The effect of electric fields and pitch-angle scattering on the radial neutral flux

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Abstract

The radial flux of 10 keV neutrals from the Asdex-Upgrade tokamak has been interpreted as a diagnostic of the radial electric field $E_r$ near the plasma edge (Herrmann W and Asdex-Upgrade Team 1995 Phys. Rev. Lett. 75 4401), with the conclusion that $E_r$ changes gradually at a transition from the L-mode confinement regime to the H-mode regime. In contrast to the Asdex-Upgrade results, a similar installation on the DIII-D tokamak finds no measurable signal in H-mode plasmas with deep $E_r$ wells. Measurable signals only occur in plasmas with relatively large pitch-angle scattering rates at the plasma edge (or with anomalous beam-ion confinement). Large scattering rates require a large electron temperature and are invariably accompanied by deep ripple wells. The results suggest an alternative explanation for the gradual evolution of the neutral-particle signal from Asdex-Upgrade: as the H-mode pedestal develops, more beam ions are pitch-angle scattered into the phase space measured by the detector.

1. Introduction

Since the discovery of the H-mode nearly 20 years ago [1], H-mode and L-mode confinement regimes have been compared in order to understand fluctuation-induced transport in tokamaks. Over the years, the idea that $E \times B$ velocity shear reduces transport by suppressing the growth, radial extent, and phase correlation of turbulent eddies has gained prominence as an explanation for the reduced transport in the H-mode [2]. Spectroscopic measurements [3] found a deep, narrow well in the radial electric field (with minimum value of about $-20$ kV m$^{-1}$) near the plasma separatrix; in contrast, $E_r$ in the L-mode has little shear. The validity of the spectroscopic measurements are corroborated by spectroscopic measurements of different ion species [4], by comparisons with motional Stark effect measurements [5, 6], by heavy-ion beam probe measurements [7], and by Langmuir probe measurements of the edge floating potential.
at the L–H transition [8, 9]. DIII-D measurements suggest that the $E \times B$ shear changes prior to changes in the turbulence and the transport, as expected if the velocity shear causes the transport suppression [9–11]. The temporal resolution of the spectroscopic measurements is only about 0.5 ms so, although strong evidence for the causal relationship between velocity shear and transport exists [12], not everyone is convinced [13].

If the flux is sufficiently large to minimize statistical fluctuations, neutral-particle measurements can have better temporal resolution than the spectroscopic measurements. For example, the neutral-particle analyser used in this study has an intrinsic resolution of 30 µs and has successfully resolved 16 kHz fluctuations in edge flux caused by the fishbone instability [14]. An analyser with a 50 µs resolution has studied the L–H transition on Asdex-Upgrade [15–17]. This analyser was positioned at the outer midplane, midway between toroidal field coils, detecting neutrals that escape nearly radially from the tokamak. For this orientation, ions that charge exchange in the outer edge are in the ‘ripple-trapping’ region. In the absence of a radial electric field or collisional scattering, these ripple-trapped ions are mirror trapped between toroidal field coils in the corrugated toroidal field $B_T$ and rapidly $\nabla B$ drift out of the plasma vertically. A negative electric field, such as that associated with the H-mode, produces a vertical $E_r \times B_T$ drift that can cancel or overcome the $\nabla B$ drift, producing confined orbits [16–21]. Comparison with the results of extensive Monte Carlo and Fokker–Planck simulations [18–21] shows that when the $E \times B$ drift exceeds the $\nabla B$ drift,

$$|E_r| \gtrsim W/R$$

ripple-loss orbits are converted into confined orbits (as long as the $E_r$ well is wider than about 2 cm) [17]. Here $W$ is the ion energy and $R$ is the major radius of the orbit. Once (1) is satisfied, the ripple-loss region is quickly populated on a drift-orbit timescale of about 100 µs [18–21]. Thus, in principle, neutral-particle measurements can detect changes in the radial electric field more rapidly than spectroscopic measurements, thereby testing the causal relationship between $E \times B$ shear and turbulent transport at the L–H transition.

Herrmann and the Asdex-Upgrade Team found that the edge radial neutral flux changes gradually at the L–H transition [15]. Based on these data, they concluded that ‘the presented experimental results are in favour of theories that do not need an electric field as an active element for the L–H transition’. This conclusion stands in contradiction to the paradigm that reduced transport in H-mode and other improved confinement regimes is caused by $E \times B$ shearing of turbulent eddies [2]. In subsequent observations, Herrmann et al [16] found that the neutral flux sometimes increases prior to the L–H transition, but there was uncertainty as to the precise timing of the transition.

The purpose of this study is to clarify this controversy by simultaneously measuring the neutral-particle flux and the radial electric field in the same tokamak. An analyser that had previously measured the active charge-exchange flux from circulating beam ions [22] was redeployed to measure the radial neutral flux from the ripple-trapped region. Observations during a set of dedicated experiments failed to reproduce the Asdex-Upgrade results: essentially no signal is detected either before or after an ordinary L–H transition in DIII-D (section 2). Radial neutral flux is detected in plasmas with very strong heating and excellent confinement, however (section 3). The results indicate that pitch-angle scattering plays a crucial role in populating the portion of phase space measured by the neutral-particle analyser. This factor is at least as important as the radial electric field in determining the temporal evolution of the neutral flux (section 4).
2. Apparatus and null result of the L–H transition study

The data in this paper are from the 1999 and 2000 experimental campaigns on the DIII-D tokamak. DIII-D [23] is a moderately-sized tokamak (major radius $R_0 \simeq 1.7$ m, minor radius $a \simeq 0.6$ m). The device is operated in a variety of configurations: inner-wall limiter, upper and lower single-null divertors, and double-null divertor. Depending on the plasma shape, active cryopumps in the divertors counteract the density rise normally associated with H-mode operation. Carbon from the graphite walls is the dominant impurity and $Z_{\text{eff}}$ is inferred from absolutely calibrated measurements of carbon density by the charge-exchange recombination (CER) diagnostic [24]. The plasma shape is computed by the EFIT code [25] from the motional Stark effect (MSE) [26] and magnetic probe data. For these experiments, auxiliary heating is provided by neutral beams, with occasional application of electron cyclotron heating. (During ion cyclotron heating, the neutral-particle analysers studied beam-ion acceleration.) The neutral beams inject 65–81 keV deuterium ions into deuterium plasmas at two angles with respect to the toroidal field. For neutrals injected by the so-called Right beams (tangency radius $R_{\text{tan}} \simeq 0.76$ m), the angle between the velocity vector and the toroidal direction is about $68^\circ$ at the plasma edge; for the more-tangential Left beams ($R_{\text{tan}} \simeq 1.15$ m), this angle is about $59^\circ$ at the plasma edge. In most plasmas, the $\nabla B$ drift is downward and the neutrals are injected in the direction of the plasma current (co-injection), but some discharges with a reversed toroidal field or with a reversed plasma current (or both) are included in the study. The electron density is measured by Thomson scattering [27] and interferometry [28], the electron temperature by Thomson scattering [27] and electron cyclotron emission [29], and the ion temperature by CER spectroscopy [24]. The behaviour of the H-mode pedestal is quantified using hyperbolic tangent fits to the Thomson scattering data [30].

The neutral-particle analyser is a compact electrostatic analyser with a stripping foil that was originally developed for the PDX tokamak [31]. Usually, 10 keV neutrals are measured; the energy resolution is about 5%. The analyser is mounted 8 cm below the midplane, midway between a pair of toroidal field coils, oriented radially to measure neutrals that escape at an angle of $90^\circ \pm 1^\circ$ with respect to the toroidal direction. In addition to neutrals, the detector is sensitive to gammas produced by neutrons and to Bremsstrahlung produced by runaway electrons. (Tests indicate that interference associated with scattered ultraviolet light is negligible.) The sensitivity to neutrons was measured by closing the gate valve to the tokamak; the horizontal charge exchange (HCX) signals in this paper are all corrected for this background using the calibrated signal from a plastic scintillator. Spurious signals associated with bremsstrahlung are more problematic. Fortuitously, an ion gauge mounted at the same toroidal location is even more sensitive to x-ray interference than the neutral-particle analyser. Discharges with significant x-ray interference (as determined from the ion gauge signal) were excluded from this study, as were bursts of signal at the time of a major or minor disruption. Tests with the deflection plate bias turned off confirm that the retained data are free from x-ray contamination.

Initially, the primary goal was to reproduce the behaviour observed on ASDEX-Upgrade, but a null result was obtained. In a shaped tokamak, the ripple-trapping boundary occurs where [32]

$$\delta = \frac{|B_R|}{N_c |B|}$$

where the field ripple $\delta = (B_{\text{max}} - B_{\text{min}}) / (B_{\text{max}} + B_{\text{min}})$, $N_c = 24$ is the number of field coils, and $B_R$ and $B$ are the radial and total magnetic fields, respectively. Two sets of dedicated experiments were conducted. The injected power level was modest (1–5 MW) and the plasma was shifted downward to give better alignment of the ripple-trapping region with the analyser line of sight. The plasma shape, ripple-trapping boundary, and analyser line of sight for one of
the discharges in the study are shown in figure 1. The magnetic axis is located $z_0 = -7.2$ cm below the centre of the vacuum vessel in this discharge. The radial electric field measured by CER is $E_r = 10.0 \pm 2.7$ kV m$^{-1}$ at the plasma edge in this discharge; the well is only about 1 cm wide. According to the simple criterion (equation (1)), this field is sufficiently strong to confine ripple-trapped ions up to 22 keV, although the narrowness of the well may diminish its effectiveness somewhat. The HCX signal was $0.01 \pm 0.01$ under these conditions; i.e. at least 40 times smaller than the signals discussed in the next section. In these dedicated experiments, plasma positions of $z_0 = -15, -7, -2, +3,$ and $+6$ cm and neutral energies of 10.6 and 18.1 keV were measured during the ELM-free H-mode phase.

In addition to dedicated experiments, neutral-particle measurements at about 10 keV were acquired for most of the discharges in the 1999 and 2000 experimental campaigns. A database of 951 conditions from about 300 beam-heated discharges was assembled. Most parameters in the database are averaged over 25 ms. The database spans the following plasma conditions: plasma current $I_p = 0.4–2.0$ MA for co-injection and 0.6–1.6 MA for counter-injection, toroidal field $B_T = 1.3–2.1$ T in the normal direction and 1.6–2.1 T in the reversed direction, beam power $P_B \leq 14$ MW, line-averaged electron density $\bar{n}_e = 0.6–11.8 \times 10^{19}$ m$^{-3}$, central electron temperature $T_e(0) = 0.8–5.6$ keV, and central ion temperature $T_i(0) = 1.0–16.6$ keV. Typically, the analyser line of sight was a few centimetres below the plasma centre, which optimizes the sensitivity to $E_r$ effects [33]. This broader set of data is consistent with the results of the dedicated scans. Overall, for the discharges in this database, the average HCX signal was $0.00 \pm 0.02$ for ELM-free H-modes, with no correlation of the signal with vertical position $z_0$. 

Figure 1. Elevation of the DIII-D vessel showing the plasma shape and ripple-trapping boundary (equation (2)) during the ELM-free H-mode at 1.55 s. In this dedicated discharge, $z_0 = -7$ cm to align the ripple-trapped region with the HCX line of sight. The lines of sight of the V1 and V2 vertical neutral-particle analysers are also shown. $I_p = 1.4$ MA, $B_T = 1.4$ T, $\bar{n}_e = 4.4 \times 10^{19}$ m$^{-3}$, $P_B = 1.2$ MW of Right beams.
3. Dependence of the HCX signal on the density of edge beam ions

The passive charge exchange signal depends on the ion distribution function $f(W, \chi)$ in the portion of phase space measured by the analyser and on the neutral density $n_0$. (Here, $\chi$ is the angle between the velocity vector and the toroidal direction and $W$ is the measured energy.) The measured signal is proportional to the product of these two ‘densities’ along the line of sight, $\int n_0(l) f(W, \chi, l) \, dl$. Generally, the neutral density peaks very strongly near the plasma edge, decreasing with an exponential decay length of 1–2 cm as the neutrals attempt to penetrate the plasma. In contrast, the fast-ion distribution, which is composed of both decelerating beam ions and thermal ions, generally peaks strongly in the plasma centre. The relative importance of beam and thermal ions depends sensitively on the ratio of $W$ to $T_i$, with beam ions predominating for $W \gtrsim 10T_i$, which is generally the case in this study.

Figure 2, from an upper-single-null divertor discharge with a weak but detectable HCX signal, illustrates several typical features of the radial neutral-particle signal. No HCX signal is detected during the L-mode phase of the discharge (prior to 1.14 s) nor during the ELM-free H-mode. A small signal appears immediately after the neutron rate reaches its maximum value at 1.285 s, immediately prior to the first ELM. A large spike occurs in the HCX signal at the time of the minor disruption at 1.71 s; this signal probably contains an admixture of x-ray and neutral-particle contributions and is excluded from this study. A second high-performance phase ensues after the minor disruption, with non-zero HCX signal reappearing with the onset of ELMs. As the confinement deteriorates with the onset of an $n = 1$ tearing mode, the HCX signal gradually returns to zero.

Several features of this discharge are generally observed.

- Steady HCX signals are only observed under conditions with relatively large neutron rates ($\gtrsim 2 \times 10^{15} \text{ n s}^{-1}$) and enhanced confinement relative to L-mode.
- The charge exchange signals from a pair of vertical detectors (figure 1) are much larger than the horizontal signal. In particular in discharges with an upper divertor, the vertical signals often correlate directly with the $D_\alpha$ recycling light, while the HCX signal is only weakly correlated. For the database, the HCX signal is uncorrelated with the V1 and V2 vertical signals. Evidently, the neutral density is both larger and more variable in the divertor region than at the outer midplane. Independent measurements of the neutral density show $n_0$ is typically an order of magnitude larger at the X-point of the divertor than at the midplane.
- Apart from transient events, a steady HCX signal only occurs in discharges with ELMs, possibly because the neutral density is too low at the outer midplane under ELM-free conditions.

Calibrated measurements of $D_\alpha$ recycling light from the midplane are available for the 2000 experimental campaign. For the database, the HCX signal does not correlate with the light intensity for any of the eight midplane viewing chords. In addition to its sensitivity to the neutral density, the $D_\alpha$ light intensity also depends sensitively on the edge electron temperature. Analysis [34] of one discharge with substantial variation in the magnitude of the HCX signal (discharge 102 323) indicates that the midplane separatrix neutral density was approximately $6 \times 10^{15} \text{ m}^{-3}$ and barely changed as the discharge evolved. Apparently, at least in H-modes with ELMs, variations in the neutral density are not the dominant factor controlling variations in the HCX signal.
3.1. Discharges with classical beam-ion confinement

Figure 3 shows data from a discharge with a relatively large HCX signal. The signal is largest when the neutron rate, stored energy, and edge temperature pedestal are largest. The HCX signal only appears during ELMs and increases about 100 ms after the increases in the neutron rate, stored energy, and electron temperature that begin at 1.86 s. After 4.05 s, the confinement degrades slightly. The HCX signal falls to about half its previous level with a delay of about 80 ms with respect to the neutron rate, stored energy, and electron temperature. Although the HCX signal in this discharge is fairly steady, appreciable fluctuations are present.

Measurable steady HCX signals are only observed in discharges with large neutron rates, plasma stored energy, and electron temperatures. Figure 4(a) shows the dependence
Figure 3. Beam power (a), line-average electron density (b), neutron rate (full curve) and plasma stored energy derived from the equilibrium $W_{\text{MHD}}$ (broken curve) (c), electron temperature at the top of the edge pedestal (d), midplane Balmer alpha light (e), and HCX signal (f) in a lower-single null divertor discharge with $I_p = 1.4$ MA and $B_T = 2.1$ T. Approximately half of the beam power is injected by Left sources and half by Right sources.

of the HCX signal on the neutron rate. Only discharges with good beam-ion confinement are included in figure 4. A convenient measure of the average beam-ion confinement is the ratio of the measured neutron rate $S_m$ to the neutron rate $S_{\text{th}}$ predicted by a zero-dimensional code \[35\]. This zero-dimensional code was previously shown to give excellent agreement with the measured rate in MHD-quiescent discharges, agreeing as well as more sophisticated calculations \[35\]; on the other hand, in discharges with beam-driven Alfvén activity, the measured rate deviates from the code predictions \[36\]. Accordingly, the parameter $S_m / S_{\text{th}}$ is a useful figure of merit that divides discharges with nearly classical beam-ion confinement from discharges with anomalous beam-ion losses. (Discharges with anomalous neutron rates are discussed in section 3.2.) The data in figure 4(a) are divided into conditions with and without near-perpendicular Right beam injection. The largest signals occur in discharges that satisfy
three conditions:

- large neutron rate,
- classical beam-ion confinement,
- at least one near-perpendicular (Right) source.

As discussed below, all of these requirements are ultimately related to the requirement that perpendicular edge beam ions must lie in the analyser line of sight. When one or more of these conditions is not satisfied, the steady HCX signal is small or non-existent. When near-tangential Left beams alone are injected into plasmas with classical beam-ion confinement (triangles in figure 4(a)), the HCX signals are generally much smaller than in discharges with mixed beam injection (squares).

Since the neutron rate correlates strongly with the stored energy (correlation coefficient \( r = 0.89 \)) and more weakly with the edge pedestal temperature and pressure (\( r \approx 0.61 \)) in our database, it is not possible to isolate the parameter or parameters that determine the HCX signal statistically. Not surprisingly, many different combinations of parameters yield correlation coefficients comparable to that shown in figure 4(a). One such example is shown in figure 4(b). In this figure, the HCX signal is plotted against an approximate measure of the edge beam-ion density, \( P_B \tau_{th} n_e \). Here \( \tau_{th} \) is the Stix thermalization time [37], evaluated using the electron temperature at the top of the edge pedestal. Figure 4(b) shows similar trends as figure 4(a): a steady detectable HCX signal only occurs during Right beam injection into a discharge with classical beam-ion confinement and a large edge density of beam ions. For
Figure 5. Deceleration time $\tau_W$ (broken curve) and adjusted pitch-angle-scattering time $\tau_{\text{PAS}}$ (full curve) as a function of the plasma radius $\rho$ for eight different plasma conditions. The panels are arranged in order of increasing HCX signal (the number in the upper-left-hand corner). The 90° pitch-angle-scattering time is multiplied by $(22/90)^2$ in the cases with some Right beam injection and by $(31/90)^2$ for the two cases with only Left beams. The radius $\rho$ is the normalized square root of the toroidal flux. Discharge 102 323 at 1.5 s from figure 3 (a), discharge 100 303 at 1.55 s from figure 1 (b), discharge 100 369 at 1.33 s from figure 2 (d), discharge 100 364 at 1.57 s: $I_p = 1.2$ MA, $B_T = 1.6$ T, $\bar{n}_e = 4.9 \times 10^{15}$ m$^{-3}$, $P_B = 8.6$ MW (Left beams only), $S_x = 1.9 \times 10^{15}$ n s$^{-1}$, double-null divertor (e), discharge 100 336 at 1.6 s from figure 6 (f), discharge 102 323 at 4.5 s from figure 3 (g), and discharge 102 323 at 2.5 s from figure 3 (h).

The open squares in figure 4(b) the correlation coefficient of HCX with $P_B \tau_{\text{PAS}} \bar{n}_e$ is $r = 0.52$; if $P_B$ is replaced with the power in the Right beams the correlation coefficient increases to $r = 0.65$. This value is similar to the correlation of the classical, mixed beam HCX signal with the neutron rate ($r = 0.62$) in figure 4(a). The ratio of the edge pitch-angle scattering rate to the edge deceleration rate (the quantity discussed in figure 5), yields a similar correlation. The strongest correlation in the database is with the central Thomson electron temperature ($r = 0.73$). Weaker correlations are observed with the Right beam power ($r = 0.57$), stored energy ($r = 0.46$), and central ion temperature ($r = 0.43$). The correlations with the electron density, the pressure pedestal height, the safety factor $q$, the amplitude of low-frequency MHD, the direction of the plasma current, and the various shaping parameters are all very weak ($r < 0.40$). All of these trends are consistent with the interpretation that the edge density of perpendicular beam ions is the dominant factor governing the HCX signal.

To be detected by the analyser, beam ions must have no toroidal velocity at the time of the charge exchange reaction. Injected neutrals that ionize near the edge have a velocity vector that differs by 22° from the perpendicular direction (for the Right beams). This implies that,
in order to be detected, a beam ion must pitch-angle scatter \(22^\circ\) before it thermalizes. If it thermalizes first, it cannot be detected by the neutral-particle analyser.

The competition between pitch-angle scattering and energy loss is governed by the classical Coulomb scattering processes. The dilute beam-ion population slows down on both thermal electrons and thermal ions. Because of the mass difference, if the beam ions slow down predominately on electrons, very little pitch-angle scattering occurs. Electron drag is large when the electrons are slow, i.e. at low values of \(T_e\). In cold plasmas, the beam ions decelerate before they pitch-angle scatter into the analyser line of sight. In contrast, in hotter plasmas, drag on thermal ions becomes important. In this case, pitch-angle scattering is appreciable and the beam ions can scatter into the analyser line of sight prior to thermalization.

Figure 5 shows calculations of the characteristic deceleration and pitch-angle scattering times [38] of 75 keV test ions at the plasma edge under eight different conditions with fairly steady HCX signals. The calculations utilize profiles of \(n_e\), \(T_e\), \(T_i\), and carbon density \(n_C\) obtained from spline fits to the measured data. The standard ‘pitch-angle-scattering time’ \(\tau_{90}\) is the characteristic time for a test distribution to broaden to a width of \(90^\circ\). Since this broadening is a diffusive process in velocity space, \(\langle \Delta \theta \rangle^2 \propto t\). This implies that the characteristic time to scatter into the line of sight is \(\tau_{PAS} = (22/90)^2 \tau_{90}\) for the case of Right beams and \(\tau_{PAS} = (31/90)^2 \tau_{90}\) for the case of Left beams. The deceleration time \(\tau_W\) is the characteristic energy loss time, \(1/\nu_E\). As shown in figure 5, when \(\tau_W \ll \tau_{PAS}\), no HCX signal is measured because the beam ions thermalize prior to scattering into the line of sight. When the rates are comparable, tiny signals are observed. The largest signals are seen in plasmas where \(\tau_{PAS}\) exceeds \(\tau_W\) over most of the edge. The smaller signals observed during injection with exclusively Left beams are explained by the fact that, for comparable plasma conditions, the characteristic scattering time \(\tau_{PAS}\) is twice as long for the Left beams as for the Right beams.

The time evolution of the HCX signal is also consistent with classical scattering processes. The HCX signal is expected to respond to changes in plasma conditions on a timescale of \(\tau_W \ln(W_{inj}/W) \approx 2\tau_W\). (The \(\ln\) factor arises because \(\tau_W\) is the time to lose \(1/e\) of the initial energy, but the beam ions must decelerate from \(W_{inj} \simeq 75\) keV to about \(10\) keV.) Figure 6 shows the HCX signal and the ratio of \(\tau_{PAS}/\tau_W\) in a double-null divertor discharge. HCX signal appears about \(40\) ms after the criterion \(\tau_{PAS} \lesssim \tau_W\) is satisfied at \(1.18\) s and persists for approximately \(50\) ms after the criterion is transiently violated at \(1.95\) s. These timescales are comparable to the expected response time of \(2\tau_W \approx 30\) ms. The HCX signal often responds to changes in confinement on a \(20–50\) ms timescale.

Figure 6 also illustrates why effects associated with ripple trapping and the formation of the \(E_r\) well are difficult to observe in our data. The criterion \(\tau_{PAS} \lesssim \tau_W\) requires a large electron temperature in the plasma edge. A sufficiently hot edge only occurs in the presence of a steep edge pedestal. Because of the large pressure gradient, a steep pedestal invariably implies a region with a deep \(E_r\) well. So, when the criterion for sufficient pitch-angle scattering is satisfied, the criterion for ripple-trapping confinement (equation (1)) is also satisfied.

### 3.2. Discharges with anomalous beam-ion confinement

In plasmas with anomalous beam-ion confinement, transient bursts of signal are occasionally observed. An example is shown in figure 7. In this discharge, the measured neutron rate is \(60\%\) of the expected rate. An Alfvén instability with a frequency of approximately \(200\) kHz is detected by a magnetic probe early in the discharge when the density is low and the beam-ion pressure is high. At about \(1.08\) s, the density rises and the neutron rate decreases, suggesting a reduction in the number of beam ions in the plasma. The Alfvén activity decreases in
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Figure 6. Beam power (a), line-average electron density (b), divertor Balmer alpha light (c), HCX signal (d), the average of $\tau_{\text{PAS}}/\tau_W$ in the region normalized radius $\rho = 0.96$–0.98 (e), and the minimum measured edge radial electric field (f) in a double-null divertor discharge with $I_p = 1.2$ MA and $B_T = 1.6$ T. Approximately half of the beam power is injected by Left sources and half by Right sources. If $E_r$ is below the broken line in (e), the criterion for confinement of ripple-trapped ions (equation (1)) is satisfied. If $\tau_{\text{PAS}}/\tau_W$ is below the broken line in (f), beam ions can pitch-angle scatter into the analyser line of sight prior to thermalization. Because the $E_r$ well can be narrow, the spectroscopic channels that measure $E_r$ sometimes ‘straddle’ the well (missing the absolute minimum), so the measured values constitute an upper bound on the well depth.

amplitude (probably because the beam-ion drive for the instability weakens). Bursts of HCX signal appear in the 100 ms following this change in activity.

This phenomenon is readily explained. In the plasma core, the deceleration time is long compared to the adjusted pitch-angle-scattering time (figure 5), so there are many beam ions with pitch angles of $90^\circ$. In a plasma with classical beam-ion confinement, radial transport is negligible and few core ions arrive in the edge region where the neutral density is large. However, in the presence of instabilities, anomalous radial transport is possible. When the instability is strong, as it is before 1.08 s in figure 7, the anomalous radial transport is probably so effective that beam ions are ejected from the plasma by the instability. The HCX signal
Figure 7. Neutron rate (full curve) and electron density (broken curve) (a), HCX signal (b), and magnetic-probe spectrogram (c) for an inner-wall limiter plasma with $B_T = 2.1$ T. Approximately 6 MW of Right beams and approximately 4 MW of Left beams are injected opposite to the plasma current (counter-injection). The plasma current increases from 1.1 MA to 1.6 MA between 0.8 and 1.3 s.

Figure 8. HCX signal against neutron rate for the complete database. The open circles represent data with neutron rates that are over 75% of the expected neutron rate, while the full symbols represent data where $S_m/S_{th} < 75\%$. Discharges with only near-tangential Left beam injection are represented by triangles; conditions with some near-perpendicular Right beam injection are represented by squares.

is barely enhanced during this stage. However, as the instability weakens, the anomalous radial transport no longer ejects the interacting beam ions. Some energetic ions are moved to the plasma edge, where they are subsequently detected with a delay that is characteristic of collisional deceleration.

For the discharges studied, the majority of plasmas with anomalous neutron rates contain fast-ion driven instabilities that degrade beam-ion confinement, as in figure 7. In other cases, particularly in discharges with counter-current injection at low plasma current, unusually low values of $S_m/S_{th}$ are caused by very large values of $Z_{eff}$ or excessive prompt losses. (The simple zero-dimensional code used to calculate $S_{th}$ for the purposes of discharge classification
assumes a constant value of deuterium depletion $n_d/n_e$ and does not include a correction for prompt losses.) Figure 8 compares data from discharges with anomalous neutron rates (full symbols) with data from discharges with classical neutron rates (open symbols). Generally, no signal is observed even in discharges with Right beam injection and neutron rates greater than $3 \times 10^{15} \text{ ns}^{-1}$ (full squares). However, in a few cases with either Left or Right beam injection and anomalous confinement, bursts of HCX signal are observed. All of the full points with detectable signals and $S_{\text{in}} < 10^{15} \text{ ns}^{-1}$ in figure 8 represent transient bursts of signal similar to that shown in figure 7 (although the correlation with Alfvén activity is not as clear in every case). We conclude that conditions with anomalous beam-ion confinement usually reduce the beam-ion density near the edge, but occasionally transport central beam ions into the line of sight of the detector.

4. Discussion and comparison with ASDEX-Upgrade

The hypothesis that the pitch-angle scattering rate is the dominant factor in the appearance of HCX signal accounts for all of the features of the data presented in sections 2 and 3.

- Signals are larger for Right beam injection than for Left beam injection because the scattering angle is smaller (figure 4).
- Measurable signals require a relatively hot edge so that injected beam ions can scatter into the line of sight prior to thermalization (figure 5).
- The delay between the formation of a hot edge and the rise in the HCX signal occurs on a collisional timescale (figure 6).
- No direct effect of an $E_r$ well is observed on the HCX signal because a sufficiently deep $E_r$ well always exists in plasmas with a hot edge (figure 6).
- In most discharges with anomalous beam-ion transport, no signal is observed because beam ions are lost from the volume measured by the analyser (figure 8). However, in some discharges, bursts are seen. These bursts depend on the vagaries of anomalous radial transport (figure 7).
- Residual fluctuations in the signal and the apparent requirement that the plasma contain ELMs may be associated with variations in the neutral density.

An alternative explanation is that beam ions born near the plasma centre make a major contribution to the observed signal. Because the slowing-down time is long for central beam ions, these ions undergo sufficient pitch-angle scattering for detection. However, their detection also requires either an anomalously broad neutral-density profile or anomalous beam-ion transport to the high-density edge region. These are both remote possibilities. There are no central neutral-particle sources at the toroidal location of the analyser and, in the absence of MHD activity, the confinement of beam ions is generally excellent [39]; moreover, the neutron rate is classical in the discharges with a steady non-zero HCX signal. It is very unlikely that the measured neutrals originate in the plasma centre.

In many ways, these DIII-D experiments are quite similar to the experiments on ASDEX-Upgrade, but there are some important differences. The analyser line of sight is similar, as is the injection angle of the most perpendicular beam lines. The analysers are different. One possibility is that the ASDEX-Upgrade analyser is more sensitive than the DIII-D analyser (which has not been absolutely calibrated), but this seems rather unlikely. The null results of section 2 are at least 40 times smaller than the signal in figure 3. These signals are themselves an order of magnitude smaller than the signals from the vertical analysers (figure 2) and two orders of magnitude smaller than the signals from the horizontal analyser when it was oriented to make active charge exchange measurements of beam ions [22]. The measured flux variation
of about 40 times is similar to the variation between the L-mode and the ELMing H-mode reported for ASDEX-Upgrade [15–17], but it is possible that a tiny variation in flux at the L–H transition is obscured by electronic noise.

A second difference between the experiments is the magnitude of the field ripple. ASDEX-Upgrade has 16 coils, DIII-D has 24. The resulting ripple-trapping region penetrates about half as far into the plasma. This certainly reduces the sensitivity to changes in confinement associated with $E_r$ (simulations predict an order of magnitude reduction in sensitivity [33]), but it is hard to understand how reduced ripple can eliminate confined edge beam ions altogether.

Another possibility is that the neutral-density profiles are different. The midplane neutral density is highly sensitive to many factors including divertor behaviour, baffling, plasma profiles, and wall conditioning. Perhaps the neutral density in DIII-D is an order of magnitude smaller, dropping the feeble neutral flux in the ELM-free H-mode to below the analyser noise level. Also, even if the neutral-density profiles were identical, the DIII-D diagnostic would be less sensitive to ripple-trapping effects because the neutral density must decay within the ripple-loss region for optimal sensitivity [33].

Irrespective of the explanation for the difference between DIII-D and ASDEX-Upgrade, it is clear that the ASDEX-Upgrade signals are also affected by the competition between pitch-angle scattering and deceleration. Evidence of some effects are available in the published literature. For example, in figure 12 of [17], the 10 keV neutral flux increases a factor of four after the radial electric field exceeds the simple criterion (equation (1)). Similarly, the larger L-mode signal in discharges with counter injection [16] may be associated with higher $Z_{\text{eff}}$ and stronger pitch-angle scattering.

Because of the sensitivity to pitch-angle scattering, interpreting edge neutral-particle measurements as an $E_r$ diagnostic is problematic. Simulations indicate that injection of an approximately 20 keV, perpendicular diagnostic neutral beam that directly populates the ripple-trapped portion of phase space gives enhanced sensitivity to rapid changes in $E_r$ [33].

5. Conclusion

Analysis of the radial neutral flux from DIII-D shows that the competition between pitch-angle scattering and deceleration is the most important factor in determining the magnitude and time evolution of the signal. No distinct effects associated with the radial electric field are observed.

The geometry of the ASDEX-Upgrade measurements are similar to those of the DIII-D measurements. One factor that affects the time evolution of the signal is the development of the $E_r$ well that converts ripple-trapped ions from loss orbits to confined orbits. Another, equally important, factor is the rate at which beam ions scatter into the perpendicular analyser line of sight (which is governed primarily by the electron temperature). Yet another factor is the neutral density, which steepens in profile as the pressure pedestal develops. At the L–H transition, the $E_r$ well, the edge $T_e$, and the neutral density profile all rapidly evolve. In light of the complex factors affecting the neutral flux, a gradual increase in signal need not imply the gradual formation of the $E_r$ well, as was previously argued [15]. Direct measurements of $E_r$ are more credible.

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References

[1] Wagner F et al 1982 Phys. Rev. Lett. 49 1408
[2] Burrell K H 1997 Phys. Plasmas 4 1499
[3] Groebner R, Burrell K H and Seraydarian R P 1990 Phys. Rev. Lett. 64 3015
[4] Kim J et al 1994 Phys. Rev. Lett. 72 2199
[5] Rice B W, Burrell K H, Lao L L and Lin-Liu Y R 1997 Phys. Rev. Lett. 79 2694
[6] Rice B W, Nilson D G, Burrell K H and Lao L L 1999 Rev. Sci. Instrum. 70 815
[7] Ida K et al 1999 Nucl. Fusion 39 1649
[8] Tynan G R et al 1994 Phys. Plasmas 1 3301
[9] Moyer R A et al 1995 Phys. Plasmas 2 2397
[10] Burrell K H 1996 Plasma Phys. Control. Fusion 38 1313
[11] Burrell K H 2001 Rev. Sci. Instrum. 72 906
[12] Burrell K H 1999 Phys. Plasmas 6 4418
[13] Hugill J 2000 Plasma Phys. Control. Fusion 42 R75
[14] Beiersdorfer P, Kaita R and Goldston R J 1984 Nucl. Fusion 24 487
[15] Herrmann W and Asdex Upgrade Team 1995 Phys. Rev. Lett. 75 4401
[16] Herrmann W, Heikkinen J A, Kurki-Suonio T and the ASDEX Upgrade Team 1998 Plasma Phys. Control. Fusion 40 683
[17] Herrmann W and the ASDEX Upgrade Team 1998 Rev. Sci. Instrum. 69 3165
[18] Heikkinen J A, Herrmann W and Kurki-Suonio T 1997 Phys. Plasmas 4 3655
[19] Heikkinen J A, Herrmann W and Kurki-Suonio T K 1998 Nucl. Fusion 38 419
[20] Heikkinen J A, Kurki-Suonio T and Herrmann W 1998 Plasma Phys. Control. Fusion 40 679
[21] Heikkinen J A and Kurki-Suonio T 1998 Phys. Plasmas 5 692
[22] Carolipio E M and Heidbrink W W 1997 Rev. Sci. Instrum. 68 304
[23] Luxon J L and Davis L G 1985 Fusion Technol. 8 441
[24] Gohil P, Burrell K H, Groebner R J and Seraydarian R P 1990 Rev. Sci. Instrum. 61 2949
[25] Lao L L, St John H, Stambaugh R D, Kellman A G and Pfeiffer W P 1985 Nucl. Fusion 25 1611
[26] Rice B W, Burrell K H, Lao L L and Nilson D G 1999 Rev. Sci. Instrum. 70 815
[27] Carlstrom T N et al 1992 Rev. Sci. Instrum. 63 4901
[28] Carlstrom T N, Ahlgren D R and Crobbie J 1998 Rev. Sci. Instrum. 59 1063
[29] Wang Z et al 1995 Proc. 9th Workshop on Electron Cyclotron Emission and Electron Cyclotron Heating (Borrego Springs, CA) p 427
[30] Groebner R J and Osborne T H 1998 Phys. Plasmas 5 1800
[31] Beiersdorfer P, Roquemore A L and Kaita R 1987 Rev. Sci. Instrum. 58 2092
[32] Putvinskij S V, Tubbing B J D, Eriksson L-G and Konovalov S V 1994 Nucl. Fusion 34 495
[33] Kurki-Suonio T, Sipila S K and Heikkinen J A 2000 Plasma Phys. Control. Fusion 42 A277
[34] Colchin R J et al 2000 Nucl. Fusion 40 175
[35] Heidbrink W W, Taylor P L and Phillips J A 1997 Rev. Sci. Instrum. 68 536
[36] Heidbrink W W et al 1999 Phys. Plasmas 6 1147
[37] Stix T H 1972 Plasma Phys. 14 367
[38] Book D L 1990 NRL Plasma Formulary (Washington, DC: Naval Research Laboratory)
[39] Heidbrink W W and Sadler G J 1994 Nucl. Fusion 34 535