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Turbulence correlated widening of the near SOL power width in ASDEX Upgrade

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Abstract

The plasma phase space as predicted by fluid simulation by Roger, Drake, Zeiler (RDZ) and Scott is compared to the plasma conditions at the separatrix position in ASDEX Upgrade. A turbulence parameter $\alpha_t \propto q^2 Rn/T^2$ is motivated, similar to the α_d from RDZ but not including any decay length. This turbulence parameter is used for a generalized scaling of the near SOL electron temperature decay lengths in conjunction with the known neoclassical drift-orbit power width scaling. In the limit of low separatrix densities the well established multi-machine scaling is recovered as a lower limit, whereas at higher separatrix densities the turbulent term causes an increased temperature decay length by a factor of about two in ASDEX Upgrade. This generalized scaling implies that for ITER at high separatrix densities of about half Greenwald turbulence will widen the power width λ_q qualitatively in agreement with recent simulation predictions.

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In a diverted tokamak device, plasmas are confined in a toroidally symmetric region of closed magnetic field lines referred to as the core plasma. These are surrounded by an open field line region, known as the scrape-off-layer (SOL), with field lines that begin and end on material surfaces of a structure known as divertor. Energy is temporarily confined within the core plasma, but finally enters into the SOL and the divertor region giving rise to high heat fluxes. The resulting heat flux density on the divertor target plates must be kept below a material dependent technical limit and hence this places restrictions on the permissable tokamak operational space. The most critical quantity for determining the divertor heat flux density is the power decay length in the SOL, λ_q, and extrapolations of this quantity has enormous consequences for the operational range for ITER and any tokamak based reactor designs [1–4]. The high confinement mode, or H-mode [5], is chosen for the ITER baseline scenario and is discussed as a candidate scenario for future fusion reactors [6]. A multi-machine attempt was carried out for divertor heat flux data from various tokamaks (JET, DIII-D, ASDEX Upgrade, Alcator C-Mod, NSTX and MAST) found that the power width λ_q for H-mode operation is inversely proportional to the poloidal magnetic field, B_{pol}. Equally important, no dependence on the machine size was detected [7, 8]. Both aspects can be interpreted as a combination of ion-carried neoclassical drift-orbit particle losses and anomalous electron heat diffusion filling that loss channel [9, 10]. The obtained prediction for the near SOL power width matches closely experimental data and is described by [11, 12]

$$\lambda_q \simeq 2 \times \frac{a}{R}\, \rho_{i,pol} \,\text{with}\, \rho_{i,pol} = \frac{\sqrt{T_i\, m_D}}{B_{pol}\, e}, \tag{1}$$

with minor and major radii a and R, elementary charge e, ion temperature T_i and Deuterium ion mass m_D. This way the poloidally averaged power width for ITER is predicted to be of the order of 1mm. Recently the power width data base of Alcator C-Mod has been extended up to (outer mid plane) poloidal magnetic fields of > 1.2 T, hence ITER like values, for low edge density discharges suitable for such divertor heat load studies. They report $\lambda_q \propto B_{pol}^{-0.96}$ and present also a remarkable close match in absolute numbers to the multi-machine scaling [13].

Simulations focusing on the role of turbulence for the power decay width report a widening when electron turbulence becomes stronger at elevated edge densities and also for larger devices since the turbulent energy flux scales positively with machine size [12, 14–17]. In particular the work by Chang using the XGC1 code predicts a significant widening of the power width for ITER conditions reporting $\lambda_q \approx 5\,\mathrm{mm}$ at the outer equatorial mid plane [12, 18].

In this work we revisit the former multi-machine attempt which is based on careful interpretation of heat load profiles on the outer divertor target [7] and by default comes with the caveat that the analyzed data base is constrained to low edge density H-mode plasmas since only then infra-red (IR) thermography can be reliably used to reconstruct the power width. However, good agreement is reported for comparison of the power width reconstructed by such divertor measurements and the electron temperature decay length measured at the outer equatorial mid plane for both H-mode and L-mode conditions in ASDEX Upgrade, DIII-D and JET [19–22, 24] as predicted by Spitzer-Härm parallel heat conduction explicitly giving

$$\lambda_T \simeq \frac{7}{2}\lambda_q. \tag{2}$$

For this reason either $2/7\,\lambda_T$ or λ_q are considered here as the power width in tokamaks as they both equally well describe the volume in which the power entering the SOL must be dissipated in order to meet the technical requirement for divertor integrity [1]. Taken together, this makes an extension of the former work possible by establishing a scaling for λ_{Te} measured at the outer mid plane and including plasmas with highest possible edge densities until reaching the so called H-mode density limit [25]. In this paper we use poloidally averaged values for the decay lengths at the separatrix (for further details see [19]) and assume electron and ion temperature to be equal. All discharges are deuterium plasmas.

In order to quantify the strength of anomalous fluxes we apply the turbulence control parameters, α_{MHD} and α_d from the work of Roger, Drake, Zeiler (RDZ) introducing the concept of the plasma phase space [26] and also compare to the similar approach by Scott [27, 28]. We use these turbulence control parameters to quantify the influence of the turbulence on the electron temperature decay width. To justify our approach we present first a comparison of the plasma phase space prediction to a large data base for separatrix plasma conditions in ASDEX Upgrade. Already in 1999 Suttrop found good agreement between experimental data and the plasma phase space prediction in ASDEX Upgrade [30]. Further agreement was found in the work by LaBombard [29] using probe measurements just outside the separatrix for Alcator C-Mod plasmas. A major advantage of the here presented data base in comparison to the earlier attempts [29, 30] is the use of a dedicated edge Thomson scattering diagnostic allowing for a large range of operational conditions in ASDEX Upgrade. This includes L-Mode, I-mode, H-modes, disruptive L-mode, and explicitly non-disruptive H-mode density limited discharges.

Even though we are aware that plasma edge turbulence is a complex phenomenon that can hardly be described by two parameters only, to quantify a possible broadening of the near SOL width by turbulence, a control parameter of plasma edge turbulence is desirable such as the Reynolds number in fluid turbulence. This control parameter should describe the strength of the plasma edge turbulence and its transport. In their fundamental work Rogers, Drake and Zeiler [26] proposed that the plasma edge is controlled by two main parameters, the ideal MHD ballooning parameter $\alpha_{MHD} = R\, q_{cyl}^2 \frac{\beta}{\lambda_p}$, where $\beta = 4\mu_0\, p_e/B_{tor}^2$, the plasma pressure gradient scale length λ_p, the magnetic field strength B_{tor}. The major radius R and safety factor q_{cyl} are defined in standard notation. A turbulence control parameter, the so-called the diamagnetic parameter α_d , controlling the impact of drift-wave dynamics on interchange turbulence, is defined as

$$\alpha_d = \sqrt{\frac{(m_i/m_e)c_s}{(2\pi\, \hat{\kappa}\, q_{cyl})^2 R\, \nu_{ei}}} \left(\frac{4R}{\lambda_p}\right)^{1/4} . \tag{3}$$

The electron ion collision frequency is denoted as ν_{ei}, ion and electron mass as $m_{i,e}$ and ion sound speed as $c_s = \sqrt{T_e/m_i}$. The extended parallel scale length due to the elongation κ_{geo} when compared to the circular cross-section is taken into account by substituting $q_{cyl}\, R$ with $\hat{\kappa}\, q_{cyl}\, R$, with $\hat{\kappa} = \sqrt{(1+\kappa_{geo}^2)/2}$. Scott [27, 28] investigated the same phenomenon from another perspective, namely the impact of the interchange effect on drift-wave turbulence controlled by the so-called resistive ballooning parameter $C\omega_B$, with normalized collisionality $C = 0.51\nu_{ie}\frac{\lambda_p}{c_s}\left(\frac{q_{cyl}R}{\lambda_p}\right)^2$, $\nu_{ie} = Z_i \nu_{ei}(m_e/m_i)$ the ion-electron Braginskii collision frequency, Z_i the ion charge state, $(q_{cyl}R/\lambda_p)^2$ the typical ratio of parallel to perpendicular scale length controlling the adiabaticity of the electrons and λ_p/c_s due to the time normalization. Within the work of Scott the parameter $\omega_B = 2\lambda_p/R$ sets the strength of the curvature drive and hence the strength of the interchange turbulence. Similar to α_d the parameter $C\omega_B$ controls the relative strength of interchange and drift-wave turbulence by the cross-phase between pressure and potential perturbations. It is shown in Eq. (6) that $\alpha_d = (1/2\pi)(C\omega_B)^{-1/2}\, 2^{1/4}\omega_B^{-1/4} \simeq 0.5\,(C\omega_B)^{-1/2}$, hence both parameters α_d and $C\omega_B$ are directly linked. Both parameters, C and ω_B, depend on the gradient length scale λ_p, however, the combination $C\omega_B$ does not depend on λ_p. As we need to avoid collinearity

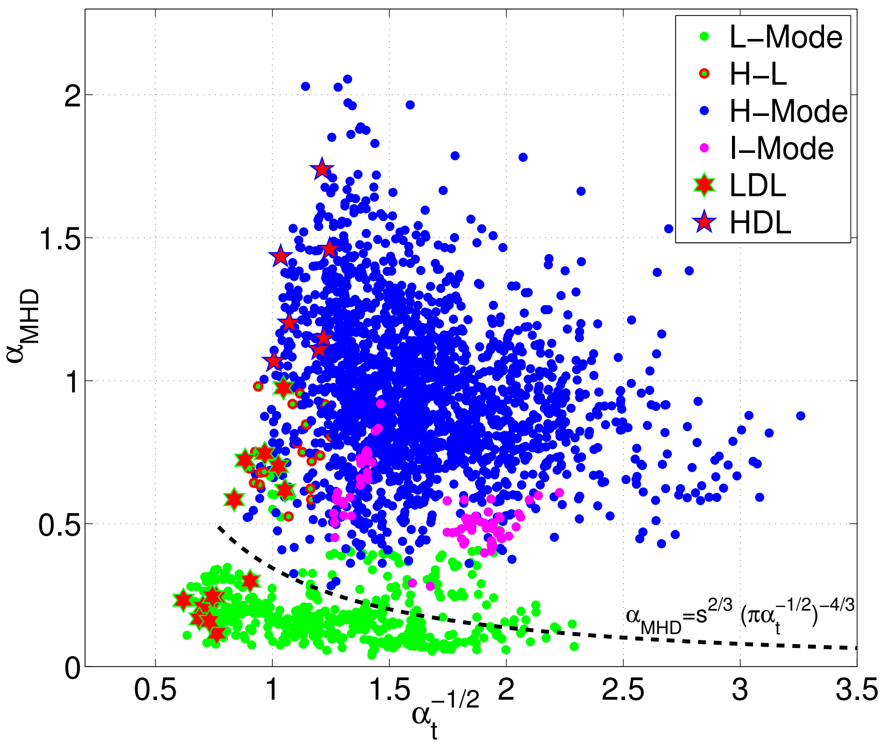

FIG. 1: The plasma phase space for ASDEX Upgrade as proposed by RDZ using α_{MHD} and $\alpha_t^{-1/2} \simeq 2\alpha_d$. The region of inaccessible operation is reproduced. According to RDZ magnetic perturbations become not negligible above the dashed line.

with the SOL power width we consider $C\omega_B$ to be the more suitable edge plasma turbulence control parameter for our studies here when compared to α_d.

In order to derive a generalized scaling law for the temperature decay length, λ_T, we define a turbulence parameter $\alpha_t = C\omega_B$ as

$$\alpha_t = Z_i \sqrt{\frac{m_e}{m_D}} (\hat{\kappa}^2 q_{cyl}^2 R) \frac{1.02 \cdot \sqrt{2} e^4 \ln \Lambda \sum_i n_i Z_i^2}{12\pi^{3/2} \epsilon_0^2 T_e^2}. \tag{4}$$

We set the Coulomb logarithm $\ln \Lambda \approx$15 and $\sum_i n_i Z_i^2 = n_e Z_{eff}$ to rewrite Eq. (4) as

$$\alpha_t \approx 1.7 \cdot 10^{-18} \hat{\kappa}^2 \, q_{cyl}^2 \, R \frac{n_e Z_i Z_{eff}}{T_e^2}. \tag{5}$$

In the work by RDZ the plasma phase space is derived for a fixed gradient scale length ω_B=0.02 which is well in line with the observed experimental values ω_B=0.01–0.04. Thus for $\omega_B^{1/4} = 0.38 \pm 0.08$ balancing Eq. (3) with (4) yields

$$\alpha_d = \frac{2^{1/4}}{2\pi} \, \alpha_t^{-\frac{1}{2}} \, \omega_B^{-\frac{1}{4}} \approx 0.5 \pm 0.1 \; \alpha_t^{-\frac{1}{2}}. \tag{6}$$

Figure 1 shows the plasma phase space using α_{MHD} and $\alpha_t^{-1/2}$ ($\propto \alpha_d$) based on 123 discharges (2529 data points) in ASDEX Upgrade covering various operation conditions (I_p= 0.6–1.27 MA, B_{tor}= 1.5–2.6 T, P_{heat}= 0.3–20 MW). The turbulence parameter α_t in conjunction with α_{MHD} describes the edge plasma phase space well w.r.t. some of their key findings. The operationally inaccessible region at low $\alpha_t^{-1/2}$ (or low α_d) is clearly reproduced and the density limit leads to a steep boundary to the inaccessible region, also changing with α_{MHD}. Data where the discharges in L- and H-Mode are right at the density limit are labelled as LDL and HDL, respectively. It is interesting to note that the inaccessible region appears where $\alpha_t = C\omega_B \simeq 1$. At this point the transition from drift-wave to interchange dominated turbulence is predicted by Scott [27]. Further, RDZ note in their work that electromagnetic effects become important when $\alpha_{MHD} \simeq \hat{s}^{2/3}(2\pi\,\alpha_d)^{-4/3} \simeq \hat{s}^{2/3}(\pi\,\alpha_t^{-1/2})^{-4/3}$ with $\hat{s} = 2$ being the global shear at the separatrix position. This boundary is displayed in Fig. 1 and indicates roughly a boundary between low (L-mode) and improved/high (I-mode/H-mode) confinement discharges. It should be noted, however, that the RDZ proposed transition to H-Mode confinement based on their code result is not reproduced as already clearly shown by Gohil [23]. Finally we note that no data are found above the ideal MHD limit at about $\alpha_{MHD} \simeq 2$ consistent with the findings in [24].

Our new data base covers tokamak operation in ASDEX Upgrade w.r.t. lowest to highest possible edge densities. Figure 2 compares the temperature decay length versus the poloidal magnetic field with color coding according to α_t for all H-mode discharges of Fig.1. The shortest decay lengths for each poloidal field match the multi-machine prediction. Data with low α_t values are in line with the previous scaling, data with largest α_t are about a factor of two larger than the previous scaling. For values of α_t exceeding about unity the H-mode density limit is reached and thus, at least for ASDEX Upgrade, a stronger widening of the temperature decay length cannot be achieved. It is further important to note here that data with elevated densities and hence $\alpha_t \simeq 1$ are observed to still follow the narrowing of the temperature decay length with the poloidal magnetic field.

We propose a new ansatz to describe the temperature decay length (or power width) as a combination of the well established neoclassical drift-orbit like scaling following solely an B_{pol} dependence and the turbulence parameter α_t:

$$\lambda_T = (C + C_\alpha\,\alpha_t^a)\,B_{pol}^b \tag{7}$$

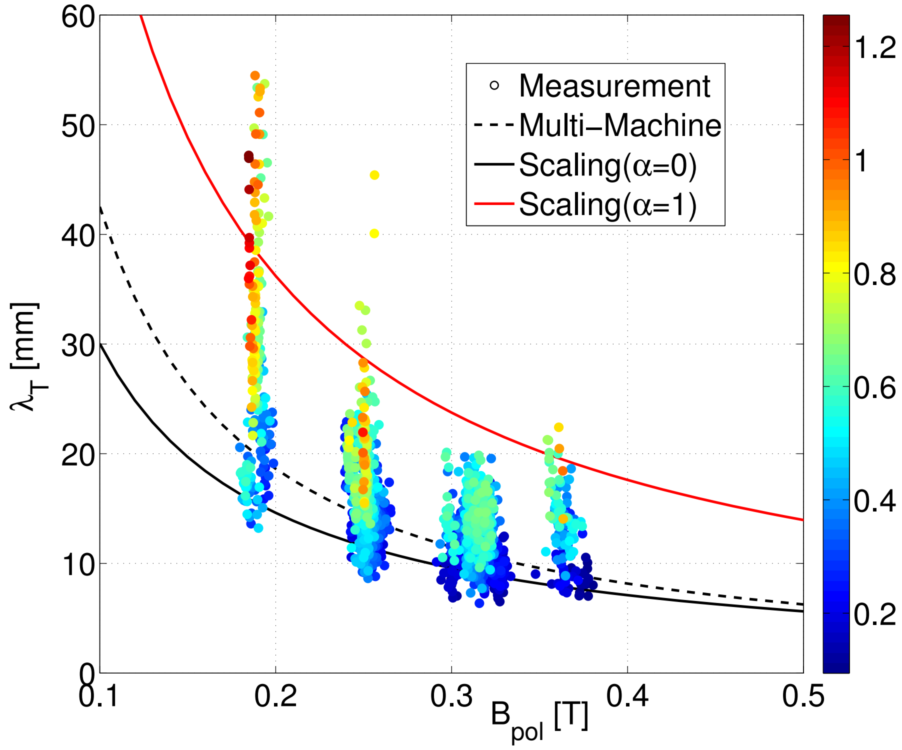

FIG. 2: The near SOL electron temperature decay length is displayed with color coding according to the turbulence parameter α_t. The solid lines display the scaling in Eq. (8) with $\alpha_t = 0$ in black and $\alpha_t = 1$ in red. The black dashed line displays the multi-machine Regression #14 times 7/2.

This compact expression allows for both the observed narrowing of the temperature decay length with poloidal magnetic field and its widening due to the anomalous electron heat transport controlled by α_t as concluded in [12, 18]. By least square-fitting (R^2=0.72, 1918 data points) carefully taking into account experimental errors

$$\frac{\lambda_T}{\mathrm{mm}} = \frac{(2.73 \pm 0.26) + (4.03 \pm 0.46)\, \alpha_t^{1.63 \pm 0.18}}{(B_{pol}/\mathrm{T})^{1.04 \pm 0.06}} \tag{8}$$

is obtained. A lower limit of this generalized scaling is found when $\alpha_t \approx 0$ (see Fig.1, $\alpha_t^{-1/2} \approx 3$ and $\alpha_t \approx 0.1$) representing conditions with low density, low impurity content and high separatrix temperature as present in the dedicated divertor heat flux studies. An upper limit is given for $\alpha_t \approx 1$. Both limits are displayed in Fig. 2. Additionally we plot the multi-machine scaling (Regression #14 in [8]) which gives as expected only slightly larger values than the lower limit of the generalized scaling. We note finally for completeness that an earlier attempt using ASDEX Upgrade data [31] reported $\lambda_T \propto q_{cyl}/T_e$ based on regression

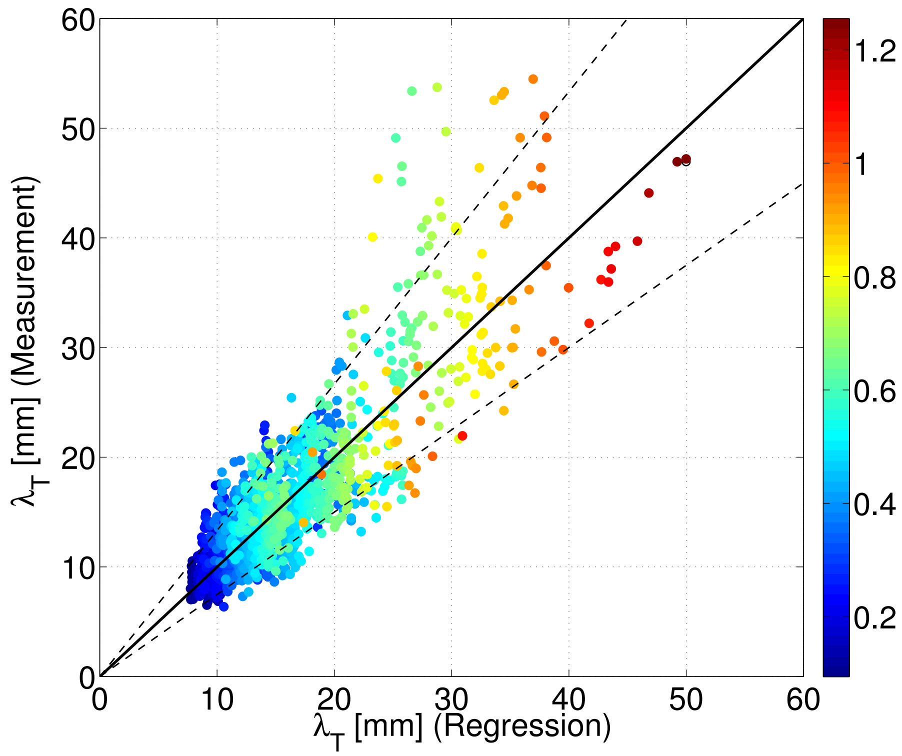

FIG. 3: Scaling of the near SOL temperature decay length using Eq. (8). The color coding is due to the turbulence parameter α_t. The lines show identity and $\pm 33\%$ deviation.

studies for 36 discharges (36 data points) containing low density (attached) plasmas. We test directly this reported regression law with the new data base and find $\lambda_T \propto q_{cyl}^{1.09} T^{-1.05}$. A further attempt finds $\lambda_T \propto B_{pol}^{-1.11} \alpha_t^{0.52}$. Our new work is hence consistent with the earlier approach as $q_{cyl}/T_e \propto \alpha_t^{0.5}$. However, both latter attempts have a reduced regression quality.

Figure 3 compares the measured versus the scaled values of the temperature decay length. Clearly a remaining scatter is present. However, the bulk of the data exhibits no deviation of more $\pm$ 33 % which is of similar quality as the previous multi-machine scaling [8]) while covering an operational range from low density towards high density limited discharges in a single machine.

In summary we have shown that a turbulence parameter in conjunction with the known neoclassical drift-orbit like scaling ($\propto 1/B_{pol}$) successfully describes the temperature decay length at the separatrix. In the limit of low edge densities, to which divertor heat load measurements are restricted, the previously established power width scaling is recovered.

Eq. (8) shows an increased power width when compared to the multi-machine IR based scaling through the influence of α_t at higher edge densities. The physics picture of the interplay of ion drift-orbit losses and anomalous electron heat diffusion, as put forward by various authors [9, 10, 12, 18] is consistent with our experimental findings based on a large data base. Our work is hence qualitatively consistent with the XGC1 simulations [12, 18] as a turbulence correlated widening of the near SOL power width is detected. For ASDEX Upgrade the observed widening of the power decay lengths does not exceed values of about two.

More practically we conclude for ITER that the challenging result of the power width $\lambda_q <$ 1 mm will be relaxed at the foreseen high separatrix densities of about $n_e^{sep} = 6 \cdot 10^{19} m^{-3}$ [1] or $n_e^{sep} = 0.5\, n_{GW}$ with n_{GW} being the Greenwald density [25]. Ideally, a new extrapolation to ITER will use data from tokamaks of varying size. Keeping this caveat of the current, purely AUG based, data base in mind we use the following ITER parameter. We calculate from Eq. (5) an $\alpha_t^{ITER} \approx$ 0.85 by using R = 6.2 m, $T_e^{sep} = 175$ eV, $Z_{eff} = 1.8$, $\kappa = 1.8$, $q_{cyl} =$ 2.42 [1] and find from Eq. (8) $\lambda_q = 2/7\lambda_T =$1.7 mm. The multi-machine divertor heat load based scaling gives $\lambda_q = 0.9$mm and the new data base for $\alpha \approx$ 0.1 gives about the same number $\lambda_q = 0.8$mm. While the beneficial aspect of the power decay length broadening of a factor of about two may appear as only a moderate increase it is of greatest importance to note that the onset of detachment is predicted to scale roughly $\propto n_{e,sep}^2/\lambda_q$ [3, 4]. Hence the required edge density could be roughly a factor of $1/\sqrt{2}$ relaxed for ITER as currently projected. As ITER needs to run at high elevated edge densities close to the HDL in order to meet the requirements of power exhaust, the latter relaxation is very important for the operational space of this device or fusion reactor designs.

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