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Modeling of tokamak edge plasma for discharges with neutral beam injection

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Abstract

Edge plasma of tokamak ASDEX-Upgrade is simulated for discharges with unbalanced neutral beam injection. Toroidal momentum transport through the separatrix and further to the divertor plates is simulated and compared with simple analytical solution. Structure of radial electric field near the separatrix is simulated and compared with the predictions of neoclassical theory. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Sol modeling

1. Introduction

During unbalanced NBI, toroidal momentum is transported in radial direction through the separatrix and further to the divertor plates. Toroidal rotation changes also radial electric field in the core and SOL. These processes are simulated by means of B2-solps5.0 2D transport fluid code [1] for ASDEX-Upgrade. In SOL transport of toroidal momentum causes asymmetry of pressure and of parallel fluxes and, therefore, results in the additional difference of particle and heat fluxes to the plates. Structure of radial electric field near the separatrix in the presence of both co- and counter-injection is simulated and compared with neoclassical theory. For the case of co-injection radial electric field becomes less negative near the separatrix and positive in the core, for the case of counter-injection radial electric field is more negative than for ohmic heating (OH) case. This tendency is in qualitative agreement with the predictions of neoclassical theory.

2. Model

The full set of transport equations based on Braginskii fluid equations is used for simulation. To avoid numerical problems divergence free terms in particle and current balance equations are cancelled analytically. Similar cancellation is made in the parallel momentum balance and energy balance equations, where inertia terms are combined with gyroviscosity terms, and the fact that the diamagnetic heat fluxes are almost divergence free is taken into account. All the important perpendicular currents caused by viscosity, inertia and collisions with neutrals are taken into account. Detailed description of the equations can be found in [2,3].

At the inner boundary (few centimeters inside the separatrix) two types of boundary conditions were imposed. For regime without momentum input the condition $\Gamma^{(m)}|_{\text{in}} = (m_i V_\| \Gamma_y - \eta(\partial V_\| / h_y \partial y))|_{\text{in}} = 0$ was taken (Γ_y is radial particle flux, η is anomalous viscosity coefficient, $V_\|$ is parallel velocity), while NBI was simulated by imposing constant radial momentum flux $\Gamma^{(m)}|_{\text{in}} = \text{const}$ or $V_\||_{\text{in}} = \text{const}$. Here the y-axis is perpendicular to the flux surfaces, x is the poloidal and z is the toroidal coordinate. Positive direction of z-axis coincides with the magnetic field direction, which corresponds to the ∇B drift of ions directed towards the X-point. Tokamak current is negative. For other boundary conditions see [2,3].

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3. Simulation results

For simulation typical discharge of ASDEX-Upgrade with NBI was chosen. Parallel velocities at the outer midplain averaged over the flux surface are shown in Fig. 1. Average velocity gradually decreases towards the separatrix, while radial flux of toroidal momentum remains almost constant since toroidal momentum is generated in the core and then is transported to the separatrix. Positive (in the counter direction) averaged toroidal velocity was observed even in the absence of unbalanced NBI. Therefore, part of the momentum is generated by averaged parallel viscosity and pressure gradient.

Existence of counter-current average toroidal velocity in the core in the absence of NBI can be understood from the toroidal component of momentum balance equation: $\mathrm{d}\Gamma^{(m)}/\mathrm{d}t = -j_y B_x$, where the l.h.s. represents radial transport of toroidal momentum. Since the net current through the flux surface in the core should be 0, the following condition should be fulfilled:

$$\int \frac{\sqrt{g}}{h_y B_x} \frac{\mathrm{d}\Gamma^m}{\mathrm{d}t} \mathrm{d}x = 0. \tag{1}$$

This condition requires finite $\langle V_\parallel \rangle$ in the core, because of the complicated character of $V_\parallel$ distribution over flux surface. The latter is to a large extent determined by the coupling with the SOL, where poloidal distribution of $V_\parallel$ is connected with geometrical effects (different particle fluxes to the plates due to different plasma densities, temperatures, angle of incidence and plate surfaces). Poloidal dependence of the particle flux from the core is also important.

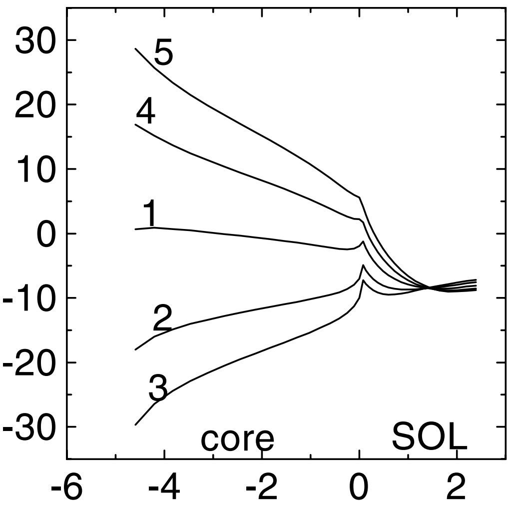

Fig. 1. Radial profile of average parallel velocity at the outer midplane. (1) No NBI; (2) $V_\parallel|_{\mathrm{in}} = -18$ km/s; (3) $V_\parallel|_{\mathrm{in}} = -30$ km/s; (4) $V_\parallel|_{\mathrm{in}} = +18$ km/s; (5) $V_\parallel|_{\mathrm{in}} = +30$ km/s. In SOL $V_\parallel$ was averaged over the region above X-point.

Transport of the toroidal momentum through separatrix and further to the plates could be understood from the simplified slab model of a SOL with the x-axis directed from inner to the outer plate. Neglecting the parallel and anomalous viscosity in SOL, integrating the parallel momentum balance equation over the SOL volume, we find

$$\begin{aligned}\int_{x_-}^{x_+} \Gamma_{\mathrm{s}}^{(m)} \,\mathrm{d}x &= m_i \langle V_\parallel \rangle_{\mathrm{s}} \int_{x_-}^{x_+} \Gamma_{\mathrm{s}} \,\mathrm{d}x \\ &= m_i \int \mathrm{d}y (\Gamma_{x+} V_{\parallel +} - \Gamma_{x-} V_{\parallel -}) \\ &\quad + \int \mathrm{d}y (B_x/B)(p_+ - p_-). \end{aligned} \tag{2}$$

Here subscript s corresponds to separatrix, '−' and '+' correspond to inner and outer plates, respectively. This equation means that radial flux of parallel momentum through the separatrix (l.h.s. of Eq. (2)) is transported by the poloidal particle flux to the plates and also causes pressure asymmetry. Pressure asymmetry produces difference in particle and energy fluxes to the plates. This effect was observed in ASDEX [4]. Substituting simplified boundary conditions (neglecting $\vec{E} \times \vec{B}$ drifts) $V_{\parallel\pm} = c_{\mathrm{s}\pm} = \sqrt{(T_{e\pm} + T_{i\pm})/m_i}$ into Eq. (2), we notice that, since $\Gamma_x = (B_x/B) V_\parallel$ (in the absence of $\vec{E} \times \vec{B}$ drifts), two terms in the r.h.s. of Eq. (2) are equal to each other. Hence,

$$\frac{1}{2} m_i \langle V_\parallel \rangle_{\mathrm{s}} \int_{x_-}^{x_+} \Gamma_{\mathrm{s}} \,\mathrm{d}x = \int \mathrm{d}y (B_x/B)(p_+ - p_-). \tag{3}$$

In other words, in this simplified model half of the radial flux of toroidal momentum, which is generated in the core and then flows through separatrix, is responsible for the pressure asymmetry at the plates. For the case of co-injection we have $p_- > p_+$, and vice versa.

Small pressure asymmetry and asymmetries of poloidal and parallel fluxes in SOL exist even in the absence of unbalanced NBI, due to geometrical effect. Pressure asymmetry for NBI is shown in Fig. 2. The quantity $\int\int \sqrt{g}/h_x (B_x/B)(\partial p/\partial x)\,\mathrm{d}y\,\mathrm{d}x$ calculated in the code for SOL (which corresponds to r.h.s. of Eq. (2) in the simple model) minus the value for balanced NBI equals $k \int_{x_-}^{x_+} \Gamma_{\mathrm{s}}^{(m)} \sqrt{g}/h_y \,\mathrm{d}x$, where $k = 0.31,\ 0.44$ for co- and counter-injection accordingly and $\langle V_\parallel \rangle|_{\mathrm{in}} = \mp 30$ km/s. Hence, Eq. (3) is a reasonable estimate. The effect is modest, since it should be of the order of $\langle V_\parallel \rangle_{\mathrm{s}} / c_{\mathrm{s}\pm}$, where $\langle V_\parallel \rangle_{\mathrm{s}}$ is the average parallel velocity at the separatrix and $c_{\mathrm{s}\pm}$ sound velocity at the plates. Parallel velocities in SOL are shown in Fig. 3.

Potential profile is shown in Fig. 4. One can see that the electric field in the core region far from separatrix is positive during co-injection and negative for

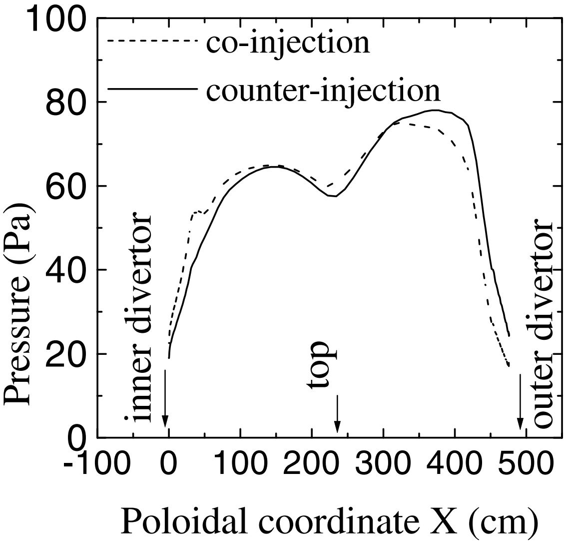

Fig. 2. Pressure profiles on the open field lines near the separatrix for co- and counter-injections ($V_\parallel|_{\rm in} = \mp 30$ km/s).

counter-injection, Figs. 5 and 6, according to the prediction of neoclassical theory, where combination $\langle BV_\parallel \rangle - (B\partial\varphi / \; B_x h_y \partial y)$ should remain a function of density and temperature gradients. However, close to separatrix electric field is negative as in OH regime. For counter NBI shear of poloidal $\vec{E} \times \vec{B}$ rotation near the separatrix is larger, so that the threshold for L–H transition should be lower. Both for co- and counter-injection at the separatrix vicinity from the core side there exists a region of strong electric field (a 'dip'). Its spatial scale is of the order of a few mm, and electric field here significantly differs from neoclassical value. The scale of the 'dip' is to a large extent determined by the closing of divergence of anomalous radial particle flux by divergence of poloidal $\vec{E} \times \vec{B}$ drift. Further inside

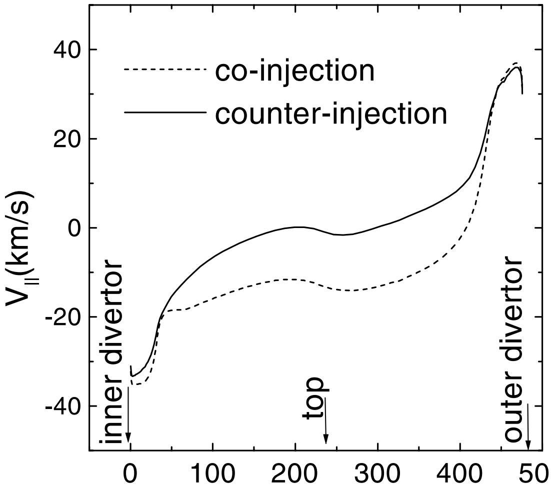

Fig. 3. Parallel velocity profiles on the open field lines near the separatrix for co- and counter-injections ($V_\parallel|_{\rm in} = \mp 30$ km/s).

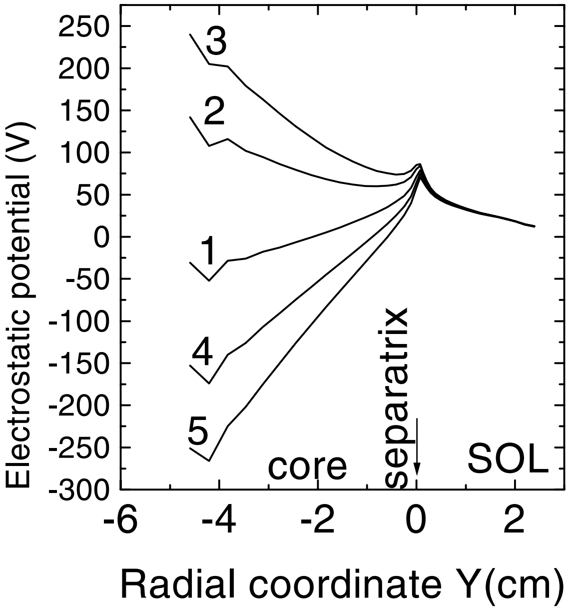

Fig. 4. Potential profiles at the outer midplane for different regimes of NBI. (1) No NBI; (2) $V_\parallel|_{\rm in} = -18$ km/s; (3) $V_\parallel|_{\rm in} = -30$ km/s; (4) $V_\parallel|_{\rm in} = +18$ km/s; (5) $V_\parallel|_{\rm in} = +30$ km/s.

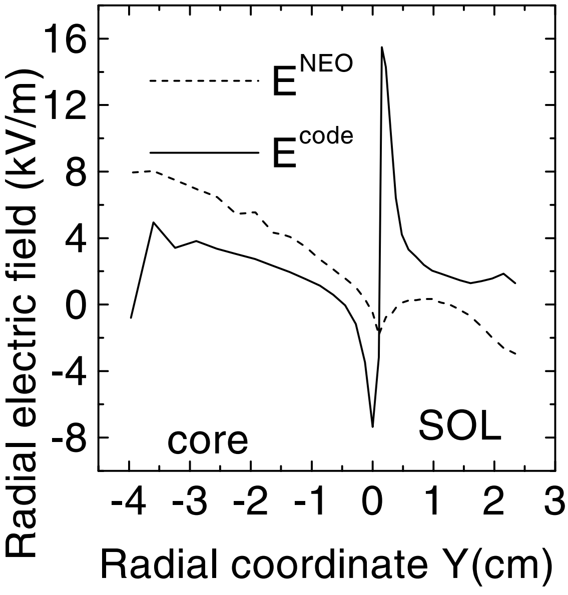

Fig. 5. Radial electric field at the outer midplane for co-injection ($V_\parallel|_{\rm in} = -23$ km/s).

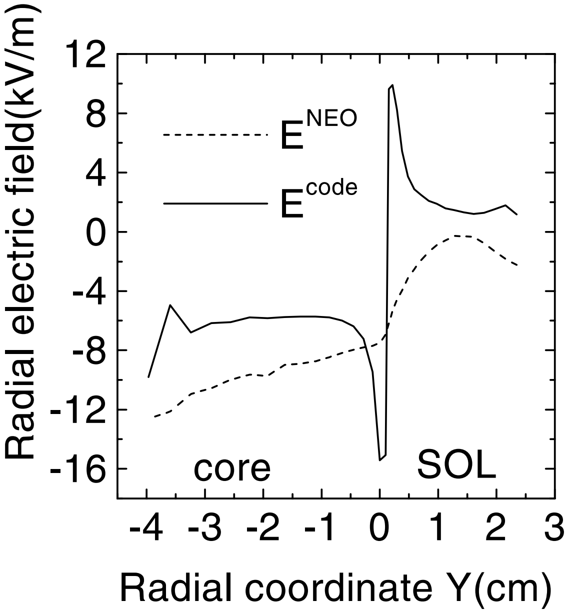

Fig. 6. Radial electric field at the outer midplane for counter-injection ($V_{\parallel}|_{in} = +23$ km/s).

electric field is more gradual and more close to neoclassical field, however one can notice considerable difference. Electric field profiles qualitatively agree with measurements of electric field on DIII-D [5] and calculations of [6].

During NBI additional radial electric field is generated also in SOL in the separatrix vicinity, Fig. 7. Indeed, due to momentum transport average velocity in SOL becomes more negative in the case of co-injection and more positive for contra-injection, Fig. 3. In the first case the point, where parallel velocity changes its sign, is shifted towards the outer divertor plate. For contra-injection this point is shifted towards the inner plate. If we assume for a moment that particle flux from the core is carried poloidally only by parallel flux, we would have to conclude that most of the particle flux from the core would flow to the inner divertor in the first case, and to the outer divertor in the second case. This, however, is inconsistent with parallel momentum balance and modest change in pressure profile, Fig. 2. Therefore, additional radial electric field should arise to generate additional poloidal $\vec{E} \times \vec{B}$ drift, which would keep almost the same poloidal flux as in the absence of NBI. Indeed, in contrast to the parallel flux, the poloidal flux is less sensitive to the direction of NBI torque, as can be seen from Fig. 8. The observed effect is inverse of that typical for the biasing experiments, which was predicted in [7] and observed on TdeV [8]. There radial electric field was generated by biasing, and medium toroidal velocity was observed to keep the poloidal flux more or less independent of biasing voltage.

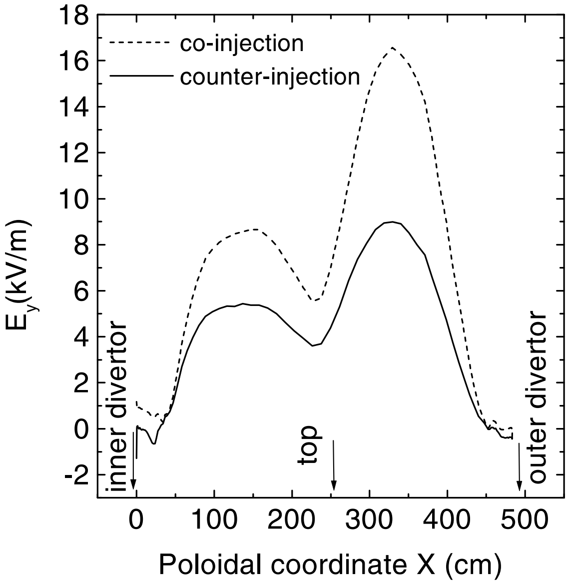

Fig. 7. Poloidal profile of radial electric field in SOL in the vicinity of separatrix for co- and counter-injections ($V_{\parallel}|_{in} = \mp 30$ km/s).

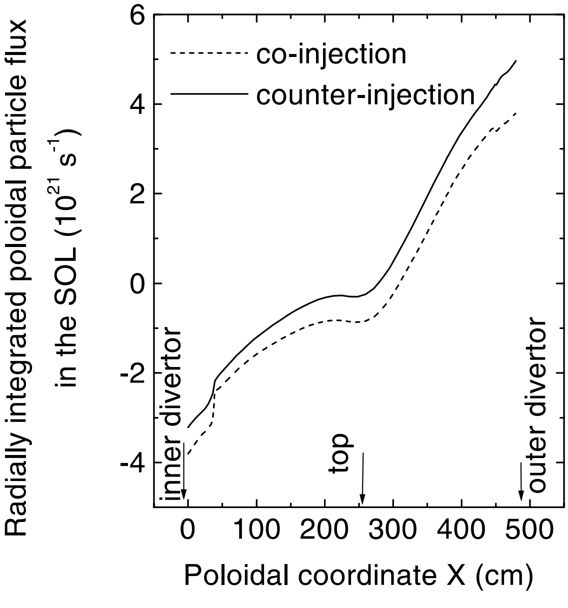

Fig. 8. Poloidal particle flux integrated over radial and toroidal coordinate in SOL for co- and counter-injections ($V_{\parallel}|_{in} = \mp 30$ km/s), particles per second.

4. Conclusions

Momentum input during neutral beam injection causes asymmetry of pressure and of parallel fluxes in SOL. Poloidal fluxes in SOL are less sensitive to NBI direction. Momentum torque leads to additional difference of particle and heat fluxes to the inner and outer plates. In the core radial electric field becomes less negative near the separatrix for the case of co-injection and positive for the case of counter-injection. This tendency is in qualitative agreement with the predictions of neoclassical theory. Just in the separatrix vicinity at distance less than 1 cm radial electric field remains always negative and larger than the neoclassical value.

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