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Neutral Flux Measurements as Diagnostics for Edge Radial Electric Field

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Abstract. Neutral particle analyzers (NPA) can provide the critical tool for deciding on the causality in an L-H transition. With a careful choice of the viewing parameters, NPA could give information on small changes in the radial electric field E_r right next to the separatrix with a sub-millisecond (50-100 μs) resolution.

Introduction. At an L-H transition, a sudden change in the edge radial electric field has been observed [1], but the question of causality in a spontaneous L-H transition is yet to be solved. The time resolution of the spectroscopic measurements has not yet been good enough to determine whether the plasma switches to the H-mode before or after the changes in E_r [2].

In a tokamak with a discrete set of magnetic coils, ions with very small parallel velocity are blocked into toroidal magnetic mirrors formed at large values of major radius. As a result of the ∇B-drift, these ripple-blocked ions are expected to escape the plasma very fast, in about 50 μs (see Fig. 1(a)). A neutral particle analyzer (NPA) monitoring

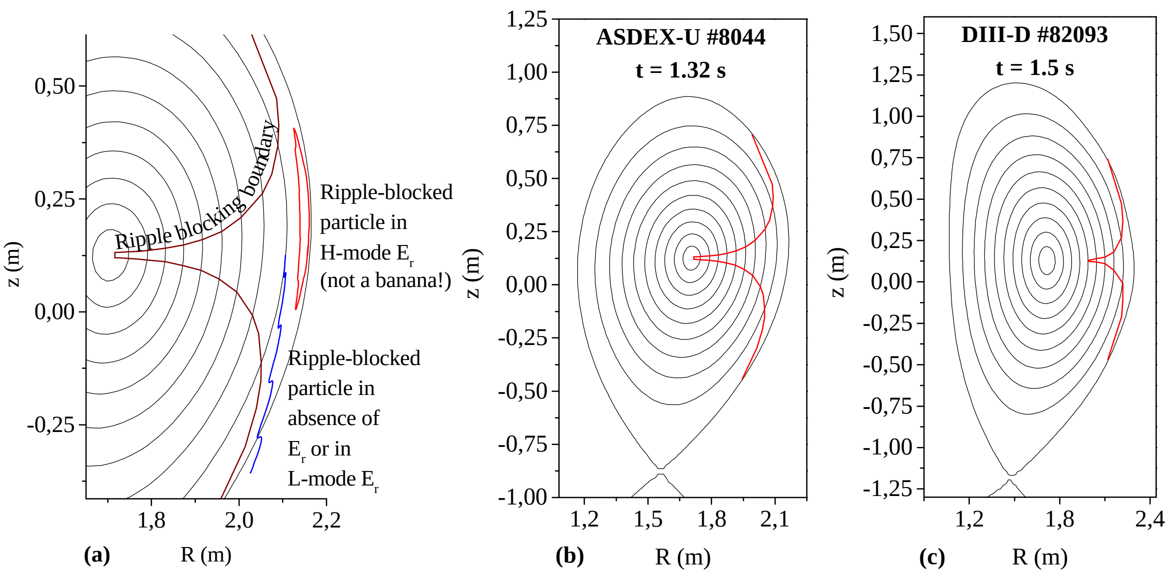

Figure 1: (a) typical trajectories of ripple-blocked particles in the cases of non-confining (L-mode) and confining (H-mode) radial electric field. The boundaries of the ripple-blocking region are shown in (b) and (c) for ASDEX-Upgrade and DIII-D, respectively.

the slowing-down neutral beam ions that are ripple-blocked should thus receive a negligible flux. However, if a radial electric field of sufficient magnitude (and right direction) appears in the ripple-loss domain, the corresponding $E \times B$-drift can compensate the ∇B-drift and confine the ripple-blocked ions (see Fig. 1(a)). If the profile of the electric field is wide enough, it also connects the inner, well-confined ripple-trapping region to the loss region, resulting in a fast, convective filling of the latter. Consequently, the neutral particle fluxes reach levels that are comparable to or even exceed the banana background [3,4].

On ASDEX Upgrade tokamak, NPA has already been successfully applied to monitor E_r across an L-H transition [5]. In these measurements E_r was observed to evolve only on a 'slow' time-scale of several milliseconds. However, the measurements were carried out for only one poloidal viewing angle θ_{CX}, which was not optimal for detecting *narrow* E_r profiles, as we shall show in the present work.

We investigate the effect of a non-uniform E_r on the ripple-blocked neutral beam ions using the guiding center orbit following Monte Carlo code ASCOT [6]. The analyses are carried out for ASDEX Upgrade and DIII-D plasmas, which both have a downward ∇B-drift but differ significantly in their ripple geometries, as shown in Fig. 1. The neutral density is assumed to decay rapidly as one moves inwards from the plasma boundary, $n_n = n_{n_0} e^{(r-a)/d_n}$ with $d_n = 1$ cm. The test particles are initialized according to ions born in the neutral beams. The magnetic field ripple is modelled by $B_0\Delta(\rho) = B_0\Delta_0 e^{\rho/w_B}$, where $B_0\Delta_0$ is the ripple strength, B_0 is the toroidal magnetic field at the geometric center of the plasma, and ρ is the normalized minor radius. For ASDEX Upgrade, with $\Delta_0 = 2.36{\cdot}10^{-4}$ and $w_B = 0.32$, the model fits quite well the ripple strength obtained from more detailed calculations. For DIII-D, the corresponding parameters are $\Delta_0 = 2.73{\cdot}10^{-6}$ and $w_B = 0.146$. The ripple in DIII-D is significantly smaller than in ASDEX Upgrade due to the larger number of toroidal coils ($N_c = 24$ as compared to $N_c = 16$ on ASDEX Upgrade).

The test particles (deuterons) are launched only at radial locations greater than $\rho = 0.87$. This is well justified because both the neutral beam flux and the neutralization probability (relevant to the detection) drop very rapidly as the distance to the separatrix increases. The ions are followed until they either reach the divertor or vessel wall, or their energy falls below 3 keV. We have allowed a finite-width scrape-off layer so that the ions can make an excursion there and return to the plasma, but the charge-exchange (CX) signal is collected only from inside the main plasma.

The simulations are carried out for two different radial electric field profiles, adopted from Ref. [7]: the L-mode field is positive at all radii, while the H-mode field exhibits a well-like structure near the separatrix (see Fig. 2). It should be noted that this well is quite narrow in major radius, and thus provides a good test bed for detecting early development of the radial electric field near the L-H transition.

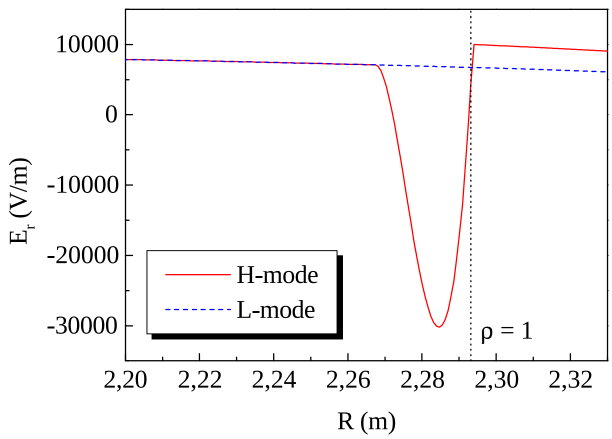

Figure 2: H-mode and L-mode radial electric field near the separatrix in DIII-D, approximated from experimental data [7].

Results. In Fig. 1(a) typical trajectories of ripple-blocked ions are shown for L-mode and H-mode cases. In L-mode, the upper part of the ripple-loss region should contribute a negligible CX signal to a NPA viewing ripple-blocked ions, while the lower part contributes a residual signal due to the downward drifting ions. Furthermore, due to plasma shaping, at large major radii the magnetic field strength lacks up-down symmetry: on ASDEX Upgrade the magnetic field increases faster when moving downward from the equator along a flux surface, while on DIII-D it increases faster when moving upward. In H-mode, this causes the closed ripple-blocked orbits to shift upward in ASDEX Upgrade and downward in DIII-D and, consequently, one expects a higher signal from positive poloidal viewing angles in ASDEX Upgrade and from negative poloidal viewing angles in DIII-D. Therefore, for the highest detection accuracy, neutral particle analyzers should be viewing the plasma from above the midplane on ASDEX Upgrade, and from below the midplane on DIII-D.

In Fig. 3 we show the enhancement in the CX signal from simulations carried out for ASDEX Upgrade and DIII-D with different NPA viewing angles. The signal is collected in the energy range of 5 keV$< E <$ 15 keV, the particle pitch is limited to $-0.03 < |\xi| < 0.03$, and the detector's poloidal field of view is 4° wide. Varying the poloidal viewing angle θ_{CX} from -16° through 0° to +16°, we find that $\theta_{CX} = -15°$, currently used at ASDEX Upgrade, gives only a modest signal enhancement for this narrow E_r profile. As shown in Fig. 3(a), for ASDEX Upgrade the optimal NPA viewing angle is *above* the midplane. However, a naive application of these NPA settings to a DIII-D plasma would lead to a complete failure, see Fig. 3(b). Figure 1 provides a straightforward explanation for this: in DIII-D, the ripple-loss region has very thin 'arms' extending to the larger poloidal angles. Therefore the signal obtained from these poloidal angles is likely to be dominated by banana orbit tips. In ASDEX Upgrade, in contrast, the ripple-loss region at these poloidal angles is much wider and, therefore, the signal is predominantly from the 'diagnostic' particles.

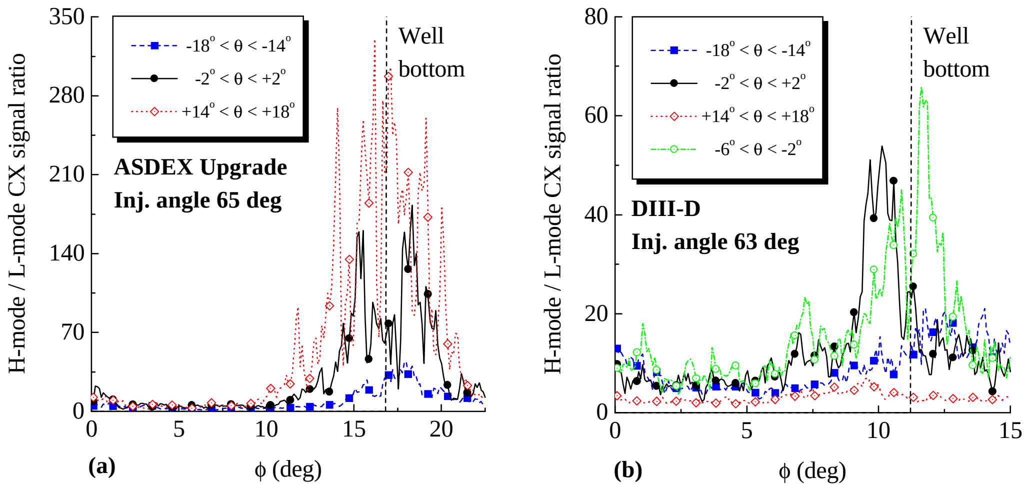

Figure 3: H-mode/L-mode signal ratio from different poloidal viewing angles in ASDEX Upgrade and DIII-D. The injection angle is defined as the angle at which the beam centerline intersects with the magnetic axis. The angles used in the simulations are based on the NBI installations at ASDEX Upgrade and DIII-D.

The DIII-D geometry, with its small toroidal ripple, is much less forgiving and thus requires a careful optimization of the NPA parameters. For DIII-D, the optimal NPA poloidal viewing angle should be close to the equator. Due to plasma shaping, the bulk of the confined ripple-blocked orbits is shifted downwards, and thus $\theta_{CX} < 0°$ is preferred. For a fairly tangential beam injection, which produces predominantly banana particles, it might also be beneficial to view the plasma toroidally slightly off the midplane between two adjacent coils.

Conclusions: We have shown that, for tokamaks with downward ∇B-drift, neutral particle analyzers can provide a sensitive diagnostic for even very narrow negative radial electric fields appearing near the plasma edge. For good sensitivity the crucial NPA parameter is the poloidal viewing angle, which should be optimised differently for different tokamaks: As a rule of thumb, for a tokamak with a fairly large ripple (like ASDEX Upgrade) θ_{CX} should be quite large and positive (upper hemisphere), while for tokamaks with a small ripple the analyzer should view the plasma close to the equatorial plane. However, in the presence of significant plasma shaping, also the effect of the up-down asymmetry has to be taken into account.

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