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Efficiency of transport suppression due to $\boldsymbol{E} \times \boldsymbol{B}$ flow shear—a parameter study

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Abstract. Turbulence suppression by shear in the $\boldsymbol{E} \times \boldsymbol{B}$ flow is a widely accepted mechanism. Edge polarization experiments on TEXTOR-94 have been used to study the dependence on the toroidal magnetic field, plasma current and plasma composition of the critical $\boldsymbol{E} \times \boldsymbol{B}$ shear, defined as the highest rate of change in the diffusion coefficient with shear. Our experiments show that an increase of the isotopic mass and/or a decrease of the toroidal magnetic field leads to higher critical $\boldsymbol{E} \times \boldsymbol{B}$ flow shear, whereas a change of the plasma current seems to have no effect.

1. Introduction

The potential of $\boldsymbol{E} \times \boldsymbol{B}$ flow shear for establishing particle transport barriers and improving particle confinement has been demonstrated on TEXTOR-94 by inducing positive electric fields in the edge plasma [1]. A radial current which is drawn by a mushroom-shaped electrode, positioned inside the last closed flux surface and biased with respect the toroidal belt limiter ALT-II leads to a poloidal rotation and hence to high electric fields. The electrode voltage is slowly ramped up during the flat-top phase of a deuterium plasma discharge at standard parameters of a line-averaged central target density $\overline{n}_{e,0} = 1.0 \times 10^{13}$ cm^{-3}, a plasma current $I_P = 200$ kA and a central toroidal magnetic field $B_{t,0} = 2.33$ T. In order to check the influence of B_t the toroidal magnetic field was varied in the range of 1.8–2.6 T. In addition, a set of discharges was performed in hydrogen to study the influence of the isotope on the polarization experiment. For the exploration of the role of the edge temperature the plasma current was scanned from 150 kA to 233 kA, while keeping the edge q at a constant value of 7.2 by adjusting the toroidal magnetic field appropriately. Each series of discharges was performed within the same experimental day. Thus, possible differences due to changing machine conditions are minimized.

2. Critical $\boldsymbol{E} \times \boldsymbol{B}$ flow shear

In [2] the critical $\boldsymbol{E} \times \boldsymbol{B}$ flow shear is introduced, which corresponds to the electrical field gradient for which the poloidal turbulence shearing rate τ_s^{-1} is equal to the turbulence decorrelation rate τ_{co}^{-1}. Assuming the turbulence to be isotropic, we find for the critical electric field gradient

$$\nabla E_{crit} = \sqrt{2}(\langle k_\perp^2 \rangle D)_0 B_t(r). \tag{1}$$

The critical field gradient is a measure for how efficient an induced $\boldsymbol{E} \times \boldsymbol{B}$ flow shear can quench turbulent transport. Higher values for ∇E_{crit} indicate that more shear has to be applied in order to achieve the same amount of turbulence suppression.

Even for infinite shear a certain level of transport will remain, which will be denoted by D_{rest}, whereas the part of the particle transport subject to be quenched by the $\boldsymbol{E} \times \boldsymbol{B}$ shear is considered to be the anomalous diffusion D_{ano}. In [3] a generic form for the change of the particle diffusion coefficient D independent of the specific poloidal shear mechanism is proposed, which can be written, with the help of the definition of (1), as

$$D = D_{\mathrm{rest}} + \frac{D_{\mathrm{ano}}}{1 + (\nabla E_{\mathrm{r}}/\nabla E_{\mathrm{crit}})^{\gamma}}. \tag{2}$$

The exact value of the exponent γ depends on the model assumed for the nonlinear decorrelation. In case of strong shear Biglari *et al* [4] proposed $\gamma = 2/3$. If only weak shear is present, Shaing *et al* [5] found $\gamma = 2$. Zhang and Mahajan [6] have concluded $\gamma = 2$ for arbitrary shear. It is not the subject of this paper to try a distinguish among the various models. Nevertheless our analysis shows γ to be in the range of two to four.

3. Experimental results

The effect of the flow shear on confinement will be analysed along two different lines: on the basis of a local plasma quantity, the particle diffusion coefficient D at the location of the edge barrier in particle transport, and on the basis of a global plasma parameter, the reciprocal particle confinement time τ_{p}^{-1}. The strength of the barrier is quantified by κ_D

$$\kappa_D = \frac{D}{D_0} = \frac{\nabla n_0}{\nabla n}\frac{\Gamma}{\Gamma_0} = \frac{\nabla n_0}{\nabla n}\frac{H_\alpha}{H_{\alpha,0}} \tag{3}$$

where Γ is the outward flux of particles as monitored by the edge-recycling H_α and the pre-biased values are indicated by the index '0'. For easy comparison the global change in τ_{p} is illustrated by $\kappa_{\tau_{\mathrm{p}}}$

$$\kappa_{\tau_{\mathrm{p}}} = \frac{\tau_{\mathrm{p},0}}{\tau_{\mathrm{p}}} = \frac{(N_{\mathrm{e,tot}})_0}{N_{\mathrm{e,tot}}}\frac{\Gamma}{\Gamma_0} = \frac{(N_{\mathrm{e,tot}})_0}{N_{\mathrm{e,tot}}}\frac{H_\alpha}{H_{\alpha,0}} \tag{4}$$

where $N_{\mathrm{e,tot}}$ denotes the total number of electrons in the discharge. Using the normalized values $\kappa_D = D/D_0$, $\kappa_{\tau_{\mathrm{p}}} = \tau_{\mathrm{p},0}/\tau_{\mathrm{p}}$ and the definition $\kappa_{\alpha,\mathrm{rest}} + \kappa_{\alpha,\mathrm{ano}} = 1$, with $\alpha = D$, τ_{p} equation (2) becomes

$$\kappa_\alpha(\nabla E) = (1 - \kappa_{\alpha,\mathrm{ano}}) + \frac{\kappa_{\alpha,\mathrm{ano}}}{1 + (\nabla E/\nabla E_{\mathrm{crit}})^{\gamma}} \tag{5}$$

with $\kappa_{\alpha,\mathrm{ano}}$, γ and ∇E_{crit} as free parameters. κ_{ano} is that part of transport which can be fully suppressed.

While such analysis could be performed on any measured quantity, which is related to particle transport, for example the turbulent outflow flux $\tilde{\Gamma}$, in the following sections we will apply the analysis to the measured changes in the diffusion coefficient and particle confinement time, and will refer to it as the D analysis and τ_{p} analysis. The values for the electrical field gradient and density gradient have been taken at the location of the maximum electric field gradient, where the transport barrier is also found.

An example of such analysis of a deuterium plasma discharge with a plasma current of 233 kA and a toroidal magnetic field of 2.75 T is illustrated in figure 1. Although the decrease of the diffusion coefficient is larger than the relative gain in the particle confinement time, the highest rate of change appears for both quantities at approximately the same electric field

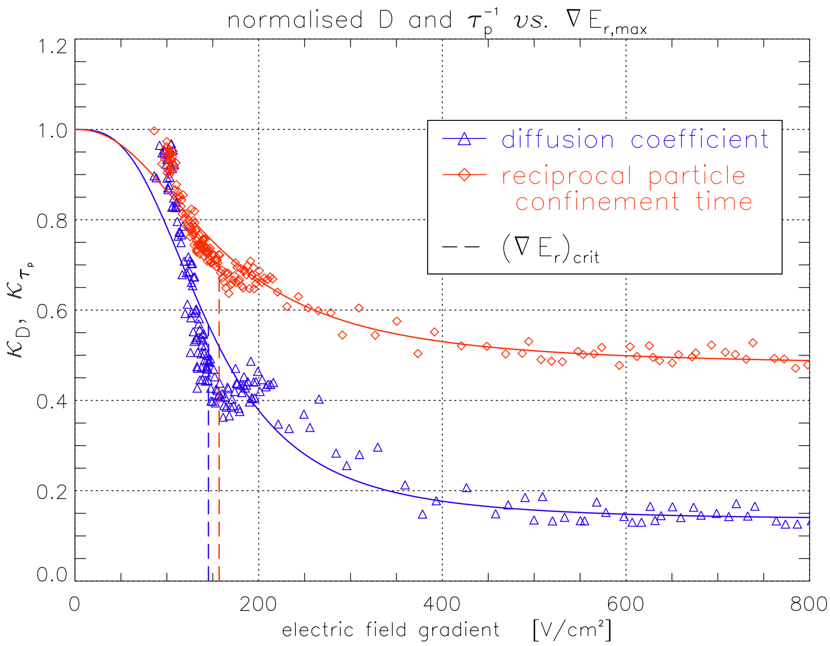

Figure 1. Relative change of the barrier diffusion coefficient (△) and of the reciprocal particle confinement time (◇) plotted against the maximum electrical field gradient in a deuterium plasma with $I_p = 233$ kA and $B_t = 2.75$ T. The full curves show the best fits according to (5), which revealed the critical electric field gradients as indicated by the vertical broken lines.

gradient. The broken lines represent the critical field gradients as retrieved from the analysis as described above. The exponent γ was found from the fit of the diffusion coefficient to be 2.9 and from the particle confinement time to be 2.3. The non-uniform decrease of κ_D in the vicinity of ∇E_{crit} could point to a multi-mode feature of the turbulence.

The toroidal magnetic field B_t was varied in deuterium plasmas on a shot to shot basis in the range of 1.8–2.6 T, which corresponds to a q_{edge} of 5.2 and 7.5, respectively. It is important to note that no changes in the edge profiles of density and temperature in the pre-biased phase were observed. In figure 2 the experimental findings for ∇E_{crit} over the explored B_t range are summarized. One notes that the critical field gradient values inferred from the D and τ_p analyses are increasing with B_t and that a least-squares fit reveals a power dependence on B_t of 1.4 for each set of data. One should be aware that in equation (1) the local magnetic field value has to be considered, which, in our experiment, is $B_t(a) = 0.8B_{t,0}$. However this matters only for the multiplier in the proportionality between ∇E_{crit} and B_t.

Discharges under standard conditions ($B_t = 2.33$ T, $I_p = 200$ kA) were performed in hydrogen and deuterium gas. The values of the critical electric field gradients ∇E_{crit}, which resulted from an ensemble average of comparable discharges, are brought together in figure 3. A clear decrease of ∇E_{crit} with increasing isotopic mass is seen. A least-squares fit of the combined D and τ_p data sets yield a power dependence of ∇E_{crit} on A with an exponent of $\beta = -1.2$. A separate calculation of the scaling, based on the data of the D analysis and of the τ_p analysis, results, respectively, in $\nabla E_{crit} \propto A^{-1.6}$ and $\nabla E_{crit} \propto A^{-0.7}$. The limited range of the data prevents us from deciding if the effect of the isotopic mass is systematically weaker for τ_p than for D.

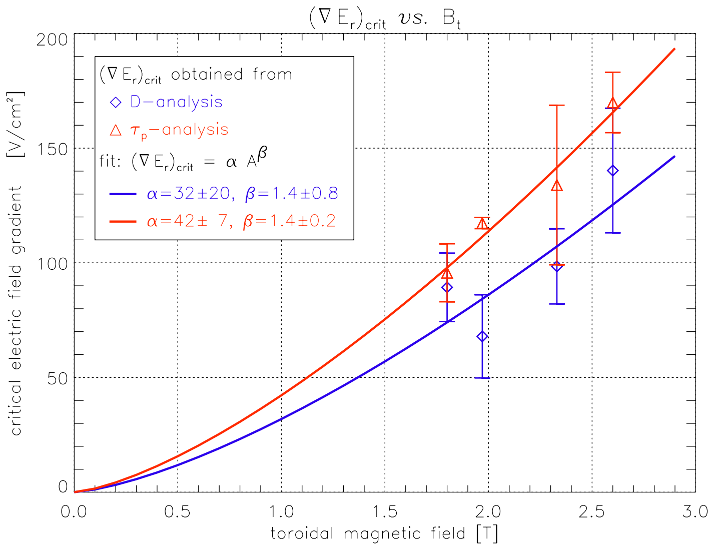

Figure 2. Obtained critical electric field gradients from fits on κ_D (◇) and on κ_τ (△) plotted against the toroidal magnetic field. The full curves show the best fit of a power dependence of $\nabla E_{\mathrm{crit}} \propto B_{\mathrm{t}}^{\beta}$ with a power $\beta = 1.4$ applied separately to each set of data.

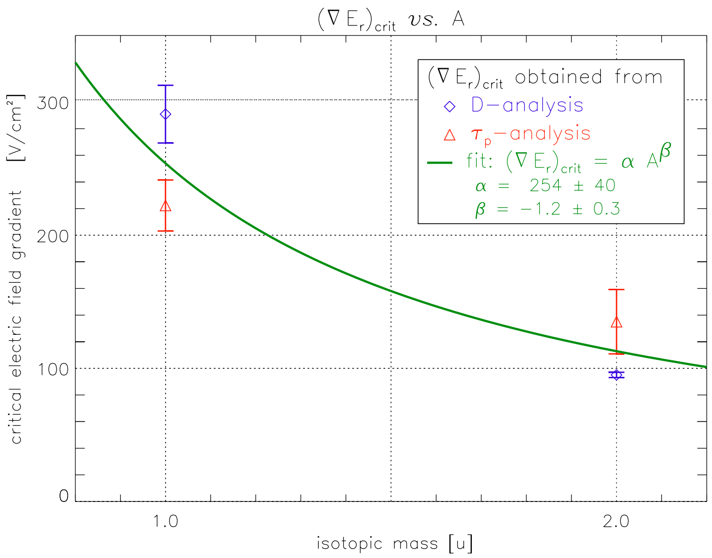

Figure 3. Deduced critical electric field gradients plotted against the isotopic mass. The curve is the best fit of a power dependence $\nabla E_{\mathrm{crit}} \propto A^{\beta}$ with an exponent $\beta = -1.2$, applied to the combined data sets from the D and τ_{p} analyses.

We also performed a constant-q scan where the edge value of q was kept at a constant value of 7.2, by changing the plasma current in the range of 150–233 kA and adapting the magnetic field accordingly from 1.8 to 2.8 T. As can be seen from figure 4, the critical field gradient shows only a weak dependence on the plasma current, meaning that the expected variation of ∇E_{crit} with B_{t} appears to be off set by a scaling of the critical field gradient with the plasma current with an exponent of about -1.66.

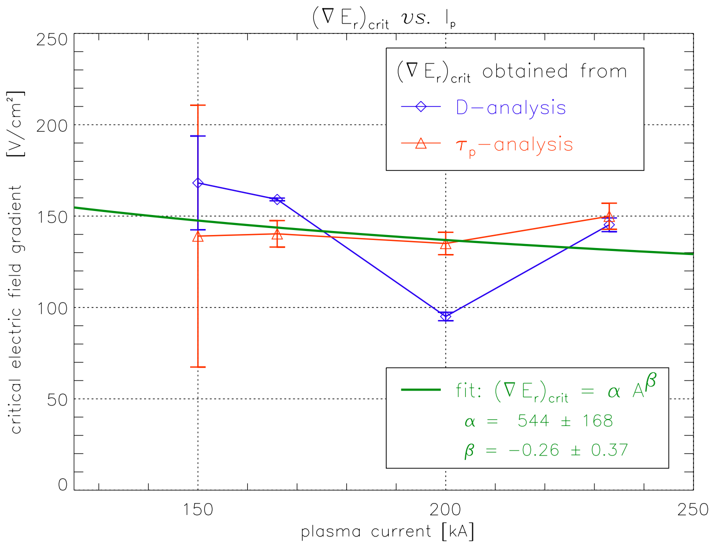

Figure 4. Critical electric field gradients yield from discharges at various plasma currents. The full line represents the least-squares fit applied to the combined data sets suggests ∇E_{crit} to slightly decrease with I_p with an exponent of -0.26.

4. Summary and conclusion

Our results point to a scaling of the critical electric field gradient in terms of the global plasma parameters B_t, A and I_p of the form:

$$\nabla E_{crit} \approx 5.8 \times 10^5 B_t^{1.4} A^{-1.2} I_p^{-1.66} \qquad (\mathrm{V\ cm^{-2}, T, u, kA}). \tag{6}$$

Because of uncertainties in the local edge T_e measurement, we have hitherto been unable to establish a scaling in which this very important local plasma parameter appears alongside B_t and A. It is however, already important to find out what the theory predicts for the dependence on the magnetic field and the isotopic mass. Assuming Bohm scaling for the diffusion coefficient $D_0 \propto T/B$ in the absence of $\boldsymbol{E} \times \boldsymbol{B}$ shear and a perpendicular wavenumber of the turbulence $k_\perp$ to scale as the inverse Larmor radius and the electron temperature T_e of order of the ion temperature T_i, the critical field gradient should scale with the magnetic field and the isotopic mass as

$$\nabla E_{crit} \propto B_t^2 A^{-1}. \tag{7}$$

The dependence on the isotopic mass comes into play only via the perpendicular wavenumber. Our scans of the magnetic field show ∇E_{crit} to indeed increase with B_t with a scaling as $B_t^{1.4}$. The experimental scaling (equation (6)) is remarkably similar to the Bohm prediction (equation (7)).

Instead of assuming the edge particle confinement to be Bohm-like one could actually use our results on ∇E_{crit} as a means to study the background plasma, namely the scaling of the diffusion coefficient in the absence of shear D_0. According to (1) and with the help of the measured ∇E_{crit}-scaling D_0 as

$$D_0 \propto \frac{\nabla E_{crit}}{\langle k_\perp^2 \rangle_0 B_t} \propto \frac{A}{B_t^3} \nabla E_{crit} \propto A^{-0.2} B_t^{-1.6} \tag{8}$$

which is between the Bohm ($D_0 \propto T B^{-1}$) and gyro-Bohm ($D_0 \propto T^{1.5} L_n^{-1} B^{-2}$) scaling.

Summarizing, we confirm in our electrode biasing experiments that B_t and A are the experimental parameters having a significant impact on the mechanism of turbulence suppression due to $\boldsymbol{E} \times \boldsymbol{B}$ shear. Whether they are the sole agents, as suggested by the simplified theoretical prediction equation (7), is a far-stretching prediction that still deserves further investigation. In particular, the role of the plasma current as a global parameter, or of the temperature or density as additional local parameters is still unclear. As the toroidal magnetic field increases or the isotopic mass decreases, higher electric field gradients are needed for D and τ_p to react. Thus the H-mode regime is more difficult to achieve. This observation could have some bearing on the scaling of the power threshold in spontaneous H-mode discharges. Finally, we like to stress that the concept of the critical electric field gradient offers a means for an universal comparison of experiments in which transport suppression due to $\boldsymbol{E} \times \boldsymbol{B}$ shear is taking place.

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