Radial Electric Field Simulations in T-10 Tokamak Plasma with Magnetic Field Ripples

M.Yu. Isaev[1], C.D. Beidler[2], A.N. Chudnovskiy[1], K.S. Dyabilin[1],
H. Maaβberg[2], A.V. Melnikov[1], S.V. Perfilov[1] and Y. Turkin[2]
[1]*National Research Centre "Kurchatov Institute", Moscow, Russia*
[2]*Max-Planck-Institut für Plasmaphysik, Greifswald, Germany*

1. Introduction

Measurements of plasma potential in T-10 tokamak shots #57641, #57412 using the heavy ion beam probe diagnostic have been described in [1]. For these discharges we present the first results of the radial electric field simulations for T-10 rippled tokamak performed with the 3D neoclassical orbit code VENUS+δf with a full collisional operator [2] and with the drift kinetic equations solver code DKES with the momentum correction [3].

The toroidal field ripple of the tokamak magnetic field *B* is produced by a set of toroidal field coils, the toroidal ripple function δ is defined as $\delta = (B_{max} - B_{min})/(B_{max} + B_{min})$. The comparison between the experimentally measured radial electric field and that expected from the neoclassical transport computations has been performed for Tore Supra (δ up to 7% near the edge) [4] and JET (max(δ) = 1%) [5], detailed computations of the ripple effects have been done for the building ITER with max(δ) = 1% [6]. An example of extremely large analytical ambipolar radial electric field E_r in a rippled tokamak as a function of the ion density and temperature n_i, T_i (neglecting the electron contribution) has been obtained in a very low collisional regime with a factor γ = 3.37 in [7]:

$$E_r = T_i\ (n_i{}' / n_i + \gamma\, T_i{}' / T_i) \qquad (1)$$

The set of 16 toroidal coils in the T-10 tokamak produces the ripples of the magnetic field with δ = 3% near the edge (Fig. 1), which have been taken into account in our simulations (Section 2). We use the measured in shots #57641, #57412 smoothly fitted stationar profiles of the electron density, ion and electron temperatures, safety factor and another T-10 parameters, given in [1]. The increase in the computed monoenergetic neoclassical diffusion coefficient due to the magnetic field ripples has been found in a low-collisional regime. The comparison between the measured plasma potential and that expected from neoclassical simulations is discussed in the Section 2 and in the Summary.

2. Simulation results

T-10 #57641 and #57412 discharges described in [1] have the central ion temperature values of 0.70 and 0.45 keV and the central electron density values of $5.5\cdot10^{19}$ and $3.0\cdot10^{19}$ m^{-3}. The average normalized electron collisional frequency ν* of the selected shots lays in the range 0.1 - 1. DKES neoclassical code [8] creates the data base of the transport coefficients with the different values of the frequency ν*, plasma radii, radial electric fields and particle velocity V. Typical dependence of the monoenergetic diffusion coefficients D_{11}* is shown in Fig. 2 as a function of normalized electron collisionality for T-10 at the minor radius r = 15 cm, shot #57641 without the ripples (dotted line), with the ripples and $E_r/VB = 0.0$ (red squares), with $E_r/VB = 3\cdot10^{-5}$ (green circles), with $E_r/VB = 10^{-4}$ (blue diamonds), with $E_r/VB = 3\cdot10^{-4}$ (triangles), with $E_r/VB = 10^{-3}$ (magenta), with $E_r /VB = 3\cdot10^{-3}$ (yellow). The increasing of the monoenergetic neoclassical diffusion coefficient due to the magnetic field ripples has been found in a low-collisional regime with $\nu^* < 0.001$, while the average collisional frequency $\nu^* = 0.1 - 1$ of the selected shots lays near the "plateau" collisional regime. DKES monoenergetic database, energy convolution and the momentum correction technique [3] are used to obtain the profiles of the particle and the heat fluxes, the bootstrap current and the ambipolar radial electric field, shown as diamonds in Fig. 3 (shot #57641) and Fig. 4 (shot #57412).

VENUS+δf neoclassical code computes the drift particle orbits in the rippled T-10 equilibrium 3D magnetic fields with the full conservative Monte-Carlo collisional operator and with the particle weight evolution [2]. Ambipolar radial electric field E_r is obtained from the zero ion radial flux condition ("ion root"), neglecting the small electron contribution. E_r profile computed for the T-10 #57641 shot with the VENUS code without the toroidal field ripple is shown in Fig. 3 by circles, with a large toroidal field ripple (max(δ) = 7%) – by crosses. For the comparison, Fig. 3 shows the standard “plateau” analytical E_r profile computed from (1) with $\gamma = 1.5$ (solid line) and with the HIBP experimental fit, $\gamma = 2.5$ (squares). The Fig. 3 demonstrates that the module of the radial electric field E_r computed with the VENUS and DKES neoclassical codes is in a factor of 2 - 3 less than $|E_r|$, measured with the heavy ion beam probe (HIBP) diagnostic in #57641 shots.

Fig. 4 shows the radial electric field E_r profiles computed for T-10 shot #57412 with the DKES code (diamonds), with the VENUS code (circles), with the analytical theory in plateau regime with $\gamma = 1.5$ (solid line). For this shot #57412 the radial electric field $|E_r|$ profiles computed with the neoclassical codes are also in a factor of 2 - 3 less than $|E_r|$ from the HIBP experimental diagnostic fit with $\gamma = 2.5$ (squares). Visible difference between the radial electric field values, computed with the DKES and the VENUS codes, can be connected with the different momentum correction methods and the different energy convolutions and will be considered in more details in the near future.

3. Summary and future plans

The absolute values of the radial electric field E_r, computed for the first time with the VENUS and DKES neoclassical codes for the rippled T-10 tokamak, are in a factor of 2 - 3 smaller than $|E_r|$ measured with the heavy ion beam probe (HIBP) diagnostic in shots #57641 and #57412. Average collisional frequency of these shots belongs to the "plateau" regime, where the large toroidal magnetic field ripple (up to $\delta = 3\%$ at the edge) should impose a very small effect on the neoclassical transport. More accurate transport simulations will include a free boundary rippled T-10 equilibria, wide magnetic field spectra, electron contribution in the VENUS code, plasma rotation and anomalous effects. More accurate measurements of the plasma rotation, radial electric field, density and temperature profiles in T-10 shots with a low collisionality can probably induce more accurate comparison between E_r, simulations and experiments.

Acknowledgements

The authors thank Dr. S.P. Hirshman for providing us the VMEC and the DKES codes and Prof. W.A. Cooper for providing us the TERPSICHORE code. The work was supported by the RosAtom Contracts H.4A.52.90.12.1006, H.4X.45.90.12.1023, by the grant 4361.2012.2 of President of RF for Leading Scientific Schools. The computations were performed on the cluster LSPP-ITER (Kurchatov Institute, Russia) and in the IPP Greifswald, Germany. M. Isaev and K. Dyabilin thank T-10 team, Profs. P. Helander, J. Nührenberg, S.V. Konovalov and M.I. Mikhailov for the collaboration support and fruitful discussions.

References

[1] A.V. Melnikov *et al*, Nucl. Fusion 51, 083043(2011).

[2] M.Yu. Isaev *et al*, Nucl. Fusion 49, 075013(2009).

[3] H. Maaβberg and C.D. Beidler, Phys.of Plasmas 17, 052507(2010).

[4] E. Trier *et al*, Nucl.Fusion 48, 092001(2008).

[5] K. Crombe *et al*, PPCF, 51, 055005(2009).

[6] K. Shinohara *et al*, Nucl.Fusion 51, 063028(2011).

[7] P.N. Yushmanov, Nucl.Fusion 22,1199(1982).

[8] W. van Rij and S.P. Hirshman Phys. Fluids B, 1, 563(1989).

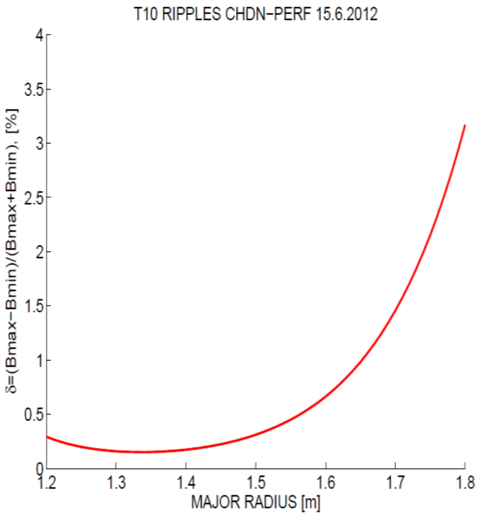

Fig. 1. T-10 tokamak toroidal field ripple profile produced by the set of 16 toroidal field coils

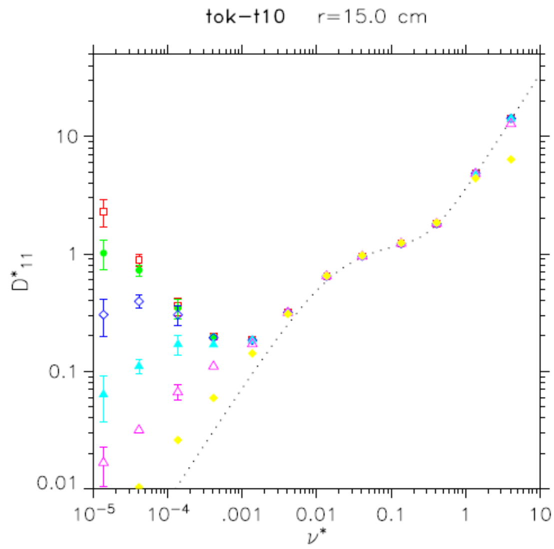

Fig. 2. Monoenergetic diffusion coefficients D_{11}* as a function of normalized electron collisionality computed with the DKES code for T-10 without the ripples (dotted line), with the ripples and $E_r/VB = 0.0$ (red squares), with $E_r/VB = 3{\cdot}10^{-5}$ (green circles), with $E_r/VB = 10^{-4}$ (blue diamonds), with $E_r/VB = 3{\cdot}10^{-4}$ (triangles), with $E_r/VB = 10^{-3}$ (magenta), with $E_r/VB = 3{\cdot}10^{-3}$ (yellow).

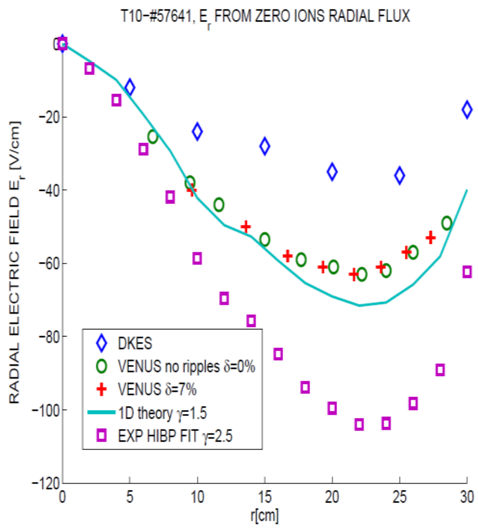

Fig. 3. Radial electric field E_r profile computed for the T-10 #57641 shot by the DKES code with a parallel momentum conservation [3] (diamonds), with the VENUS code without the toroidal field ripple (circles), with a large toroidal field ripple (δ = 7%) (crosses), with the analytical Eq.1, γ = 1.5 (solid line), with the HIBP experimental fit, γ = 2.5 (squares).

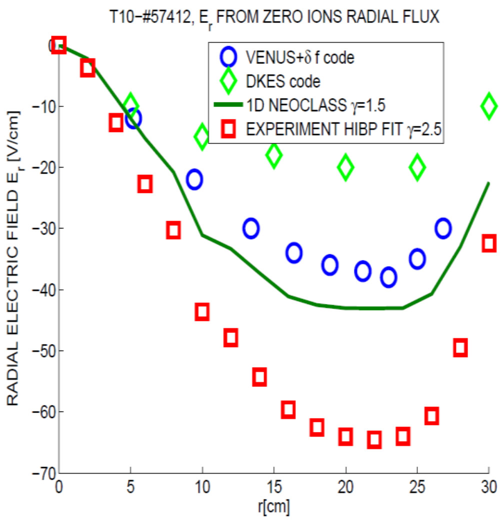

Fig. 4. Radial electric field E_r profile computed for the T-10 #57412 shot by the DKES code with a parallel momentum conservation (diamonds), computed by the VENUS code (circles), with the analytical Eq.1, γ = 1.5 (solid line), with the HIBP experimental fit, γ = 2.5 (squares).