Modeling of Electric Fields in Tokamak Edge Plasma and L-H Transition

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1. Introduction

The radial electric field in the separatrix vicinity is simulated by means of the B2-SOLPS5.0 2D fluid code [1], in which the most complete system of transport equations is solved including all the important perpendicular currents and $\vec{E}\times\vec{B}$ drifts. From the similar fluid codes [2]-[3] this one differs by a more detailed account of parallel viscosity and perpendicular currents. The equation system provides a transition to the neoclassical equations when the anomalous transport coefficients are replaced by the classical values. The simulations are performed for the ASDEX Upgrade (AUG) tokamak, where the plasma parameters in the separatrix vicinity and in the SOL correspond to the Pfirsch-Schlueter regime thus justifying the applicability of the fluid equations. On the basis of the simulations for different powers of additional heating, plasma densities, toroidal rotation velocities, magnetic field values and directions, it is demonstrated that the radial electric field in the separatrix vicinity is of the order of the neoclassical electric field.

2. Simulation results

The simulations were performed for typical L-mode parameters of AUG (minor radius a=0.5m, major radius R=1.65m, plasma current I=1-2 MA, toroidal field B=2-4 T, density $n=1\cdot10^{19}$-$3.3\cdot10^{19}$ m^{-3} and ion temperature T_i=40-160eV density at the reference point located at a-r=1cm at the equatorial midplane). The anomalous values of diffusion and heat conductivity coefficients were chosen: $D=\chi_{e,i}=0.5m^2/s$. The perpendicular viscosity coefficient was taken in the form $\eta = nm_iD$. At the inner boundary flux surface, which was located in the core a few cm from the separatrix, the density, the electron and ion heat fluxes and the average toroidal momentum flux were specified. The boundary heat fluxes were imposed independently from the toroidal momentum flux thus providing the opportunity to investigate the dependence of the radial electric field on these parameters. The results of the simulations were compared with the neoclassical electric field (the coefficient 2.7 corresponds to the Pfirsch-Schlueter regime)

$$E^{(NEO)} = \frac{T_i}{e}\left(\frac{1}{h_y}\frac{d\ln n}{dy} + 2.7\frac{1}{h_y}\frac{d\ln T_i}{dy}\right) - b_x \frac{\oint\sqrt{g}V_\parallel B dx}{\oint\sqrt{g}dx}, \qquad (1)$$

where x is the poloidal co-ordinate, y is the radial co-ordinate, $b_x = B_x/B$, $\sqrt{g} = h_x h_y h_z$, $V_{||}$ is the parallel (toroidal) velocity. Typical radial electric field profiles are shown in Fig. 1. Figs. *a* and *b* correspond to the absence of the NBI while Figs. *c* and *d* represent the cases of strong co- and counter-injection. In all runs the radial electric field profile inside the separatrix was close to the neoclassical field. Note, however, that to calculate the neoclassical field according to Eq. (1) it is necessary to have the radial profile of toroidal velocity, which is determined by the anomalous viscosity and diffusion coefficients and is calculated in the code. The case *c* qualitatively resembles the radial electric field profile measured at DIII-D.

In the simulations the parametric dependence of the radial electric field and its shear $\omega_s = \frac{RB_x}{B}\left|\frac{d(E_y/B_x R)}{h_y dy}\right|$ has been studied. As a reference point for the plasma parameters the equatorial midplane 1cm inside the separatrix was chosen and the shear was calculated in the same plane 1cm inside the separatrix. The linear dependence of the shear on the local ion temperature and the local average toroidal velocity was obtained. The dependence on the density was found to be rather weak. Such dependencies are similar to what one can expect for the neoclassical electric field. Indeed, calculating the shear from Eq. (1), neglecting relatively small corrections (dB_x/dy, dB/dy, dR/dy), assuming linear profiles close to the separatrix with $L_T << L_n$, where $L_n = |d\ln n/h_y dy|$, $L_T = |d\ln T_i/h_y dy|$, $L_V = |d\ln\langle V_\parallel\rangle/h_y dy|$, $\langle V_\parallel\rangle \equiv \langle V_\parallel B\rangle/\langle B\rangle$ ($\langle f\rangle = \oint f\sqrt{g}dx/\oint\sqrt{g}dx$) we find

$$\omega_s^{(NEO)} = \frac{1}{B}\left|\frac{T_i}{eL_n^2} - \frac{B_x}{L_V}\langle V_\parallel\rangle\right|. \qquad (2)$$

Since the density and ion temperature profiles remain almost the same for all runs, the shear of the neoclassical electric field should be proportional to T_i and should be independent of *n*.

On the basis of the runs the scaling for the electric field shear is obtained, Fig. 2:

$$\omega_s^{(scaling)} = \frac{1}{B}\left|\alpha T_i - \beta\langle V_\parallel\rangle - \gamma\right|, \qquad (3)$$

where T_i is in eV, ω_s is in s^{-1}, $\langle V_\parallel\rangle$ is in km/s. The best fitting was found for $\alpha=5.4\cdot10^3$, $\beta=10^4$, $\gamma=10^5$, which is consistent with the neoclassical shear given by Eq. (2). The contribution of γ is relatively small.

To obtain a scaling for the L-H transition threshold it is necessary to specify the critical shear when the transition starts. We chose the value $\omega_s = 3.5 \cdot 10^5 s^{-1}$ independently of the regime. This value gives the best fitting to the experiment. To reach the chosen critical shear it is necessary to increase heating power proportionally to the local density and toroidal magnetic field as shown in Fig. 3*a*. The scaling obtained in the simulations is consistent with the observations on the AUG [4], Fig. 3*b*. This result is explained by the neoclassical nature of the simulated radial electric field. Indeed, the linear dependence of the threshold heating power on the local density corresponds to the constant critical value of the ion temperature, which determines the critical shear. The calculated radial electric field, as well as the neoclassical field, is almost independent of the magnetic field, Fig. 4. Therefore, the shear is inversely proportional to the toroidal magnetic field *B* and to reach the same critical shear it is necessary to increase power proportionally to *B*. The shear of the radial electric field near the separatrix is smaller in the case of the reversed magnetic field which explains the larger L-H transition threshold than for the normal magnetic field. This fact is connected with the different contribution from the toroidal rotation, due to the various toroidal rotation in the SOL in two regimes regimes and deviation from the neoclassical field and deviation from the neoclassical field. It will be discussed elsewhere.

3. Conclusions

Simulations demonstrated the following: the radial electric field remains of the order of the neoclassical field; its dependencies on the local ion temperature, density, poloidal and toroidal magnetic fields and average toroidal rotation are similar to that of the neoclassical field; to reach the fixed shear value at the edge the heating power should rise proportionally to the local density and toroidal magnetic field similar to the observed for the L-H transition threshold; the shear of the radial electric field near the separatrix is smaller in the case of the reversed magnetic field which explains the larger L-H transition threshold than for the normal magnetic field.

References

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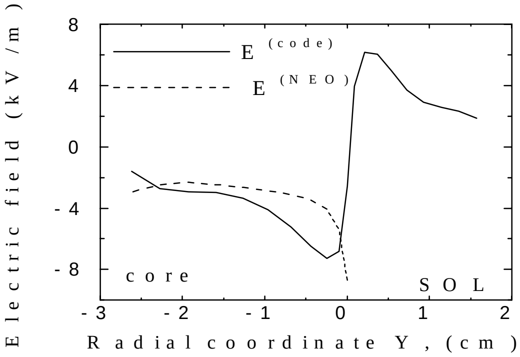

Fig. 1a. Radial electric field at the outer midplane for discharge without NBI, normal direction of magnetic field, n=2·10^{19} m^{-3}, T$_i$=98 eV in the reference point. I=1 MA, B=2 T.

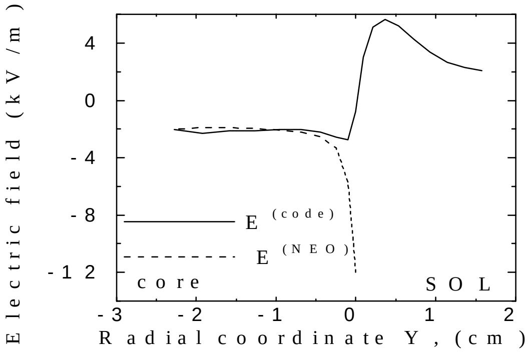

Fig.1b. Radial electric field at the outer midplane for discharge without NBI, reversed magnetic field, n=2·10^{19} m^{-3}, T$_i$=98 eV in the reference point. I=1 MA, B=2 T.

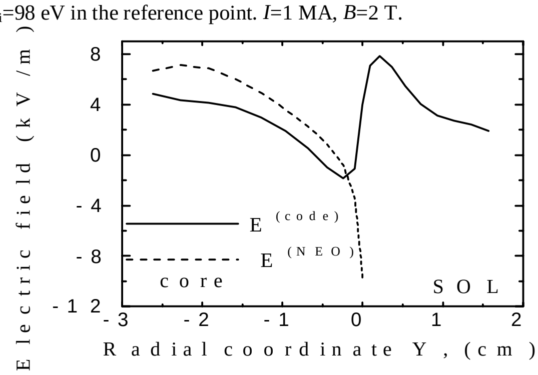

Fig.1c. Radial electric field at the outer midplane for discharge with co-injection, normal direction of magnetic field, n=2·10^{19} m^{-3}, T$_i$=98 eV, <V$_{\|}$>=-18 km/s in the reference point. I=1 MA, B=2 T.

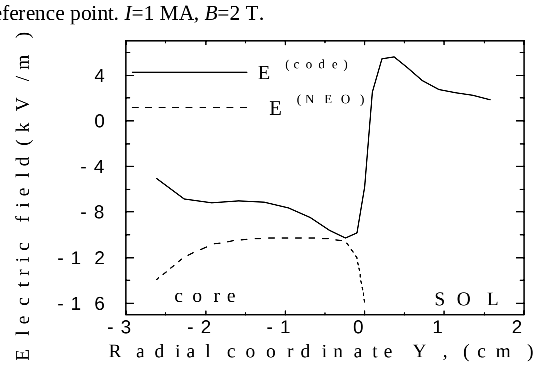

Fig.1d. Radial electric field at the outer midplane for discharge with contra-injection, normal direction of magnetic field, n=2·10^{19} m^{-3}, T$_i$=98 eV, <V$_{\|}$>=+5 km/s in the reference point. I=1 MA, B=2 T.

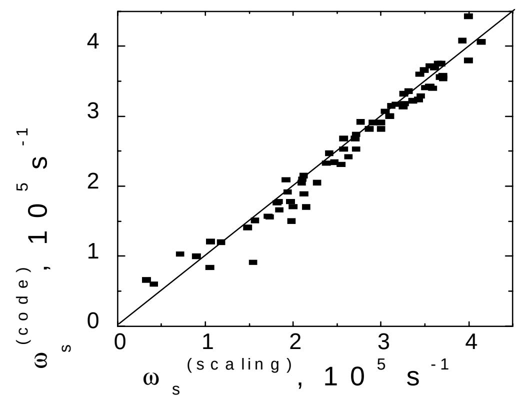

Fig.2. Comparison of shear values obtained in code and calculated according to Eq.(3), normal direction of magnetic field, n=1.3·10^{19}-2.8·10^{19} m^{-3}, T_i=40-160eV, <V$_{\|}$>=(-16)-(+6) km/s. I=1-2 MA, B=2-4 T.

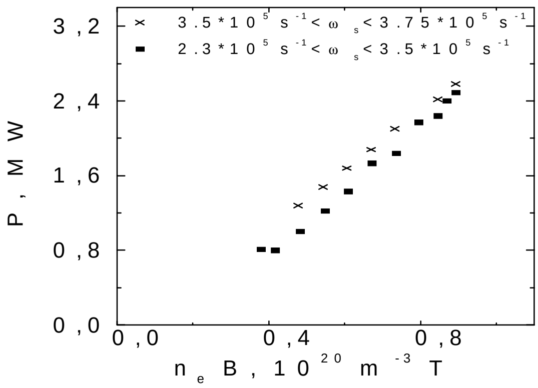

Fig.3a. Heating power, which is necessary to achieve a given value of electric field shear (ω_s=3.5·10^5 s^{-1} at reference point) for different plasma densities (at r-a = 2 cm). I=1 MA, B=2 T.

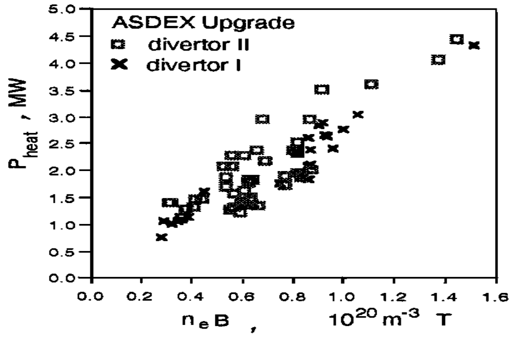

Fig.3b. H-mode power threshold in ASDEX-Upgrade against edge density (at r-a = 2 cm) multiplied by the toroidal magnetic field.

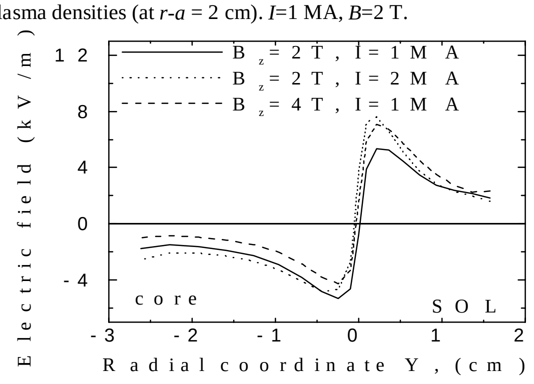

Fig.4. Radial electric field profiles at the outer midplane for discharges with different toroidal magnetic fields B and plasma currents I. No NBI, normal direction of magnetic field, n=2·10^{19} m^{-3}, T_i=80 eV in the reference point.