schematic layout of the MDI components. There are potentially three computers involved and five separate processes. The network connection between a *Mathematica* front-end and the *Mathematica* kernel is controlled by the *Mathematica* software. These two processes can either run on the same computer or be connected through a network or by modem.

Results

A. Scrape off layer characteristics

The scrape-off layer (SOL) is the open field line plasma region outside the last-closed-flux-surface (LCFS) or the separatrix. A convenient way of locating the starting point of the SOL is via turbulence measurement. Many measurements show that the propagation of the turbulence is dominated by an $\mathbf{ExB}$ rotation arising from a radial electric field and that a narrow region (≤ 1 cm) of strong shear (radial variation) of the rotation exists. Typically, the position of zero phase velocity (also corresponds approximately to the maximum velocity shear) is ≤ 0.5 cm outside the LCFS defined by the innermost scrape-off limiter edge or the separatrix. The formation of a velocity shear layer can be explained in terms of sheath formation at the plasma-limiter interface. To align the SOL measurements, we use the turbulence measurements to supplement the magnetic calculation of the LCFS.

The profiles of equilibrium electron density and temperature in the SOL often display three discernible regions. Close to the LCFS is a narrow region of steep gradient typically with electron density and temperature scalelengths (L_n and L_{T_e}) ranging from 1 to 3 cm for this group of data. The profiles then flatten further into the SOL. In a few cases, the electron density actually increases with radius giving rise to a density hump. A third region with rapid drop of n_e and T_e appears close to the vacuum vessel wall. We focus our scaling study on the first portion of the SOL region next to the LCFS.

In the SOL, field-lines are no longer closed. Their connections to the limiters or the target plates allow particles to escape along the field lines and interactions to enhance atomic processes and recycling. Indeed, while some experimental measurements show SOL density (n_e^{SOL}) scales with bulk plasma density, some others indicate n_e^{SOL} has an obscure behavior and does not scale with the bulk plasma density at all. To investigate the behavior of n_e^{SOL} , we begin by seeking a global scaling based on the parameters B_ϕ and $\bar{n}_e$. The resultant scaling, plotted in Figure 2a, is

$$\frac{n_e^{\text{SOL}}}{10^{19} \text{ m}^{-3}} = 0.22 \left(\frac{B_\phi}{\text{T}} \right)^{-1.1} \left(\frac{\bar{n}_e}{10^{19} \text{ m}^{-3}} \right)^{1.4}, \quad (1)$$

and has a regression coefficient of $C_{re} = 0.50$. The low value of C_{re} suggests that there could be hidden parametric dependencies not included in (1). To test the hypothesis that n_e^{SOL} may depend on some local parameters, the scaling is extended to include a local parameter, specifically, the normalized density fluctuation level ($\bar{n}_e^{\text{SOL}}/n_e^{\text{SOL}}$). The scaling now becomes

$$\frac{n_e^{\text{SOL}}}{10^{19} \text{ m}^{-3}} = 0.017 \left(\frac{B_\phi}{\text{T}} \right)^{-1.4} \left(\frac{\bar{n}_e}{10^{19} \text{ m}^{-3}} \right)^{1.3} \left(\frac{\tilde{n}_e^{\text{SOL}}}{n_e^{\text{SOL}}} \right)^{1.6}, \quad (2)$$

and is plotted in Figure 2b. In this case the regression coefficient is $C_{re} = 0.84$. The increase in C_{re} is statistically significant. It indicates that including the local fluctuation level ($\tilde{n}_e^{\text{SOL}}/n_e^{\text{SOL}}$) improves the scaling fit. From this result we may conclude that the local fluctuations can influence the edge density. This may be expected from the observations that fluctuations play an important role in the edge particle transport. The regression analysis has been repeated with the dataset grouped into limiter and divertor discharges to decipher any difference in the n_e^{SOL} behavior. Based on statistical inference, it is found that the data is insufficient to infer different edge density scaling law for limiter and divertor plasmas.

In this dataset all the discharges are heated ohmically, i.e., the heating power depends on I_ϕ and V_ϕ . Statistical analysis confirms that I_ϕ is a relevant global scaling parameter for the edge electron temperature (T_e^{SOL}) and V_ϕ is not. As in the case of n_e^{SOL} scaling, the local fluctuation level $\tilde{n}_e^{\text{SOL}}/n_e^{\text{SOL}}$ is found to be a relevant parameter. The scaling of T_e^{SOL} , using a minimum global parameter set of B_ϕ , $\bar{n}_e$, and I_ϕ and including $\tilde{n}_e^{\text{SOL}}/n_e^{\text{SOL}}$, is

$$\frac{T_e^{\text{SOL}}}{\text{eV}} = 0.16 \left(\frac{B_\phi}{\text{T}} \right)^{1.3} \left(\frac{\bar{n}_e}{10^{19} \text{ m}^{-3}} \right)^{-0.4} \left(\frac{I_\phi}{\text{kA}} \right)^{1.0} \left(\frac{\tilde{n}_e^{\text{SOL}}}{n_e^{\text{SOL}}} \right)^{0.5} \quad (3)$$

and has $C_{re} = 0.83$. This scaling is plotted in Figure 3. Again, it is found that the T_e^{SOL} scaling (3) can describe both divertor and limiter plasmas within statistical uncertainty.

B. Particle Transport

According to a simple scrape-off layer model, by balancing the perpendicular particle flow with the parallel particle flow, the radial particle flux is $\Gamma^{\text{SOL}} \approx 0.5 n c_s L_N / L_C$ where c_s is the sound speed and L_C is the characteristic connection length to a limiter. Despite the simplicity of the model, the estimated particle flux Γ^{SOL} is found to scale with the measured turbulence-driven particle flux Γ^{turb} . The turbulence-driven particle flux Γ^{turb} is derived from a cross-correlation between the fluctuating density $\tilde{n}_e$ and the fluctuating poloidal electric field $\tilde{E}_\theta$, i.e., $\Gamma^{\text{turb}} = \langle \tilde{n}_e \tilde{E}_\theta \rangle / B$ where $\langle \dots \rangle$ denotes an ensemble average. We note that Γ^{turb} is a local measurement and that significant asymmetries, which might give rise to a particle flux due to d.c. convection, have been observed in many experiments. This data set is amassed from measurements taken at different locations on four devices each with its own unique edge configuration. The variations in these measurements are expected to smooth out the biases from the asymmetries and to increase the spread or (scattering) of the scaling fits.

In anticipation of possible difference in the confinement of divertor and limiter plasmas, we use only the limiter discharges to determine a scaling of the turbulent particle flux to assess global particle confinement. For the limiter discharges, regression analysis yields

$$\frac{\Gamma^{\text{turb}}}{10^{21} \text{ m}^{-2} \text{ s}^{-1}} = 0.42 \left(\frac{B_{\phi}}{T} \right)^{2.3} \left(\frac{\bar{n}_e}{10^{19} \text{ m}^{-3}} \right)^{1.2} \quad (4)$$

with $C_{re} = 0.73$. The scaling result, plotted in Figure 4a, indicates a plausible separation of divertor data from limiter data. With the divertor subset included in the regression, C_{re} reduces to 0.68. However, the statistical significance of this drop in C_{re} is somewhat marginal to infer a difference in divertor and limiter plasma scaling.

The particle flux may depend on some local parameters. It has been observed in ASDEX that plasma global confinement is sensitive to edge conditions. If transport can be described by Bohm diffusion then the particle flux $\Gamma (= nD_{\text{Bohm}}/L_n = nT_e/16BL_n)$ can have a T_e dependence. With the local electron temperature T_e^{SOL} included, the scaling becomes

$$\frac{\Gamma^{\text{turb}}}{10^{21} \text{ m}^{-2} \text{ s}^{-1}} = 0.052 \left(\frac{B_{\phi}}{T} \right)^{2.0} \left(\frac{\bar{n}_e}{10^{19} \text{ m}^{-3}} \right)^{1.2} \left(\frac{T_e^{\text{SOL}}}{\text{eV}} \right)^{0.6}, \quad (5)$$

with $C_{re} = 0.71$. The lack of improvement in the regression fitting suggests that T_e^{SOL} may not be an essential parameter for the scaling of the transport parameter Γ^{turb} . A scaling including L_n is needed to give a more definitive statement.

A smaller subset of the data having similar global parameters (see Table 2) is further selected for the purpose of comparing particle transport in divertor and limiter and plasmas. An effective perpendicular diffusion coefficient can be computed from the measured particle flux using $D_{\text{eff}}^{\text{turb}} = \Gamma^{\text{turb}} L_n/n$, although it remains to be proved if the transport process is diffusive. Nevertheless, the effective diffusion coefficient may be useful in the context of comparing diffusion coefficients from other measurements or from modeling. Figure 5 shows the radial profiles of $D_{\text{eff}}^{\text{turb}}$ in the vicinity of the LCFS. There are two principal observations. First, $D_{\text{eff}}^{\text{turb}}$ is lower in divertor plasmas than in limiter plasmas and it is lower by about a factor of 2 at the LCFS (at $r/a_s = 1$). Second, $D_{\text{eff}}^{\text{turb}}$ has a strong radial variation in both types of plasmas. The value of $D_{\text{eff}}^{\text{turb}}$ increases with radius to almost 10 times the value at the LCFS. On the other hand, D_{Bohm} decreases with radius. We may conclude that the magnetic topology of a separatrix or a divertor improves particle confinement. Although values of $D_{\text{eff}}^{\text{turb}}$ is close to D_{Bohm} at the immediate vicinity of the LCFS, both the strong radial dependence of $D_{\text{eff}}^{\text{turb}}$ and the departure from the D_{Bohm} values away from the LCFS mean that taking a constant times D_{Bohm} to represent edge particle transport is not appropriate.

Conclusions

A database of edge plasma equilibrium and fluctuating parameters has been developed and compiled. Regression analysis has been applied to a data subset consisting of data from four medium size tokamaks (Phaedrus-T, Tokamak de Varennes, TEXT, and TEXT-U) to yield scaling laws for the edge density, electron temperature, and particle flux.

It is found that the magnetic topology of a separatrix or a divertor improves particle confinement. In the SOL, the perpendicular diffusion coefficient is not constant and has a radial variation to that of Bohm diffusion.

Future Work

We hope to expand the database to include edge data from other diagnostics. Divertor and H-mode data from the TEXT-Upgrade will be included.

Figure Captions

Figure 1. A schematic layout of the MDI components

Figure 2 Scaling of n_e^{SOL} with global parameters B_ϕ and $\bar{n}_e$ (a) and with an additional local fluctuation parameter $\tilde{n}_e^{\text{SOL}}/n_e^{\text{SOL}}$ (b). Including the local fluctuation level ($\tilde{n}_e^{\text{SOL}}/n_e^{\text{SOL}}$) reduces the spread (or scattering) in the n_e^{SOL} scaling.

Figure 3 Scaling of T_e^{SOL} with global parameters B_ϕ , $\bar{n}_e$, and I_ϕ and a local fluctuation parameter $\tilde{n}_e^{\text{SOL}}/n_e^{\text{SOL}}$.

Figure 4 Scaling of particle flux Γ^{turb} with global parameters B_ϕ and $\bar{n}_e$ (a) and with an additional local parameter T_e^{SOL} (b). The lack of improvement in the scaling fit in (b) may suggest that T_e^{SOL} is not an essential parameter.

Figure 5 $D_{\text{eff}}^{\text{turb}}$ of divertor and limiter plasmas in the vicinity of the last-closed flux surface at $r = a_s$.

device	edge configuration	R (m)	a (m)	B (T)	I_ϕ (kA)	n (10^{19} m^{-3})
Phaedrus-T	limiter	0.93	0.26	0.9	50 - 100	0.4 - 2
TdeV	divertor (DN)	0.87	0.27	1.4	150 - 210	2 - 4
TEXT	limiter	1.00	0.26	1 - 3	100 - 300	2 - 5
TEXT-U	limiter divertor (SN)	1.05	0.27	2	140 - 240	1.5 - 4

Table 1 Machine and operating parameters.

device	edge configuration	B (T)	I_ϕ (kA)	n (10^{19} m^{-3})
TdeV	divertor (DN)	1.4	210	2.5
TEXT-U	limiter divertor (SN)	2	180	2.5 - 3

Table 2 Discharge parameters for data shown in figure 4.

Figure 1. Schematic diagram of the MDI components

Figure 2

Figure 3

Figure 4

Figure 5

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