32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, P-4.055 (2005)

Fast Ion Distribution in the Presence of Magnetic Ripple and Radial Electric Field

T. Kurki-Suonio[1], V. Hynönen[1], W. Suttrop[2], R. Dux[2], and the ASDEX Upgrade Team[2]

Association Euratom-Tekes

[1] *Helsinki University of Technology, P.O. Box 2200, FI-02015, TKK, Finland*

[2] *Max-Planck-Institut für Plasmaphysik, EURATOM Assosiation, D-85748, Garching*

Introduction Fast ion behaviour in tokamak geometry deserves careful attention for two reasons: 1) in already existing tokamaks ions accelerated by external methods (RF, NBI) can cause significant damage on the material surfaces in today's machines, and 2) in ITER the fusion alphas have to be confined during slowing down.

In this work we have investigated the behaviour of NBI-born fast ions. In particular, the effect of a finite toroidal ripple [1] and that of a large radial electric field, present in the edge pedestal region, are studied using the Monte Carlo orbit following code ASCOT [2] in ASDEX Upgrade (AUG) magnetic geometry. The work was motivated by the quiescent H-mode in AUG, so far achieved only with counter-injection of the neutral beams [3].

Radial Electric Field and NBI-ions in ASDEX Upgrade Generally, the effect of a radial electric field is considered to arise only from its inhomogeneity [4]. This is because, for the bulk plasma, a constant radial electric field would merely shift the banana tips, making some trapped particles passing ones and, correspondingly, pushing some of the passing particles into trapped orbits. The net effect of a constant radial electric field on the bulk plasma is thus to shift the trapping cone in the velocity space.

However, when considering NBI ions, the effect of even a constant radial field is more direct: For a negative field, typical of the pedestal region, the electrostatic potential increases towards the periphery. This means that a counter-injected NBI-ion, born on an ill-confined orbit (opening outward), will lose part of its kinetic energy to potential energy as it moves along its orbit. This leads to an outward shift of the banana turning points and narrowing of the orbit. A negative radial electric field in the pedestal region will thus somewhat reduce the direct orbit losses.

For co-injected ion, the effect of a negative radial electric field is to shift the turning points inward and, consequently, widen the orbit. For positive radial electric field these effects are reversed. The effect of radial electric field E_r on orbit widths is illustrated in figure 1.

A strong enough negative radial electric field not only affects the magnitude of the toroidal

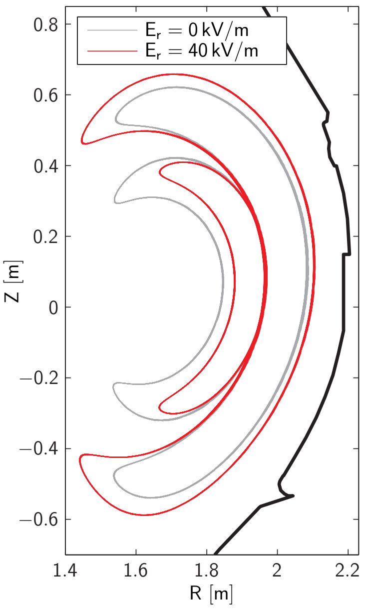

Figure 1: Effect of a constant radial electric field on orbit widths.

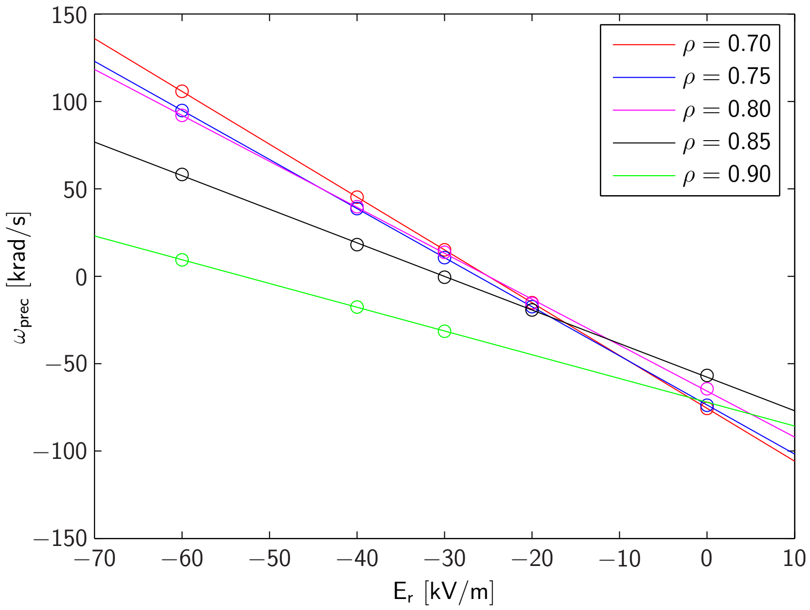

Figure 2: Effect of a constant radial electric field on the precession drift frequency (positive sign indicates co-injection direction) for different birth radii.

drift but even its direction. For a ‘typical’ counter-injected NBI-ion with the initial energy of $E_0 = 60\,\mathrm{keV}$ and pitch $\xi_0 = v_\parallel/v = 0.45$ at the equatorial plane, the critical field for reversing the direction of toroidal precession from clockwise (viewed from above) to counter-clockwise is about $-25\,\mathrm{kV/m}$, a value that is easily exceeded in the pedestal region. In the absence of radial electric field the toroidal precession frequency ω_{prec} is about $-60\,\mathrm{krad/s}$ to $-70\,\mathrm{krad/s}$ (with negative sign indicating counter-clockwise direction) for ions born in the region $\rho \in [0.7, 0.9]$. With $E_\mathrm{r} = -60\,\mathrm{kV/m}$ the precession frequency is increased to up to $+110\,\mathrm{krad/s}$ for the same particles. Due to the shape of the q-profile, ions born deeper in have higher precession frequencies. This value is only about a factor of 2–3 short of the frequencies measured for EHO. The effect of E_r on precession frequency is illustrated in figure 2.

When the radial electric field is non-uniform, the effect gets more complicated due to the orbit-squeezing caused by the gradient of the radial electric field. Unlike the constant electric field effect that widens the orbits for one injection direction and narrows them for the other, the orbit-squeezing always shrinks the orbit widths.

The effect of toroidal magnetic ripple on particle losses A set of simulations was performed using the plasma and magnetic background of AUG discharge #15839 at 4.45 s. An ensemble of 10 000 test ions were initialized in the equatorial plane at random toroidal angle with $\rho_0 = 0.9$, $\xi_0 = -0.3$, and $E_0 = 60\,\mathrm{keV}$. The ensemble is representative of fast ions produced by any external means (NBI, ICRH). The experimental magnetic ripple extracted from AUG database

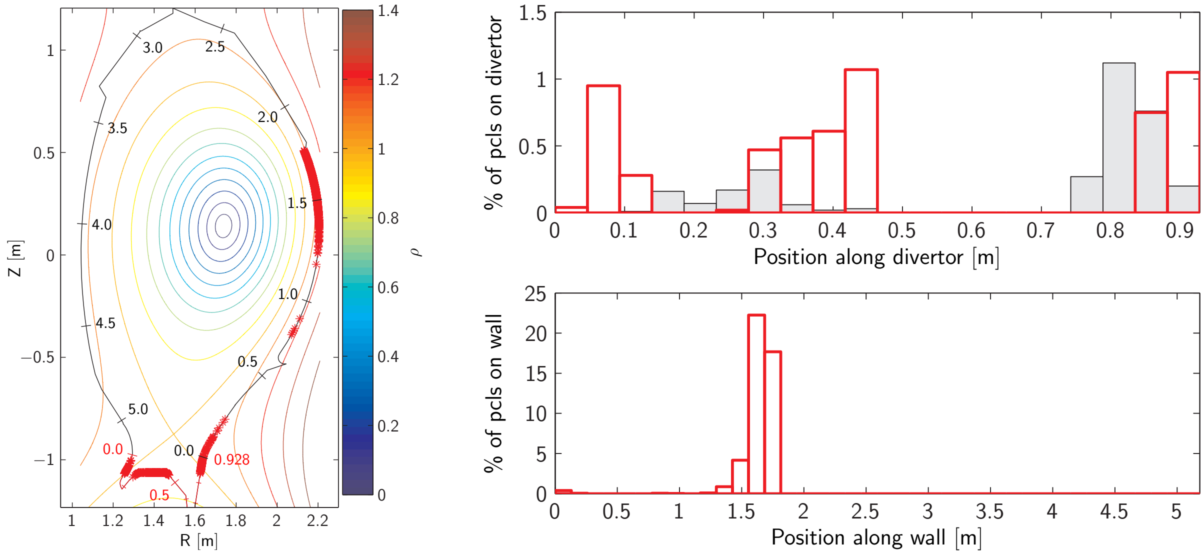

Figure 3: Fast particle (60 keV) losses to the divertor and wall structures. The poloidal cross section on the left illustrates the wall and divertor coordinates used in the histogram on the right and in figures 4 and 5. The red asterisks show the hit points in the presence of ripple. In the histogram, red and grey bars show the results with and without ripple, respectively. The percentages don't add up to 100% because the thermalized particles don't show up in the histogram.

was interpolated to the fine mesh used in the simulations and scaled to match the nominal field strength in the selected discharge. The test ions were simulated both with and without the ripple until they either hit a material surface or got thermalized.

The variation of the divertor and wall load in the poloidal cross-section is shown in figure 3. Without the ripple, the wall load is practically non-existent and most of the particles, about 97 %, are thermalized. On the divertor, most of the particles end up at the low field side, but there is also noticeable load in the private flux region. When the ripple is turned on, about 45 % of the particles are lost to the wall. Particle losses to the divertor are increased from 3.2 % to 5.9 % and they are shifted from the low field side to the high field side and the private flux region. The wall losses are localized at position $s \approx 1.6$ m along the wall, in the region near or at the poloidal limiter.

The particle losses as a function of the toroidal angle ϕ are shown in figure 4 both at the divertor and at the wall structures. Without the ripple the divertor load is uniform, but when the ripple is on, both loads have a maximum about halfway between the toroidal field coils. Figure 5 shows the energy distribution of the particles hitting the divertor and the wall structures for the two cases. The wall particles are almost inclusively high energy ions, whereas the particles hitting the divertor are closer to thermal energies, especially without the ripple.

A similar analysis was carried out for an ensemble of 17 035 neutral beam particles for AUG tangential beamlines 5 and 8. The particles were initialized in the region $\rho \in [0.8, 1.0]$, in other

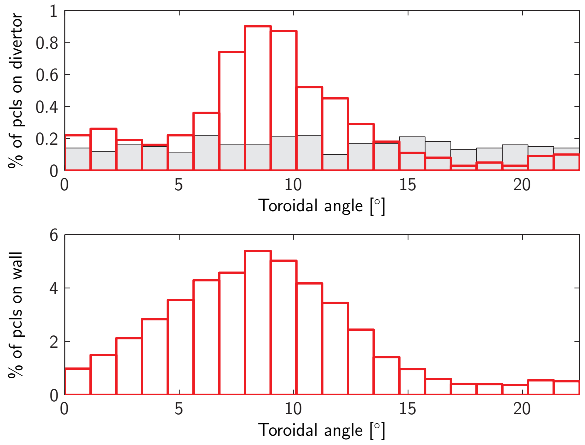

Figure 4: Toroidal variation of the fast particle losses. Red and grey bars are as in figure 3.

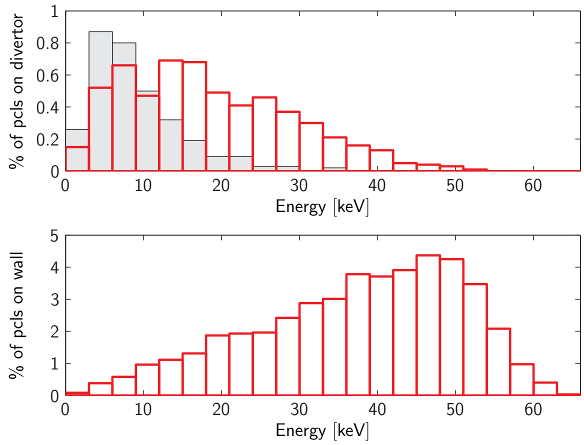

Figure 5: Energy distribution of the fast particle losses. Red and grey bars are as in figure 3.

respects the simulations with and without ripple were the same as for the 60 keV particles. Also the results were qualitatively the same, with most of the particles being lost to the limiter region and with the same dependency on the toroidal angle when the ripple is on.

Conclusions The ripple not only increases the fast ion losses but also makes them qualitatively worse: whereas in the absense of ripple most of the lost particles arrive at the divertor, with ripple a clear majority hits the wall. This is very unpleasent especially because the ions hitting the wall surfaces have much higher energies than those destined to hit the divertor. Furthermore, the released impurities migrate back to the plasma more easily. Luckily most of the wall losses occurred at the limiter region that tolerates higher loads than the rest of the wall.

In terms of physics these result imply that, as far as losses of fast ions are concerned, the banana diffusion is much more important than the ripple-induced direct losses. A similar analysis for thermal particles has been performed for JET by Kiviniemi *et al.* in these proceedings [5].

Acknowledgements: The computing facilities of CSC – Scientific Computing Ltd. were used for this work. The vacuum toroidal field with ripple has been computed by Peter Martin at AUG.

References

[1] M. H. Redi *et al.*, Nucl. Fusion **35** (1995) 1191

[2] The ASCOT code. `http://www.tkk.fi/Units/AES/projects/fusion/ascot.htm`

[3] W. Suttrop *et al.*, Plasma Phys. Control. Fusion **45** (2003) 1399

[4] R. D. Hazeltine, Phys. Fluids B **1** (1989) 2031

[5] T. Kiviniemi *et al.*, “Ripple-Induced Fast Ion and Thermal Ion Losses”, this conference