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# Numerical modelling of changes of edge plasma transport due to the presence of TEXTOR-DED

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**Abstract**

We use the 2D multifluid code TECXY to model possible changes of edge plasma transport in the vicinity of the dynamic ergodic divertor (DED) of TEXTOR tokamak. The increased effective radial transport coefficients in the stochastic magnetic field are calculated according to an analytical model of optimal paths. We also replaced our standard radial transport model (Alcator scaling) by a more sophisticated model accounting for drift turbulence. A parameter study is carried out in order to estimate possible changes of plasma profiles due to the different kinds of anomalous transport and the DED position. The influence on impurity radiation and screening is also investigated.
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## 1. Introduction and physical model

In the present paper we use an updated version of the 2D multifluid code TECXY [1–6] to model possible changes of edge plasma and carbon impurity transport in the vicinity of the TEXTOR dynamic ergodic divertor (DED) [7]. The DED creates a perturbation field which generates a stochastic (ergodic) boundary layer in the outermost region of the plasma near the separatrix. The ergodicity enhances the radial diffusive and convective transport significantly. The DED replaces the former bumper limiter which was able to trigger the evolution of Marfes. The changes to the onset and strength of Marfes in the presence of DED were treated in Ref. [4]. Here we concentrate on a low density and low power input regime because the experiments performed so far remained in this regime and avoided the approach to Marfe instability. The increased effective radial transport coefficients in the stochastic magnetic field are calculated according to Tokar's [8] model of 'optimal paths', which leads to analytical formulae involving the fieldline diffusion coefficient $D_{\mathrm{Fl}}$ and the Kolmogorov length $L_{\mathrm{K}}$ as the essential parameters.

*The physical model* in the TECXY code is based on Braginskij-like equations for the background plasma and rate equations for the impurity ions. The transport along field lines is assumed to be classical, and the radial transport is anomalous with prescribed radial transport coefficients of the order of Bohm diffusion. Hitherto we usually used an Alcator-like scaling for the anomalous transport with a diffusion coefficient $D_{\perp} = D_{\perp}^{\mathrm{ref}} \times Min(1, n_{\mathrm{e}}^{\mathrm{ref}}/n_{\mathrm{e}}(r,\theta))$. The reference density $n_{\mathrm{e}}^{\mathrm{ref}}$ is taken at the separatrix and at outboard midplane (with the

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reference coefficient $D_\perp^{\rm ref} = 1\,{\rm m}^2/{\rm s}$). We compare this Alcator scaling with a more sophisticated model accounting for different kinds of turbulent transport. In particular, we assume that on closed magnetic surfaces the transport is driven by drift resistive ballooning (DRB) instability [9] and by drift Alfvén (DA) instability [10] using simplified analytical formulae from mixing length approximation.

We do not discuss here the ITG instability and the DTE instability because they can be shown to be negligible in the parameter range considered in our calculations for the TEXTOR boundary layer. The DRB instability is driven by pressure and magnetic curvature effects. The DA instability involves a coupling between Alfvén waves and electron drift waves with increasing plasma pressure. The respective diffusion coefficients are written as

$$D_\perp^{\rm DRB} = (2\pi q\rho_{\rm e})^2 \nu_{\rm e} R\left(-\frac{{\rm d}\ln n_{\rm e}}{{\rm d}r}\right),$$
$$D_\perp^{\rm DA} = \frac{1}{\sqrt{\mu}}\chi_{\rm GB}\bar{\bar{\chi}}_\perp(\beta_{\rm n},\nu_{\rm n}), \tag{1}$$

where $q$ is the safety factor, $\rho_{\rm e}$ the electron gyro radius, $\nu_{\rm e} = \nu_{\rm ei}$ the collision frequency (with the ion charge $Z_{\rm eff}e$) and $R = 1.75\,{\rm m}$ the major radius of TEXTOR. We use the Gyro–Bohm diffusion $\chi_{\rm GB} = \rho_{\rm s}^2 c_{\rm s}/L_{\rm p}$ and the dimensionless parameters $\mu = k_\| V_{\rm the} L_{\rm p}/c_{\rm s}$ and $\bar{\bar{\chi}}_\perp(\beta_{\rm n},\nu_{\rm n})$, where $\rho_{\rm s}$ and $c_{\rm s}$ are the ion Larmor radius and the sound speed using the electron temperature $T_{\rm e}$, $L_{\rm p}$ is the (total) pressure decay length, $k_\| = 1/qR$, $V_{\rm the}$ is the thermal velocity of electrons, while $\beta_{\rm n}$, $\nu_{\rm n}$ are the normalized plasma $\beta$ and normalized collision frequency (see Ref. [10]). For the densities and temperatures we use flux surface averaged values. From these the radial gradients are derived. We note that the 'advanced' turbulent transport, contrary to Alcator scaling, cannot describe poloidal dependencies of transport coefficients and poloidally local effects.

For every ion species we solve the continuity, parallel momentum and energy equations. All ion species are assumed to have the same common temperature $T_{\rm i}$, which differs from the electron temperature $T_{\rm e}$. An analytical description of two groups of neutrals (cold and cx) allows to take into account plasma recycling as well as sputtering and self-sputtering of impurity atoms at the ALT-II limiter surface [3]. Moreover the present version of the code ([2–5,11]) incorporates drift motions and currents in a fully self-consistent way with plasma and impurity dynamics. The details of the model are described in [1–3,11] and the references cited therein. We concentrate here on the role of neutrals recycled from the DED surface and on the role of stochastic transport from the DED perturbation field for the plasma profiles. In order to model the DED region (which replaces the former bumper region) we have assumed high additional recombination losses inside this region and a suitably chosen profile for the recycled neutrals penetrating from the DED surface into the adjacent plasma. Details of the model for the hydrogen and carbon neutrals have been presented in Ref. [4].

*Transport in stochastic fields*: The transport coefficients in a stochastic magnetic field are computed according to Tokar's [8] transport formulae by taking into account analytical relationships for the distribution of plasma parameters along divergent lines of force. The transport in a stochastic field is considered as a sequence of displacements both parallel and perpendicular to the magnetic field lines, which are linked together forming 'optimal paths' with largest effective radial transport. Due to the stochasticity of the magnetic field, the radial distance between parallel sections of the path changes with their length $l$. For small $l$ this distance obeys the exponential law $\delta_1 = \delta(l) = \delta_0\exp(l/L_{\rm K})$ and characterizes the local divergence of field lines in the stochastic layer, where $L_{\rm K}$ is the Kolmogorov length. For large $l$ this is replaced by a diffusive law $\delta_1 = \delta(l) = \sqrt{2D_{\rm Fl}l}$, where $D_{\rm Fl}$ is the field line diffusivity and has also the dimension of a length (${\rm m}^2/{\rm m}$). Both parameters are determined by the spectrum and strength of the field perturbations and can be varied independently.

## 2. Description and discussion of calculated results

*Choice of parameters:* For the purpose of our parameter study we need reasonable values for the fieldline diffusion coefficient $D_{\rm Fl}$ and the Kolmogorov length $L_{\rm K}$.

For TEXTOR-DED, according to Refs. [12,4], typical values in the ergodic zone might be $D_{\rm Fl} > 0.4\times10^{-5}\,{\rm m}^2/{\rm m}$ and $L_{\rm K} \leqslant 20\,{\rm m}$ depending on $I_p$ and the helical perturbation currents. There is a fast radial decay of $D_{\rm Fl}$ and radial increase of $L_{\rm K}$ beyond $y = 44\,{\rm cm}$ towards the plasma core. For the present calculations we have chosen the values $D_{\rm Fl} = 2\times10^{-5}\,{\rm m}$ and $L_{\rm K} = 10\,{\rm m}$ which represent according to [4] a relatively high level of stochasticity corresponding to the envisaged strength of the DED coil currents. The resulting stochastic transport coefficients are radially reduced to zero by an s-like function, and they are poloidally restricted to the DED-region.

We have simulated low density low power TEXTOR discharges in deuterium with carbon as the dominant intrinsic impurity element. The total magnetic field is $B = 2.25\,{\rm T}$, the plasma current $I_p = 350\,{\rm kA}$ and the Shafranov shift $\Delta = 6\,{\rm cm}$. The DED is introduced into the scrape-off layer in a region between $-60°$ and $+60°$ below and above the high-field side, leaving a width of about 1.7 cm between the DED surface and the last closed flux surface, which in our normalized radial coordinates corresponds to 1.25 cm. Our grid covers the region $0.41\,{\rm m} \leqslant r \leqslant 0.50\,{\rm m}$. The separatrix $a = 0.46\,{\rm m}$ is defined by the toroidal ALT-II limiter, and the assumed recycling coefficient with respect to this limiter is $R = 0.75$. This value is an empirical constant for typical TEXTOR discharge conditions (see Ref. [3]). We allow for a shift of one (normalized) cm of the plasma column towards the DED, which is simulated in the code by shifting the DED surface 1 cm towards the separatrix, such that it is still 0.25 cm in the shadow of the ALT-II limiter, but nevertheless is subject to taking over a larger part of the limiter load.

We investigate the *influence of stochastic transport and DED position* on the plasma profiles first *for anomalous transport with Alcator scaling* and later pass to the modifications as produced by applying the formulae for drift turbulent transport. Our standard input particle flux is $\Gamma_{inp} = 2.5 \times 10^{21}$/s and the input power $Q_{inp} = 0.5$ MW. In the absence of stochasticity the anomalous heat conduction coefficients are related to the anomalous diffusion coefficient by $\chi_{e\perp}/n_e = 3D_\perp$ and $\chi_{i\perp}/n_i = D_\perp$. Fig. 7 illustrates the role of the additional radial particle diffusion and electron heat conduction from stochasticity (index DED). We see that a strong stochastic transport is to be expected in the transition layer in a radial interval between about 43 cm and 45 cm. Just in front of DED ($r > 45$ cm) the influence of stochastic transport is small because it is related to classical parallel transport which becomes small for the low temperatures close to the DED surface. For more details about stochastic transport we have to refer to [4].

Fig. 1 compares radial and poloidal plasma profiles for $\Gamma_{inp} = 2.5 \times 10^{21}$/s. Here and in the following radial profiles are always shown at high field side ($\theta = 180°$), whereas poloidal profiles always refer to a radius at 1.25 cm in front of the DED surface (i.e. $r = 46$ cm for normal position of DED surface, $r = 45$ cm for shifted position). Note that radial profiles beyond the DED surface are purely fictitious and have no physical meaning. We see that the effect of shifting DED is much more important than the effect of switching on stochastic transport. The latter only leads to a flattening of radial density and temperature profiles in the radial interval with large $D_\perp^{DED}$ and $\chi_{e\perp}^{DED}$. Shifting DED, however, leads to a high recycling zone in front of DED, with a density pedestal and a temperature dip, accompanied by a radial zone of counterclockwise poloidal circulation (in negative $x$- or positive $\theta$-direction), which leads to a shift of the density maxima and temperature minima towards the lower end of DED (facing the ALT ion side). There is even a tendency to an overlapping and merging of the high recycling zone in front of DED with the recycling zone belonging to the ALT ion side.

Fig. 2 shows the behaviour of the carbon impurities corresponding to the cases treated in Fig. 1. The poloidal profiles of the carbon densities $n_0$, $n_{2+}$ and $n_{4+}$ and of the line radiations $P_{2+}$, $P_{4+}$ and $\sum_z P_{z+}$ have been radially integrated and normalized by the layer width of 9 cm. Again the main effect is produced by the DED shift and the consequent increase of the impurity source. Note, however, that switching on stochastic transport, while increasing the density and radiation of $C^{2+}$, decreases the density and radiation of $C^{4+}$. This reflects the strongly enhanced radial impurity convection towards the DED surface in particular for the higher charge states (see Ref. [4]), which on the one hand increases the carbon recycling and the total integrated carbon radiation, and on the other hand screens the plasma core efficiently from impurities. In fact for normal DED position the average $Z_{eff}$ at the core boundary is reduced

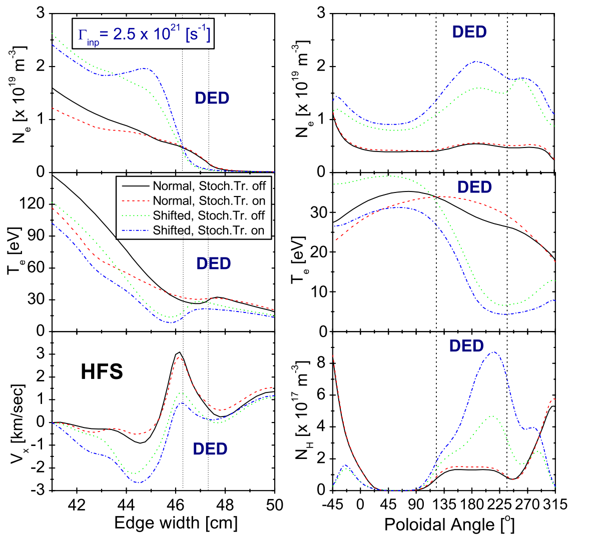


Fig. 1. DED scan – plasma profiles.

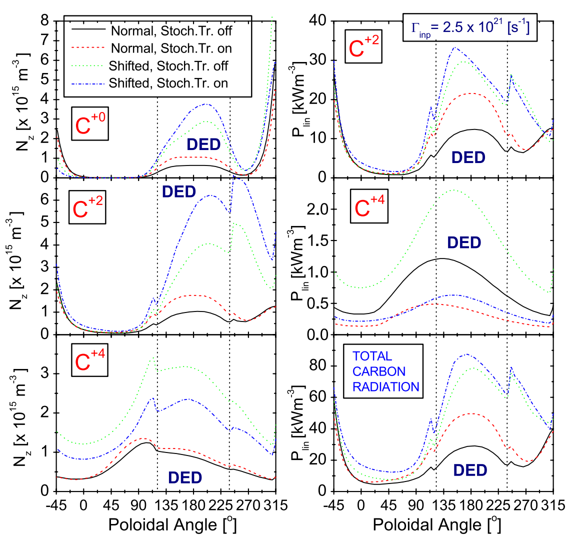


Fig. 2. DED scan – radially integrated carbon profiles.

from 1.36 to 1.26, for shifted DED position from 1.54 to 1.21. We also observe that the poloidal maxima of carbon radiation are shifted relative to the maxima of carbon density, for the lower charge states towards the upper end of the DED limiter, because we need also a sufficiently high temperature for getting an enhanced radiation. The same is true for hydrogen radiation (Fig. 5(a)), which is almost as large as the impurity radiation.

Repeating all these calculations for an increased input particle flux of $\Gamma_{\rm inp} = 3.0 \times 10^{21}$/s we would see that for normal position of DED the input flux is approaching a threshold for Marfe instability. A density peak begins to develop which is accompanied by a deep temperature depression. Impurity and hydrogen radiation is locally strongly increased. We remind that the evolution of Marfe phenomena had been investigated for the original bumper limiter in Refs. [5,6] and for the DED case in Ref. [4]. In the shifted position of DED, however, we do not see a sign for a Marfe-like thermal instability. Instead, when switching on stochastic transport, we get a high recycling regime with very broad profiles of high densities and low temperatures connecting the DED region with the ALT ion side. In this special case we have so low electron temperatures (<3 eV) immediately in front of the DED surface that the impurity production is reduced to chemical sputtering, thus strongly decreasing the available carbon densities and carbon radiation, which more than compensates the increase of hydrogen radiation. Of course we observe again carbon screening by switching on stochastic transport. For normal position the average $Z_{\rm eff}$ at the core boundary is reduced from 1.32 to 1.13, for shifted position from 1.47 to 1.15.

For the case of stochastic transport switched on we show also a $\Gamma$ scan, $\Gamma_{\rm inp} = (1.5, 2, 2.5, 3) \times 10^{21}$/s, the power input being fixed to $Q_{\rm inp} = 0.5$ MW. For normal position of DED we would see the approach to Marfe threshold. Figs. 3, 4 and 5(b) correspond to shifted position of DED and illustrate the approach to the high recycling regime with poloidally broad profiles and reduced carbon radiation. Note that for the highest $\Gamma_{\rm inp}$

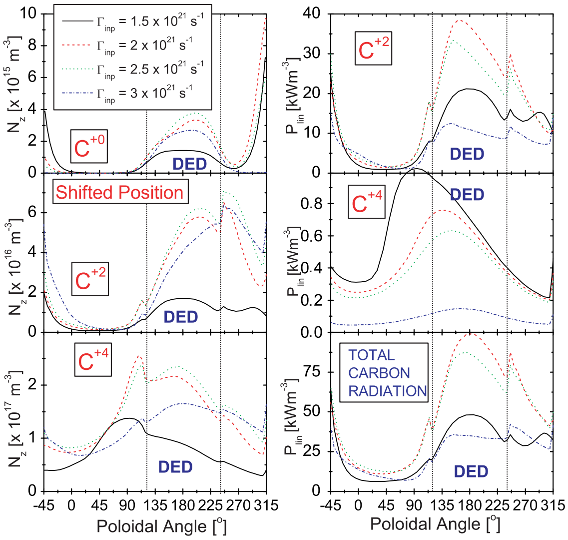


Fig. 4. Gamma scan – Shifted position – Radially integrated carbon profiles.

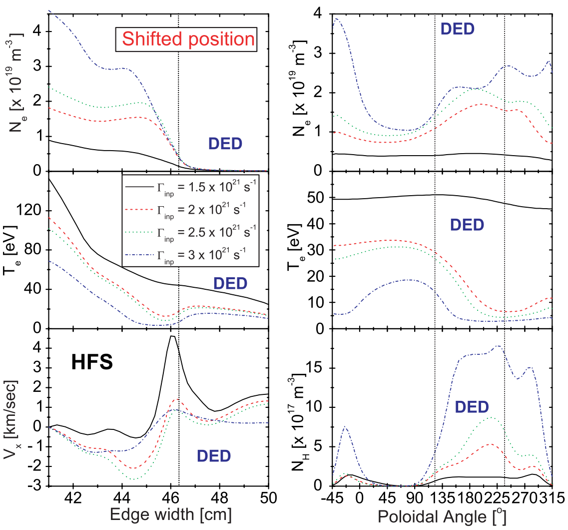


Fig. 3. Gamma scan – Shifted position – Plasma profiles.

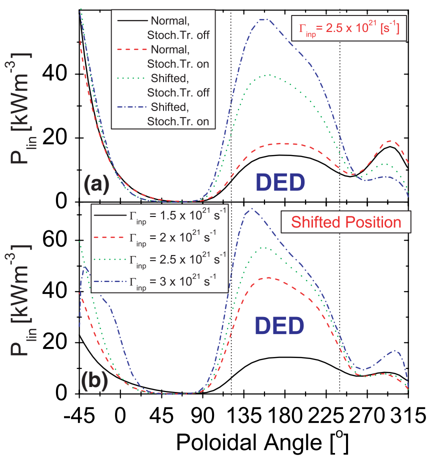


Fig. 5. Radially integrated hydrogen radiation. (a) DED scan and (b) Gamma scan.

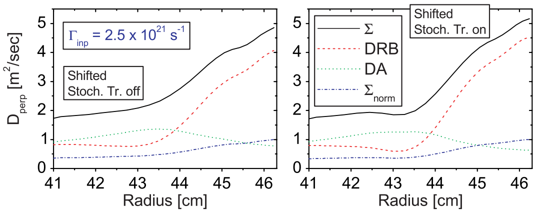


Fig. 6. Advanced turbulent diffusion coefficients.

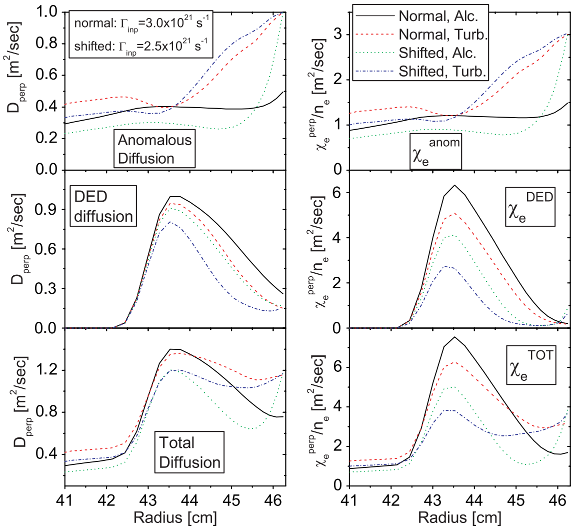


Fig. 7. Comparison of anomalous transport coefficients.

also the counterclockwise poloidal circulation is slowed down.

We now *replace the Alcator scaling by the advanced turbulent transport* and apply the formulae for DRB and DA instabilities. Examples for the resulting $D_\perp$ are plotted in Fig. 6. The sum $D_\perp^{\mathrm{turb}} = D_\perp^{\mathrm{DRB}} + D_\perp^{\mathrm{DA}}$ becomes extremely large at the separatrix, a factor 3 to 5 higher than the usual values in the TEXTOR tokamak. Such high values would lead to unphysical plasma profiles. For this reason we use a renormalized $D_\perp^{\mathrm{turb}}(r)$ which is $1\,\mathrm{m}^2/\mathrm{s}$ at the separatrix (as well as in the scrape-off layer). A comparison of the advanced (renormalized) transport coefficients with those from Alcator scaling (self-consistently calculated, same $\Gamma_{\mathrm{inp}}$, same DED position) is exhibited by Fig. 7. Despite the renormalization the advanced coefficients are still everywhere larger than those from Alcator scaling, if the stochastic transport is switched off. The additional effect from stochastic transport, however, is smaller if based on the advanced anomalous transport. Consequently the resulting total transport coefficients $D_\perp^{\mathrm{tot}} = D_\perp^{\mathrm{anom}} + D_\perp^{\mathrm{DED}}$ and $\chi_{e\perp}^{\mathrm{tot}} = \chi_{e\perp}^{\mathrm{anom}} + \chi_{e\perp}^{\mathrm{DED}}$ undergo very small changes when replacing Alcator by advanced turbulent drift transport.

## 3. Conclusions

Our calculations indicate that the effect of shifting DED is much more important than the effect of switching on stochastic transport. Shifting creates a high recycling zone in front of DED. We find even a tendency to an overlapping and merging of the recycling regions belonging to DED and the ALT-II ion side. Switching on stochastic transport, however, while increasing the density and radiation of $C^{2+}$, decreases the density and radiation of $C^{4+}$, showing that it screens the plasma core efficiently from impurities. Also the average $Z_{\mathrm{eff}}$ at the core boundary is reduced. We observe that for normal position of DED the input flux is approaching a threshold for Marfe instability. In the shifted position of DED, however, we do not see a sign for a Marfe-like thermal instability. Instead we get a high recycling regime with very broad profiles of high densities and reduced temperatures extending all around the whole transition layer.

Concerning 'advanced' turbulent transport we note that, contrary to Alcator scaling, it cannot describe poloidal dependencies of transport coefficients and poloidally local effects. The self-consistently calculated turbulent diffusion coefficients appear to be up to five times too large. For this reason it is necessary to use renormalized values, which finally lead to very small changes relative to our usual Alcator scaling.

## References


[1] H. Gerhauser, R. Zagórski, H.A. Claaßen, M. Lehnen, Contribution Plasma Phys. 40 (2000) 309.
[2] H. Gerhauser, R. Zagórski, H.A. Claaßen, M. Lehnen, J. Nucl. Mat. 290–293 (2001) 609.
[3] H. Gerhauser, R. Zagórski, H.A. Claaßen, G. Mank, et al., Nucl. Fusion 42 (2002) 805.
[4] H. Gerhauser, R. Zagórski, Contribution Plasma Phys. 44 (2004) 70.
[5] R. Zagórski, H. Gerhauser, G. Sergienko, Contribution Plasma Phys. 44 (2004) 274.
[6] R. Zagórski, H. Gerhauser, Phys. Scr. 70 (2004) 173.
[7] S.S. Abdullaev et al., Nucl. Fusion 43 (2003) 299.
[8] M.Z. Tokar', Phys. Plasmas 6 (1999) 2808.
[9] P.N. Gusdar, Phys. Fluids B 5 (1993) 3712.
[10] W. Kerner et al., Contribution Plasma Phys. 38 (1998) 118.
[11] R. Zagórski et al., Report of KFA Jülich, JÜL-3829, November 2000.
[12] S.S. Abdullaev et al., in: Proceedings of the 27th EPS Conf. CFPP Budapest, ECA Vol. 24B, 2000, p. 772.