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Monte Carlo Simulations of Edge Ion Distribution and NPA Fluxes in ASDEX Upgrade

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Abstract. Using the low energy channels of neutral particle analyzers to measure edge ion temperature profile in tokamaks is investigated. The perpendicular velocity distribution of the edge ions is simulated for an H-mode AUG discharge using the guiding-center orbit-following Monte Carlo code ASCOT, and the local temperature is extracted assuming the distribution is Maxwellian. The CX-fluxes due to the test ion ensemble are evaluated.

Introduction. The global confinement of a tokamak plasma is to a large extent dictated by the conditions at the plasma edge, a few-centimeter-wide region around the separatrix. The edge is also important for the efficient exhaust of impurities and helium ash, and it determines the lifetime of the vessel walls and divertor plates. Consequently, diagnosing and controlling the edge plasma is of prime importance.

Measuring the temperature of the tokamak plasma ions is difficult. Particularly the edge profiles pose a big challenge due to the steep gradient there. Here the possibility of using the low-energy neutral particle analyzer (NPA) *LENA* in AUG to determine the edge ion temperature profile $T_i(r)$ is investigated. The energy range of *LENA* [20 eV, 1200 eV] is suitable for measuring the flux of neutrals generated in CX-reactions close to the plasma edge. These neutral flux spectra contain information on the ion temperature profile:

$$\Gamma(E) \propto \int_0^L \langle \sigma_{CX} v_{rel} \rangle(\rho) n_0(\rho) n_i(\rho) \cdot \left(e^{-E/T_i(\rho)} / T_i^{3/2}(\rho) \right) E^{3/2} \cdot \exp\left(-\int_0^{\rho(s)} \frac{ds'}{\lambda_{tot}(s')} \right) ds,$$

where the first term describes the charge exchange reaction, the second term is due to the assumed Maxwellian velocity distribution, and the last term gives the attenuation due to re-ionization along the sightline to the detector. The integration is carried out along the sightline L, and $\rho = \rho(s)$ is the magnetic surface label at the distance s from the detector. The CX reaction rate is $\langle \sigma_{CX} v_{rel} \rangle$, n_0 is the neutral density, n_i is the ion density, and λ_{tot} is the collisionless mean-free-path.

Since the value of the neutral flux $\Gamma(E)$ depends also on the plasma and neutral density profiles, some deconvolution method appears necessary. However, *simulating* the

CX measurements together with the additional experimental profiles has shown great promise [2]: the T_i-profile is parameterized as a linear spline, with the number of knots and knot positions adjusted manually. The T_i-profile thus obtained is combined with the other profiles to calculate the neutral fluxes. These simulated fluxes are then compared to the measured fluxes, and the standard χ^2-functional, weighted by the estimated errors of the data, is used as a quantitative criterion for the difference between the data and the simulation. With this procedure the experimentally determined neutral spectra can be modelled within the experimental error. However, in H-mode discharges with very high pedestals, the estimated ∇T_i values are so large that the local Maxwellian might be severely disturbed by the hot ions with large orbits from the top of the H-mode pedestal, in contrast to the assumption made to calculate $\Gamma(E)$. In the following we describe how the ASCOT code is used to study the distortion of the local Maxwellians and the effect of these distortions on the neutral flux spectra.

Monte Carlo Simulations of Edge Ion Velocity Distribution. We have analyzed the edge ion distribution function and the corresponding neutral fluxes using the Monte Carlo code ASCOT [1] that follows the guiding-center trajectories of test particles in a real tokamak magnetic geometry. Both the magnetic background and plasma profiles for the simulation are extracted from the AUG database. The background plasma as well as the magnetic background are assumed stationary. To model collisions, ASCOT uses binomially distributed Monte Carlo operators derived from the Fokker-Planck equation, and it has a built-in realistic CX-detector to evaluate the neutral fluxes.

The ASDEX Upgrade discharge # 7985 at t = 2.7 s was chosen for the background plasma. In this discharge, when viewed from above, the toroidal magnetic field $B_T =$ 2.5 T was clockwise, and the plasma current $I_p = 1$ MA was counter-clockwise. The plasma profiles used in the simulations are shown in Fig. 1. The plasma corresponds to H-mode conditions, but the edge gradients are not very steep ($L_{Ti} \approx 2.6$ cm). During the simulation, the test particle density profile is held stationary by the ambipolar E_r, and the temperature profile by Coulomb collisions from the fixed plasma background.

Because the LENA-detector on ASDEX Upgrade is oriented to monitor particles with very small parallel velocity, we shall base our study on the *perpendicular* velocity distribution of the test particles. The test particles (deuterons) are initialized so that they correspond to the bulk plasma: the particles are distributed uniformly (in poloidal and toroidal directions) on evenly spaced radial shells, and they assume an initial velocity according to the local temperature T_i, with a random pitch value. Because the test particles represent an ensemble of real plasma particles, they are assigned weight factors

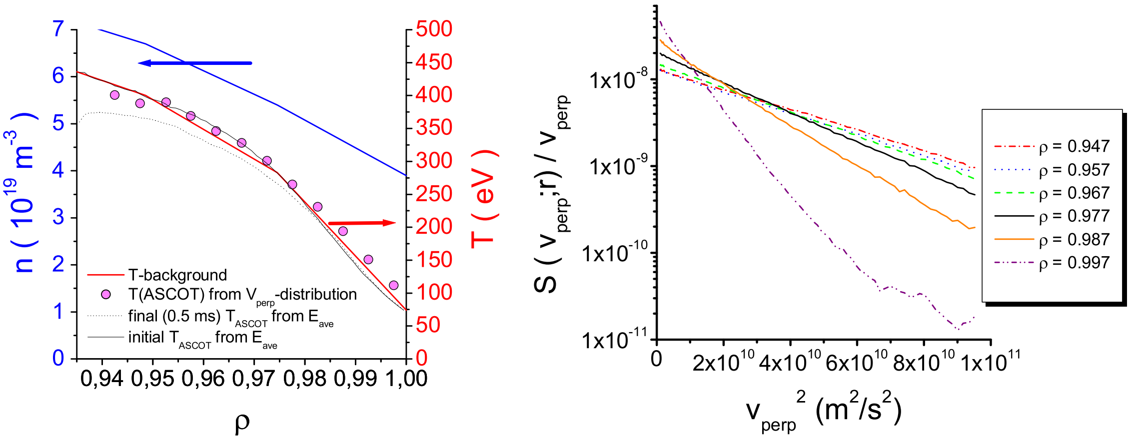

Figure 1: *(a) The plasma density and ion temperature of discharge # 7985 at t = 2.7 s. Also shown is the T_i-profile given by the average kinetic energy of the test ions, and the T_i-values given by the $v_\perp$-distribution assuming it is Maxwellian. (b) The perpendicular velocity distribution obtained from the ASCOT simulation for six radial positions. The distribution is plotted on logarithmic scale, so the slope of the distribution directly gives the inverse of the local temperature.*

w_k according to how many real particles are contained within the volume element in question. Altogether 260 000 deuterons are simulated in a radial region spanning the poloidal flux surfaces $\rho = 0.935, ..., 1.0$ and corresponding to a distance of approximately 3.4 cm along the major radius in the horizontal midplane.

The perpendicular velocity ($v_\perp$) distribution is obtained by accumulating time spent by particles in a given $v_\perp$- range, and is given by

$$\tilde{f}(v_\perp;\rho) = \sum_k \sum_j \frac{w_k \Delta t_{k,j,\Delta\rho,\Delta v_\perp}}{(2\pi)^2 R \Delta a(\rho) v_\perp \Delta v_\perp T_{sim}}. \tag{1}$$

Here, $\Delta v_\perp$ is a velocity interval around $v_\perp$, R is the major radius, and $\Delta a(\rho_k)$ is the annular surface element around ρ_k. The sum over j runs through all the time steps $\Delta t_{k,j}$ of the k^{th} particle, and k runs through the particle ensemble. $\Delta t_{k,j,d\rho_j \Delta v_\perp}$ is the fraction of the time step $\Delta t_{k,j}$ that the k^{th} particle spends in the phase space element specified by $\Delta a(\rho)$ and $\Delta v_\perp$, and T_{sim} is the simulation time. The distribution is accumulated independently inside twelve equally wide radial slots covering the simulation region. The test particles are followed for 0.5 ms to allow for the proper filling of the entire velocity space. (Extending the simulation to 1.0 ms did not change the results).

In Fig. 1(b) we show, on logarithmic scale, the perpendicular velocity distribution in six of the twelve radial slots obtained from the simulation. Figure 1(a) shows (the solid circles) the $T_i(\rho)$-profile obtained by making a linear fit to the velocity distributions of Fig. 1(b). The temperature values from the simulated velocity distributions agree very

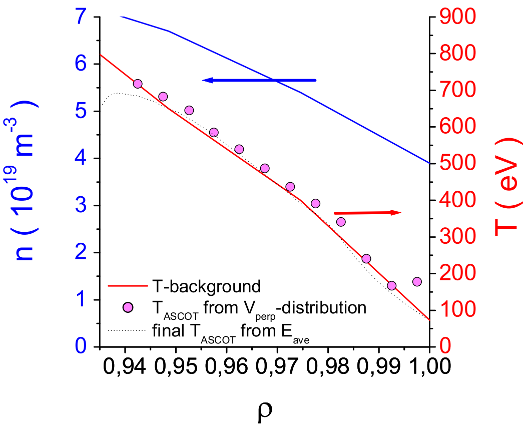

Figure 2: *The T_i-profiles obtained from a simulation where the gradient of the background temperature was increased by 30%.*

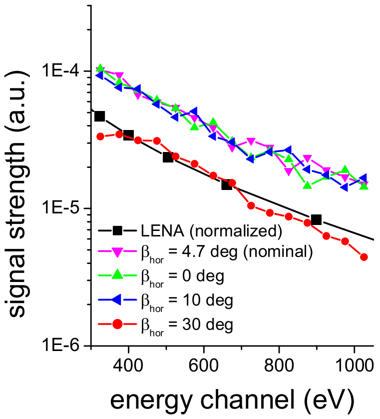

Figure 3: *The simulated neutral fluxes obtained for different horizontal sightlines. Perpendicular viewing gives the best statistics in axisymmetric geometry. Also shown is the experimental LENA-spectrum, renormalized to the level of the simulations.*

well with the background temperature. Figure 2 shows the same results for a simulation where the gradient of the background temperature was increased by a factor of two. The good agreement between the background T_i-profile and the T_i-values obtained from the simulations prevails. The neutral fluxes were evaluated during the simulation for sightlines that differ in the horizontal angle at which they view the plasma, see Fig. 3. The only qualitative difference between the sightlines is that the most tangential viewing ($\beta_{hor} = 30°$) has a lower signal level by about a factor of five. It should, however, be mentioned that these simulations were carried out for purely axisymmetric plasma. When toroidal ripple was included, the signals for the other sightlines dropped to the same level as for the tangential viewing. This is most likely due to the ripple-losses that the perpendicular particles fall victim to. The shape of the simulated neutral spectrum is similar to that measured by LENA, at least for the high end of the spectra.

Conclusions. In AUG plasmas the edge ion temperature could be determined from the $v_\perp$-distribution at least for pedestal temperatures up to 1 keV and temperature gradient lengths down to 1 cm. For much steeper gradients, non-Maxwellian tail formation by the finite-orbit effect is still possible. Future work includes taking into account the contribution that the SOL gives to the neutral fluxes. This will permit a quantitative comparison between measurements and simulations.

[1] J. A. Heikkinen *et al.*, Physics of Plasmas **4** (1997) 3655.
[2] J. Stober *et al.*, Plasma Phys. Control. Fusion **39** (1997) 1145.