Turbulence driven widening of the near-SOL power width for H-mode operation in ASDEX Upgrade

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Introduction: Operation of tokamaks with H-Mode characteristics at high densities and at least partially detached divertor conditions is generally foreseen for future high-power fusion systems, including ITER. An exact measure for the ease to access divertor detachment can only be given when the power width is known at conditions where the separatrix density is high [1, 2]. A multi-machine study was carried out to compare measurements of divertor heat flux from various tokamaks finding 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 [3]. 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 [4, 5]. This prediction for the near SOL power width matches closely experimental data and is described by

$$\lambda_q \simeq 1.6 \times \frac{a}{R}\rho_{s,pol}, \qquad \rho_{s,pol} = \sqrt{\frac{m_D T_{sep}}{e}}/B_{pol} \tag{1}$$

with minor and major radii a and R, m_D the ion mass, $T_{sep} = T_i = T_e$ being the electron temperature and B_{pol} the poloidally averaged poloidal magnetic field. This way the poloidally averaged power width for ITER was predicted to be of the order of 1mm. However, the former scaling comes with the restriction that only low-gas-puff discharges were considered. Please note that all decay lengths are given as poloidal averaged values except where noted.

Here, we set up a new data base containing data with very low to highest separatrix density plasmas until reaching the H-mode density limit using Thomson-Scattering to measure the electron density and temperature decay length at the separatrix (for details see [6, 7]), which will set the near-SOL power width through parallel heat conduction, $\lambda_{T_e} \simeq 7/2 \cdot \lambda_q$ [6, 8]. This attempt is motivated by the findings of Sun that at elevated separatrix densities a widening of the power width for H-Modes in AUG is observed outside the scaling prediction [6] as much as various authors [5, 9, 10] consider electron turbulence to become stronger at elevated edge densities and to scale positively with machine size and thus cause a widening of the power width. The work by Chang using the XGC1 code, for example, predicts a significant widening of the power width for ITER (Q=10) up to $\lambda_q \approx 5\,\mathrm{mm}$ at the outer equatorial mid-plane whilst good agreement to the empirical scaling for operating devices is found.

The edge plasma operational space in ASDEX Upgrade: In order to quantify the strength of anomalous fluxes we apply the turbulence control parameters based on the work of Scott [12] as well as based on the work of Roger, Drake, Zeiler [13] introducing the concept of a SOL plasma operational space. We use these turbulence control parameters to quantify the influence of the turbulence on near SOL electron density and temperature fall-off width. In these fundamental works it was proposed that the plasma edge is governed by two main parameters, the ideal MHD ballooning parameter α_{MHD} and a diamagnetic or turbulence parameter α_{t} which both can be expressed with good approximation for our data base as

$$\alpha_{\mathrm{MHD}} = R q_{cyl}^2 \frac{\beta}{\lambda_{\mathrm{p}}}, \qquad \alpha_{\mathrm{t}} \approx 3 \cdot 10^{-18}\, q_{\mathrm{cyl}}^2 R \frac{n_{\mathrm{e}}}{T_{\mathrm{e}}^2} Z_{\mathrm{eff}} \cdot f_{Z_{eff}} \simeq \alpha_d^{-2} \propto q_{cyl}\, \nu_e^* \tag{2}$$

Here we see that the turbulence parameter and a common description of an edge electron collisionality are linked to each other by the cylindrical safety factor, q_{cyl}. Figure 1 presents the ASDEX Upgrade operational range for L-,I- and H-Modes. We note for completeness that this attempt was pioneered by Suttrop and LaBombard for AUG and C-Mod, respectively [14, 15]. Fig.1 presents the ASDEX Upgrade data base versus α_{t}. The dashed line is empirically found and follows $\alpha_{\mathrm{MHD}} \simeq 1/2 \cdot \alpha_{\mathrm{t}}^{-2}$. All data points representing the classic H-Mode density limit are found in the vicinity of this boundary, which defines the transition to an inaccessible region of tokamak operation as predicted in [13]. The latter works conclude that the increasing non-adiabaticity of electrons cause an increase of interchange modes, consistent with the findings by Halpern [10]. The reason for the particular shape of dashed line is not obvious though we see a clear similarity to the numerical calculations as well as to the results by LaBombard for L-Mode plasmas. We also note that no data is found above the ideal MHD limit at about $\alpha_{\mathrm{MHD}} \simeq 2-2.5$ consistent with the findings in [7, 11]. In that earlier publication we claimed that the H-Mode density limit is found at the boundary of ideal-MHD, hence a horizontal range in the edge plasma operational diagram at $\alpha_{MHD} \simeq 2-2.5$. Indeed the data are restricted by this criterion. However, we find here an additional constraint on H-Mode operation based on α_t.

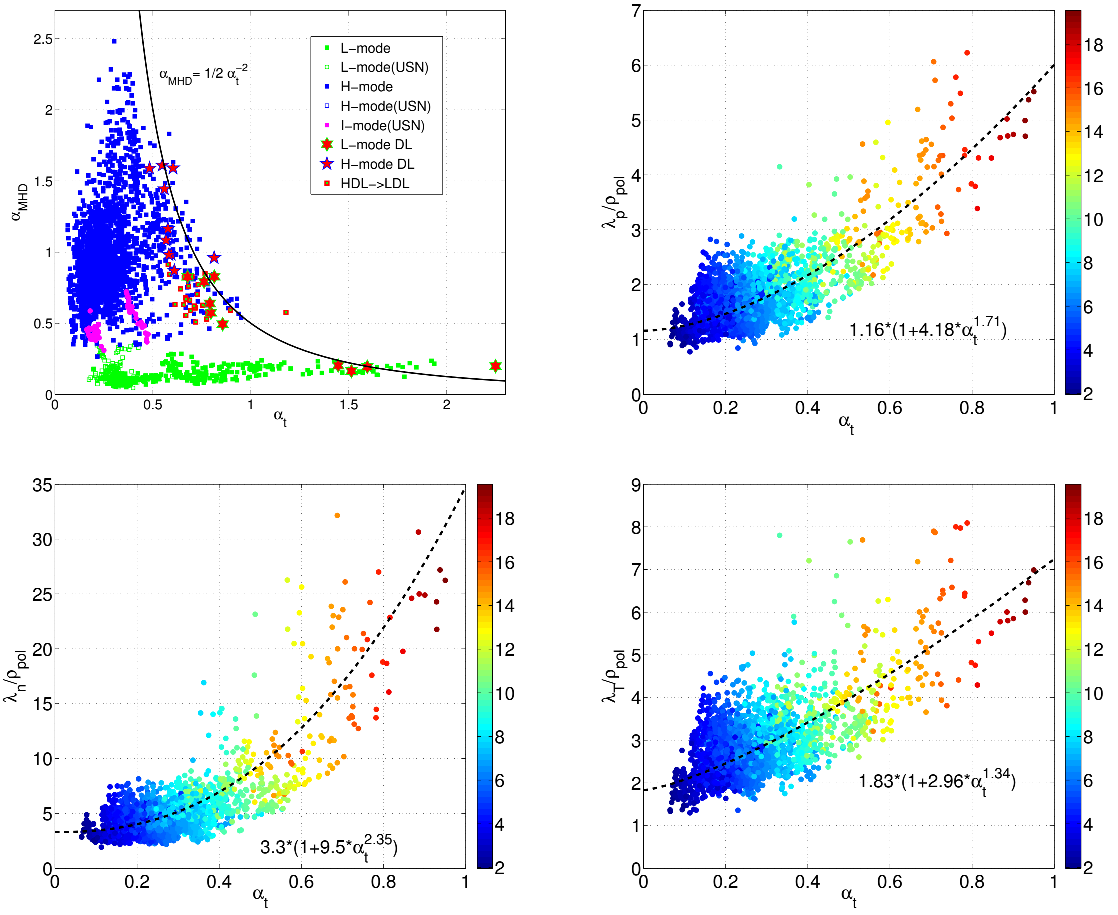

Figure 1: (a) The data base plotted in an existence diagram using α_{MHD} and α_{t}. The dashed line sets a boundary for the H-mode operation reached here by gas puffing.(b,c,d) Experimental values for the (b) pressure, λ_p, (c) density, λ_n, (d) electron temperature, λ_T, fall-off length divided by $\rho_{\mathrm{s,pol}}$ versus the turbulence parameter α_{t}. (b-d) Color coded by collisionality.

Scaling results: Our new data base covers H-Modes on the range I_p=0.6-1.2MA, P_{heat}=2-

20MW, B_{tor}=1.8-2.5T, n_{sep}=1-5e19m^{-3}, T_{sep}=70-120eV, q$_{cyl}$=3-6 and Z$_{eff}\simeq$ 1.3-2. Fig. 1 (b) displays the measured values of $\lambda_p/\rho_{s,pol}$ versus the turbulence parameter α_t. At low values of α_t, the ratio of $\lambda_p/\rho_{s,pol}$ is about unity whereas a clear widening is observed when the turbulence parameter increases. In order to find a regression law we propose a new ansatz to describe the temperature decay length (or power width) as a combination of the drift-orbit like scaling following solely $\rho_{s,pol}$ and the turbulence parameter α_t. In the limit of $\alpha_\mathrm{t}\rightarrow 0$ proportionality to $\rho_{s,pol}$ has to be found, to match the multi-machine result, thus we use the ansatz:

$$\lambda_\mathrm{p} = (1+C_\alpha\,\alpha_\mathrm{t}^a)\,C_\rho\,\rho_\mathrm{s,pol}^r. \tag{3}$$

This expression allows for both the observed ordering of low density discharges but also its widening due to the anomalous electron heat transport controlled by α_t as found in [5, 13]. For the pressure fall-off length (both λ_p and $\rho_\mathrm{s,pol}$ in units of [mm]) we find ($R^2 = 0.815$, RMSE: 2.16mm, 1721 data points used)

$$\lambda_p[mm] = (1+(4.32\pm0.29)\,\alpha_\mathrm{t}^{1.72\pm0.11})\cdot(1.3\pm0.16)\,\rho_\mathrm{s,pol}^{0.93\pm0.07}. \tag{4}$$

Here it is notable that the coefficient from the regression for the $\rho_\mathrm{s,pol}$ is close to unity. In order to employ a dimensionally correct regression we set $r = 1$ and find ($R^2 = 0.8146$)

$$\frac{\lambda_\mathrm{p}}{\rho_\mathrm{s,pol}} = (1+(4.18\pm0.24)\,\alpha_\mathrm{t}^{1.71\pm0.11})\cdot(1.16\pm0.07). \tag{5}$$

Fig.1 (b,c,d) presents the data for the pressure, density and temperature fall-off length normalized to ρ_s versus the turbulence parameter and colour coding according to collisionality. Explicitly we find for the density ($R^2 = 0.787$) and temperature fall-off length ($R^2 = 0.742$):

$$\frac{\lambda_n}{\rho_\mathrm{s,pol}} = (1+(9.51\pm2.4)\,\alpha_\mathrm{t}^{2.35\pm0.41})\cdot(3.31\pm0.75) \tag{6}$$

$$\frac{\lambda_T}{\rho_\mathrm{s,pol}} = (1+(2.96\pm0.5)\,\alpha_\mathrm{t}^{1.34\pm0.14})\cdot(1.83\pm0.28) \tag{7}$$

We detect this way that the influence of the turbulence parameter is stronger on the density than on the temperature decay length, both in the exponent and in the pre-factor. The ratio $\eta_\lambda = \lambda_\mathrm{n}/\lambda_\mathrm{T}$ is consequently dependent on α_t. In the limit $\alpha_\mathrm{t}\rightarrow 0$ a value for $\eta_\lambda\simeq$1.5 is found and for $\alpha_\mathrm{t}\rightarrow 1$ we estimate $\eta_\lambda\simeq$4.5 and hence η_λ varies about a factor of three. This means when approaching high edge densities in H-mode plasmas, the density decay length is widening far more strongly than the temperature decay length. Note that the regression quality is similar to the one obtained for the empirical heat load based scaling.

Typical numbers for α_t which are representing conditions used in prior divertor heat load studies are about $\alpha_t\simeq 0.3$. Inserting α_t into Eqn.(7) and recalling that for ASDEX Upgrade geometry $\lambda_\mathrm{q,MP}\simeq 0.59\,\lambda_\mathrm{q}$ and $B_\mathrm{pol,MP}\simeq 1.31\,B_\mathrm{pol}$ and using T_e we write

$$\lambda_\mathrm{q,MP}^{\alpha_t=0.3}[mm] = 2.5\cdot\frac{2}{7}\cdot 0.59\cdot 1.31\cdot B_\mathrm{pol,MP}^{-1} = 0.64\cdot B_\mathrm{pol,MP}^{-1} \tag{8}$$

which gives a remarkable good match to the multi-machine scaling (Reg.#4) $\lambda_{q,MP}[mm] = 0.65B_{pol,MP}^{-1.11}$. In absence of an updated multi-machine attempt an extrapolation stays speculative in nature. In particular comparison to e.g. JET is of great interest. Keeping this caveat in mind we speculate that the projected power width could be enlarged w.r.t. currently published values when the edge density is close to its maximum. However, values in the range of 5-10 as predicted by XGC1 code are not observed.

Concluding remarks:

Fig.2 plots the confinement factor $H_{98,y2}$ versus the turbulence parameter. The increase of α_t and hence the power width is observed to be accompanied by a reduction of $H_{98,y2}$. Plasma discharges with higher shaping show higher $H_{98,y2}$ values at same α_t. This observation needs further investigation and should be kept in mind when planning new multi-machine experimental measurements.

In sum, the well established multi-machine scaling is identified to define a lower limit, at a small turbulence level, for the power width. A widening of a factor of about two for the power width or temperature decay length is observed at higher values of α_t and collisionality. The observed reduction of the confinement factor is consistent with the picture of elevated turbulence at increased α_t.

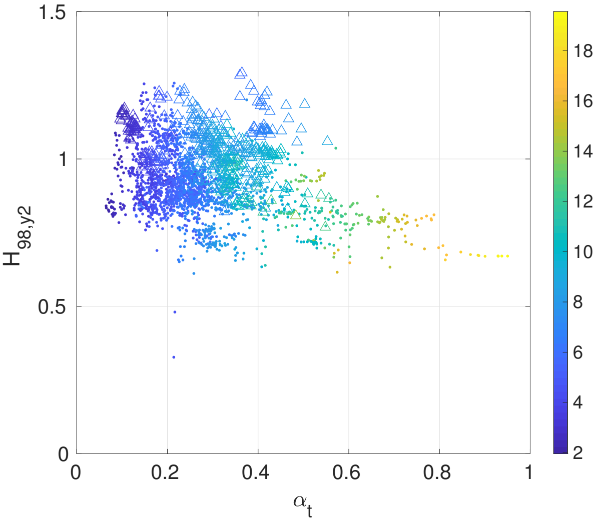

Figure 2: Reduction of H_{98} with increasing α_t values. Color coding as in Fig.1. Open triangles represent discharges with high shaping through the upper triangularity.

Acknowledgements

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