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2013 Nucl. Fusion 53 063011

(http://iopscience.iop.org/0029-5515/53/6/063011)

IOP Publishing and International Atomic Energy Agency Nuclear Fusion

Nucl. Fusion **53** (2013) 063011 (9pp) doi:10.1088/0029-5515/53/6/063011

Effect of ion orbit loss on distribution of particle, energy and momentum sources into the tokamak scrape-off layer

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Received 13 July 2012, accepted for publication 18 April 2013
Published 8 May 2013
Online at stacks.iop.org/NF/53/063011

Abstract

The effect of ion orbit loss on the poloidal distribution of ions, energy and momentum from the plasma edge into the tokamak scrape-off layer (SOL) is analysed for a representative DIII-D (Luxon 2002 *Nucl. Fusion* **42** 614) high-mode discharge. Ion orbit loss is found to produce a significant concentration of the fluxes of particle, energy and momentum into the outboard SOL. An intrinsic co-current rotation in the edge pedestal due to the preferential loss of counter-current ions is also found.

(Some figures may appear in colour only in the online journal)

1. Introduction

The excursion of ions on drift orbits that cross the last closed flux surface (or separatrix) have long been thought to be an important loss mechanism in the edge region of tokamaks that affects energy and particle confinement, poloidal and toroidal rotation, the interpretation of conductive and diffusive transport coefficients, and other observed phenomena within the confined plasma (e.g. [1–11]. Ion orbit losses should also affect the distribution of particle, energy and momentum sources into the scrape-off layer (SOL), hence the physics properties (flows, temperature and density distributions, etc) in the SOL and divertor. The purpose of this paper is to report an examination of the effect of ion orbit loss on the poloidal distribution of ions, ion energy and ion parallel momentum into the SOL from the confined plasma, for a representative DIII-D [12] H-mode plasma.

The paper is organized as follows. The basic ion orbit calculation of the minimum energy that an ion located on an internal flux surface, with a given direction cosine relative to the magnetic field, must have in order to execute a drift orbit that crosses the separatrix is described in section 2. Performing this calculation for flux surfaces near the edge leads to the definition of a cumulative (with radius) loss cone within the thermal plasma ion distribution at each flux surface, which increases with radius. This loss cone is used to construct cumulative ion particle, energy and parallel momentum loss fractions in section 3. For this purpose, ions are assumed to be lost, either by intersection of the orbit with a material wall or by interaction of the escaping ion with neutrals or plasma in the SOL, once they cross the separatrix. A separate calculation is made in section 4 to treat the ion orbit loss of ions that grad-B and curvature drift downward and radially outward in the low-B_θ region near the X-point. The effects of these ion-orbit-loss phenomena and of the compensating return currents on the poloidal distribution of ion and ion energy sources and the parallel momentum source into the SOL are discussed in section 5. The intrinsic co-current rotation in the edge plasma inside the separatrix resulting from the preferential ion orbit loss of counter-current ions is also calculated in section 6.

2. Basic ion orbit calculation

The basic ion orbit calculation is of the minimum energy an ion located at a particular poloidal position (ψ_0, θ_0) on an internal flux surface ψ_0 with a direction cosine ζ_0 relative to the toroidal magnetic field direction must have in order to be able to execute an orbit that will cross the separatrix at location $(\psi_{sep}, \theta_{sep})$ Following Miyamoto [2] and others, we make use of the conservation of canonical toroidal angular momentum

$$RmV_\| f_\varphi + e\psi = \text{const} = R_0 m V_{\|0} f_{\varphi 0} + e\psi_0 \qquad (1)$$

to write the orbit constraint for an ion introduced at a location (ψ_0, θ_0) with parallel velocity $V_{\|0}$, where $f_\varphi = |B_\varphi/B|$, R is the major radius and ψ is the flux surface value. The conservation of energy and of magnetic moment

$$\frac{1}{2}m(V_\|^2 + V_\perp^2) + e\phi = \text{const} = \frac{1}{2}m(V_{\|0}^2 + V_{\perp 0}^2) + e\phi_0 \equiv \frac{1}{2}mV_0^2 + e\phi_0, \quad \frac{mV_\perp^2}{2B} = \text{const} = \frac{mV_{\perp 0}^2}{2B_0} \qquad (2)$$

further require that

$$V_\parallel = \pm V_0 \left[1 - \left|\frac{B}{B_0}\right|(1-\zeta_0^2) + \frac{2e}{mV_0^2}(\phi_0 - \phi)\right]^{1/2}, \quad (3)$$

where ϕ is the electrostatic potential. The quantity $\zeta_0 = V_{\parallel 0}/V_0$ is the cosine of the initial guiding centre velocity relative to the toroidal magnetic field direction. Using equation (3) in equation (1) and squaring leads to a quadratic equation in the initial ion speed $V_0 = \sqrt{V_{\parallel 0}^2 + V_{\perp 0}^2}$.

$$V_0^2\left[\left(\frac{R_0}{R}\frac{f_{\varphi 0}}{f_\varphi}\zeta_0\right)^2 - 1 + (1-\zeta_0^2)\left|\frac{B}{B_0}\right|\right] + V_0\left[\frac{2e(\psi_0-\psi)}{Rmf_\varphi}\left(\frac{R_0}{R}\frac{f_{\varphi 0}}{f_\varphi}\zeta_0\right)\right] + \left[\left(\frac{e(\psi_0-\psi)}{Rmf_\varphi}\right)^2 - \frac{2e(\phi_0-\phi)}{m}\right] = 0. \quad (4a)$$

Equation (4a) is quite general with respect to the flux surface geometry representation of R, B and the flux surfaces ψ. We note, but do not take into account, that the loss orbits defined by these equations are caused by curvature and grad-B drift effects which might be modified by radial electrostatic drifts of similar magnitude caused by turbulence.

By specifying an initial '0' location for an ion with initial direction cosine with respect to B_ϕ, denoted ζ_0, and specifying a final location on flux surface ψ, equation (4a) can be solved to determine the minimum initial ion speed V_0 for which a solution can be obtained, which is the minimum initial speed that is required in order for the ion orbit to reach the final location (that the solution of equation (4a) defines the minimum speed is discussed in [10].

Thus, equation (4a) can be solved for the minimum ion energy necessary for an ion located on an internal flux surface, with a given ζ_0, to cross the last closed flux surface ψ_{sep} at a given poloidal location $\theta_{sep}(\psi_{wall}, \theta_{wall})$. Assuming that all ions which cross the last closed flux surface have an interaction with ions or recycling neutrals in the SOL or intersect a material surface, all ions with a given ζ_0 and energies greater than this minimum energy can be considered as lost. We note that there is another class of ions with orbits that execute similar excursions from the flux surface that do not reach the last closed flux surface, the separate transport effects of which are treated by neoclassical theory; only those ions whose orbits cross the last closed flux surface are included in the ion-orbit-loss theory of this paper.

At this point, in order to simplify the following computation, we introduce the approximation that RB is constant within the plasma, which is strictly valid only when the poloidal field is small compared to the toroidal field and the latter is well approximated by the vacuum field. This allows equation (4a) to be written

$$V_0^2\left[\left(\left|\frac{B}{B_0}\right|\frac{f_{\varphi 0}}{f_\varphi}\zeta_0\right)^2 - 1 + (1-\zeta_0^2)\left|\frac{B}{B_0}\right|\right] + V_0\left[\frac{2e(\psi_0-\psi)}{Rmf_\varphi}\left(\left|\frac{B}{B_0}\right|\frac{f_{\varphi 0}}{f_\varphi}\zeta_0\right)\right] + \left[\left(\frac{e(\psi_0-\psi)}{Rmf_\varphi}\right)^2 - \frac{2e(\phi_0-\phi)}{m}\right] = 0. \quad (4b)$$

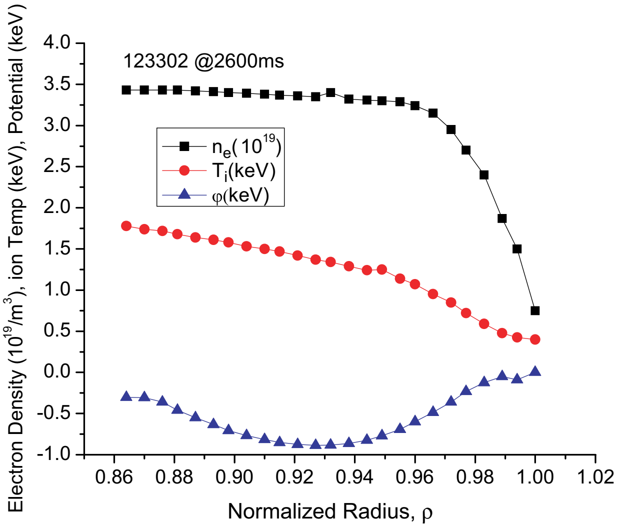

Figure 1. Electron density, ion temperature and electrostatic potential in the edge of DIII-D H-mode shot 123302.

Using an approximate representation of the magnetic flux surface geometry described by

$$[R(r,\theta) = \overline{R}h(r,\theta),\ B_{\theta,\varphi}(r,\theta) = \overline{B}_{\theta,\varphi}/h(r,\theta),\ h(r,\theta) = (1 + (r/\overline{R})\cos\theta)] \quad (5)$$

and making a uniform current density approximation in Ampere's law, $B_\theta = \nabla \times A_\varphi$ can be used to write the flux surface corresponding to a given effective circular normalized radius ρ as

$$\psi(\rho) = RA_\varphi = \frac{1}{2}\left(\frac{\mu_0 I}{2\pi a^2}\right)\overline{R}\overline{a}^2\rho^2, \quad (6)$$

where I is the plasma current and $\overline{a} = a_{minor}\sqrt{0.5(1+\kappa^2)}$ is the minor radius of the effective circular plasma model for a plasma with horizontal minor radius 'a' and elongation κ. These approximations are strictly valid only when the inverse aspect ratio is much smaller than unity.

We solve equation (4b) for the parameters of a DIII-D H-mode plasma discharge #123302: ($\overline{R} = 1.75$ m, $\overline{a} = 0.885$ m, $\kappa = 1.836$, $I = 1.50$ MA, $B_\varphi = -1.98$ T, $q_{95} = 3.86$, $P_{nb} = 8.66$ MW, $n_C/n_D = 0.03$), with the plasma current flowing in the counter-clockwise direction looking down on the tokamak and the toroidal magnetic field in the opposite clockwise direction. The curvature and grad-B drifts are vertically downward in this plasma towards a lower divertor. In this plasma, the potential difference between some internal flux surface and the outermost last closed flux surface was obtained from measurements of the local radial electric field by integrating to obtain the electrostatic potential. Some experimental data used in this calculation are shown in figure 1.

3. Ion-orbit-loss escape fractions

The minimum energy for which the orbits of ions launched from various locations on the $\rho \equiv \overline{r}/\overline{a} = 0.983$ flux surface will cross the separatrix at some location ($\rho = 1, 0 \leqslant \theta_{sep} \leqslant 2\pi$) are plotted in figure 2. All ions with a given ζ_0 and energy greater than the minimum energy shown in figure 2 would be

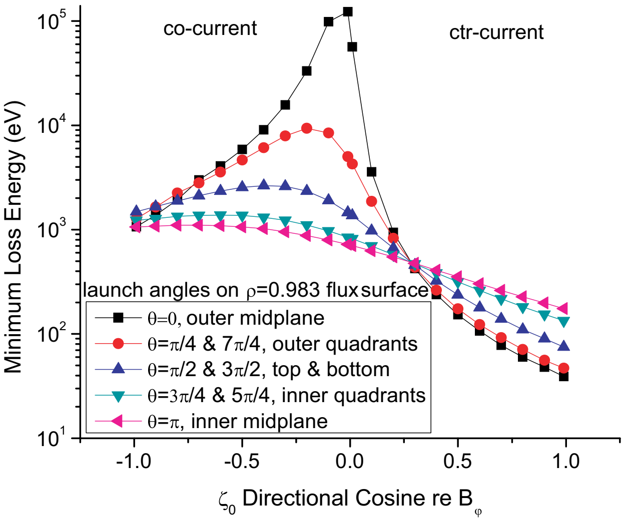

Figure 2. The minimum energy for which the orbits of ions launched from various locations on the $\rho = 0.983$ flux surface will cross the separatrix.

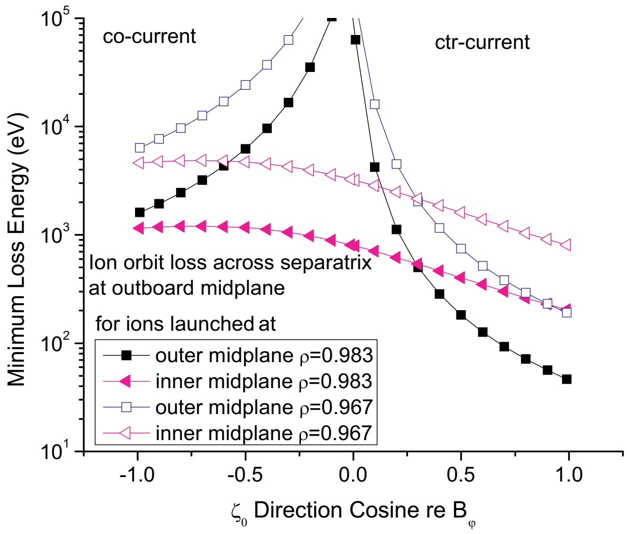

Figure 3. Minimum energies for loss across separatrix at outer midplane for ions launched at two different internal flux surfaces.

lost. Since $T_{\text{ion}} = 425\,\text{eV}$ on this flux surface, a substantial number of ions have energies greater than this minimum energy and would be lost. Clearly, the counter-current ions ($\zeta_0 > 0$) are preferentially lost from all locations on the $\rho = 0.983$ flux surface. The lowest minimum loss energy for ions with direction cosine $\zeta_0 > 0.2$ occurs for ions launched near the outer miplane, but for ions with direction cosine $\zeta_0 < 0.2$ the lowest minimum loss energy occurs for ions launched near the inner miplane

At any location on the $\rho = 0.983$ flux surface, all ions with direction cosine ζ_0 and energies greater than the minimum loss energy shown in figure 2 will have been lost by ion orbit loss; i.e. the ion distribution function for ions with direction cosine ζ_0 will be empty above the indicated minimum loss energy.

The minimum energy required for ion orbit loss across the separatrix at any point, from any internal launch point, decreases monotonically with increasing radius of the launch point, as illustrated in figure 3.

The above considerations lead to the following picture of how the upper limit of the energy distribution function of the outward flowing particle flux changes as a function of radius due to ion orbit loss in the plasma edge. Out to a certain radius $\rho_{\min}$ the minimum loss energy $E_{\min}(\rho, \zeta_0)$ is so large that a negligible number of ions are lost for any direction cosine ζ_0 for $\rho < \rho_{\min}$. In the radial interval $\rho_{\min} \leqslant \rho < \rho_{\min} + \Delta\rho_1$ all those ions with direction cosine ζ_0 in the energy interval $E_{\min}(\rho_{\min}, \zeta_0) \geqslant E \geqslant E_{\min}(\rho_{\min} + \Delta\rho_1, \zeta_0)$ are lost; in the radial interval $\rho_{\min} + \Delta\rho_1 \leqslant \rho < \rho_{\min} + \Delta\rho_1 + \Delta\rho_2$ all those ions with direction cosine ζ_0 in the energy interval $E_{\min}(\rho_{\min} + \Delta\rho_1, \zeta_0) \geqslant E \geqslant E_{\min}(\rho_{\min} + \Delta\rho_1 + \Delta\rho_2, \zeta_0)$ are lost; etc out to $\rho = 1.0$. If pitch-angle scattering of ions from direction cosine ζ_0' to direction cosine ζ_0 can be neglected, then the upper limit of the energy distribution ($E_{\text{up}} = E_{\min}(\rho, \zeta_0)$) of the outward flowing particle flux is continuously reduced with increasing radius. (It should be possible to approximately account for the effect of scattering of ions from direction cosine ζ_0' to direction cosine ζ_0 on the upper energy limit of the distribution of ions with direction cosine ζ_0, short of solving for the distribution function, but that is a subject for a future paper.)

Thus, we have the picture of an energy distribution function for the outward flowing flux of ions with direction cosine ζ_0 which has an upper limit that is continuously decreasing with radius because of ion orbit loss. The energy distribution between this upper limit and zero also changes with radius due to various sources and sinks of energy. For computational purposes, we approximate the energy distribution of ions with direction cosine ζ_0 at a given radius ρ as a Maxwellian at the local ion temperature $T_{\text{ion}}(\rho)$ but 'chopped off' above energy $E_{\min}(\rho, \zeta_0)$. This representation allows cumulative (with increasing radius) particle, momentum and energy loss fractions to be defined

$$F_{\text{orb}}(\rho) \equiv \frac{N_{\text{loss}}}{N_{\text{tot}}} = \frac{\int_{-1}^{1}\left[\int_{V_{0\min}(\zeta_0)}^{\infty} V_0^2 f(V_0)\,\mathrm{d}V_0\right]\mathrm{d}\zeta_0}{2\int_0^{\infty} V_0^2 f(V_0)\,\mathrm{d}V_0} = \frac{\int_{-1}^{1}\Gamma(3/2, \varepsilon_{\min}(\rho, \zeta_0))\,\mathrm{d}\zeta_0}{2\Gamma(3/2)}, \tag{7}$$

$$M_{\text{orb}}(\rho) \equiv \frac{M_{\text{loss}}}{M_{\text{tot}}} = \frac{\int_{-1}^{1}\left[\int_{V_{0\min}(\zeta_0)}^{\infty} (mV_0\zeta_0) V_0^2 f(V_0)\,\mathrm{d}V_0\right]\mathrm{d}\zeta_0}{2\int_0^{\infty} (mV_0) V_0^2 f(V_0)\,\mathrm{d}V_0} = \frac{\int_{-1}^{1}\zeta_0\Gamma(2, \varepsilon_{\min}(\rho, \zeta_0))\,\mathrm{d}\zeta_0}{2\Gamma\,(2)} \tag{8}$$

and

$$E_{\text{orb}}(\rho) \equiv \frac{E_{\text{loss}}}{E_{\text{total}}} = \frac{\int_{-1}^{1}\left[\int_{V_{0\min}(\zeta_0)}^{\infty} \left(\frac{1}{2}mV_0^2\right) V_0^2 f(V_0)\,\mathrm{d}V_0\right]\mathrm{d}\zeta_0}{\int_{-1}^{1}\left[\int_0^{\infty}\left(\frac{1}{2}mV_0^2\right) V_0^2 f(V_0)\,\mathrm{d}V_0\right]\mathrm{d}\zeta_0} = \frac{\int_{-1}^{1}\Gamma(5/2, \varepsilon_{\min}(\rho, \zeta_0))\,\mathrm{d}\zeta_0}{2\Gamma(5/2)}, \tag{9}$$

where $\varepsilon_{\min}(\rho, \zeta_0) \equiv E_{\min}(\rho, \zeta_0)/kT_{\text{ion}}(\rho) \equiv mV_{0\min}^2(\rho, \zeta_0)/2kT_{\text{ion}}(\rho)$ is the reduced energy corresponding to the minimum velocity for which ion orbit loss is possible. The quantities $\Gamma(n)$ and $\Gamma(n, x)$ are the gamma function and incomplete gamma function, respectively. These cumulative loss fractions at a given radius ρ represent the cumulative ion orbit loss over all radii $0 < \rho' \leqslant \rho$, not the loss fractions from radius ρ.

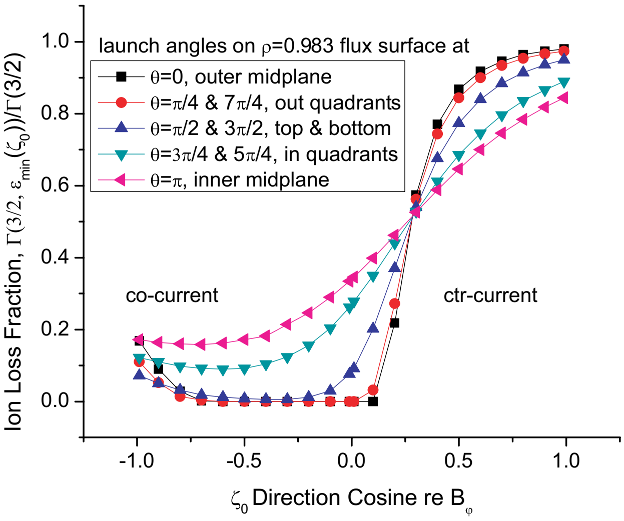

Figure 4. Ion orbit loss fraction of ions launched from various points on the $\rho = 0.983$ flux surface.

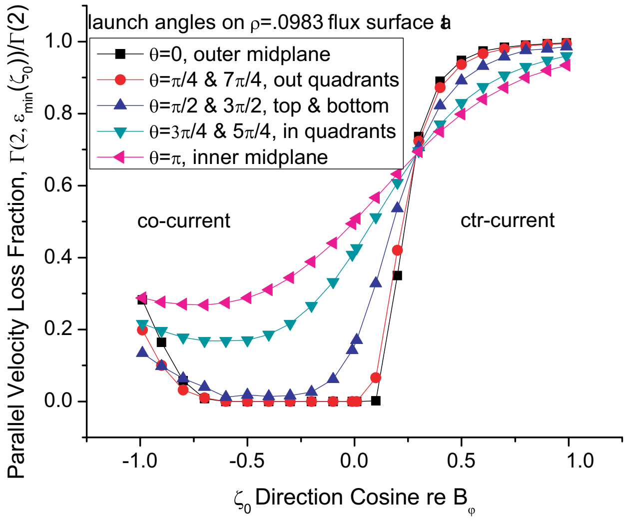

Figure 5. Ion orbit loss fraction of parallel velocity launched from various points on the $\rho = 0.983$ flux surface.

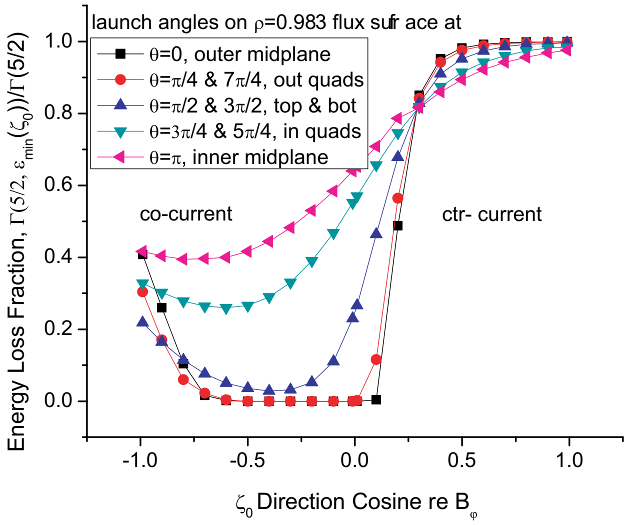

Figure 6. Ion orbit energy loss fraction of ions launched from various points on the $\rho = 0.983$ flux surface.

The minimum energy for ion orbit loss was calculated for all launch angles (θ_0) and direction cosines (ζ_0) on 25 internal flux surfaces. The location (θ_D) on the separatrix for which this minimum ion energy for loss was least was calculated to be at the outboard midplane, except for nearly co-current ($\zeta_0 < -0.75$) ions launched near the outboard midplane, for which the least value of the minimum ion energy required for crossing the separatrix was at the inboard midplane. If scattering is neglected and the rapid motion of the ions along field lines within the flux surface is taken into account, then an ion with a given direction (ζ_0) and energy will be transported outward until it reaches a flux surface at which it's energy is less than the minimum energy required for ion orbit loss from some location on the flux surface, at which point it will be lost from the plasma. The cumulative particle, angular momentum and energy loss fractions for ions with a given direction cosine (ζ_0), $\Gamma(3/2, \varepsilon_{\min}(\zeta_0))/\Gamma(3/2)$,$\Gamma(2, \varepsilon_{\min}(\zeta_0))/\Gamma(2)$ and $\Gamma(5/2, \varepsilon_{\min}(\zeta_0))/\Gamma(5/2)$, are plotted as a function of the direction cosine of the particle velocity with respect to the toroidal magnetic field in figures 4–6. For each launch location, these loss fractions correspond to the smallest of the minimum loss energies for crossing the separatrix at any location θ_{sep}—the smallest of the minimum energies plotted in figure 2. Clearly, it is the ions with a parallel velocity component in the toroidal magnetic field direction (which execute orbits outside the flux surface) that are preferentially lost. In the discharge considered, such ions are moving in the counter-current direction.

If we integrate the results shown in figures 4–6 over ζ_0, as indicated in equations (8)–(10), we can construct the cumulative ion orbit loss fractions of ions, parallel momentum and energy out to a given radius, e.g. $\rho = 0.983$, for ions launched from each of the eight different poloidal locations that we have considered, which are shown in figure 7. The ion and ion energy loss fractions are greatest for ions launched from the outboard midplane region, except for flux surfaces just inside the separatrix, for which the cumulative launch fractions are greatest for ions launched from the inboard midplane region.

Repeating the above calculation for other flux surfaces and integrating the loss fractions of figures 3–5 over direction cosine, as indicated in equations (8)–(10), leads to cumulative (with radius) loss fractions for ions, net parallel ion momentum and ion energy, for ions launched from each of the eight poloidal locations on the flux surface discussed above. If it is assumed that ions initiate loss orbits with equal likelihood from each location on the flux surface and that the ions are uniformly distributed over the flux surface, then it would be appropriate to average over these eight loss fractions to obtain *average* ion-orbit-loss fractions. On the other hand, if the rapid spiral motion of the ions over the flux surface is taken into account, the lowest loss energy for a ion launched anywhere on the flux surface would be used for calculating the ion orbit loss of all ions on a given flux surface, which leads to *maximum* loss fractions. The respective *average* and *maximum* loss fractions are plotted in figure 8.

There are a number of interesting implications of figure 8. The escape of significant numbers of higher energy (greater than the minimum loss energy) thermalized ions from internal flux surfaces across the separatrix into the SOL implies the

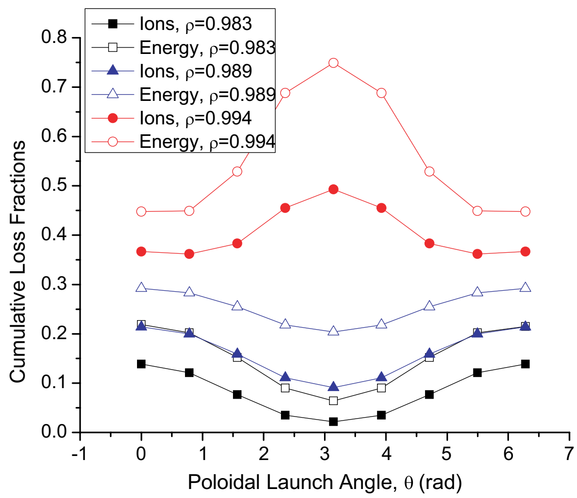

Figure 7. Ion-orbit-loss fractions for particles, parallel momentum and energy launched from the $\rho = 0.983$ flux surface at eight poloidal locations.

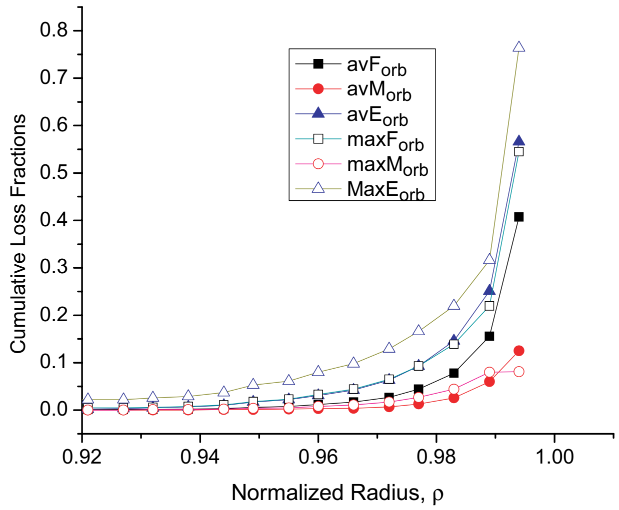

Figure 8. Cumulative ion orbit loss fractions for ions, net parallel ion velocity and ion energy.

presence of such higher energy ions in the SOL, as is commonly observed in the experimental data. The large fractions of the particle ($\Gamma_{\rm ion} F_{\rm orb}$) and energy ($Q_{\rm ion} E_{\rm orb}$) fluxes passing through the edge plasma across the separatrix on loss orbits also indicates that the distribution of particle and energy sources from the core plasma into the SOL is determined as much by ion orbit loss, which will concentrate particle and energy sources near the outboard midplane, as by conduction and convection of particles ($\Gamma_{\rm ion}(1 - F_{\rm orb})$) and energy ($Q_{\rm ion}(1 - E_{\rm orb})$), which also preferentially distributes particles and energy to the outboard SOL, but not so strongly.

Noting that $M_{\rm orb}$ is the net average over negative ($\zeta_0 < 0$) and positive ($\zeta_0 > 0$) directed velocities, the positive value of $M_{\rm orb}$ indicates a net loss of counter-current flowing ions (in this model with the typical DIII-D opposite magnetic field and current configuration—clockwise magnetic field and counter-clockwise current, looking down from above the tokamak). This preferential loss of counter-current ions produces an edge plasma with a preponderance of co-current ions; i.e. an intrinsic co-rotation, as has been observed experimentally for H-mode plasmas [9, 11]. It also provides an intrinsic counter-current rotation source to the SOL.

4. X-loss escape fractions

The treatment of the previous section did not take into account the presence of the X-point in the calculation of ion orbit loss [13], which is summarized briefly in this section. Whereas ions quite rapidly move poloidally over the majority of the flux surface by following along spiralling field lines, there is a region about the X-point in which the poloidal field is very small, $B_\theta \ll \varepsilon B_\phi$, where the field lines are almost purely toroidal and do not spiral about the tokamak to provide the usual neoclassical cancellation of drift effects. As the ions approach the X-point their poloidal motion is provided only by the slower poloidal $E_r \times B_\phi$ drift due to the radial electric field. If the poloidal spiral about the field lines in the plasma is in the same direction as the $E_r \times B_\phi$ drift into this 'x-region', ions will move poloidally into and across the null-B_θ region near the X-point until they enter a plasma region in which $B_\theta \approx \varepsilon B_\phi$ once again, in which they can rapidly move poloidally over the flux surface by following the spiralling motion of the field lines.

However, while the ions are slowly drifting poloidally across the almost null-B_θ X-region near the X-point, they are also drifting vertically due to curvature and grad-B drifts. In the lower single-null divertor configuration considered in this paper, with the toroidal field in the clockwise direction (looking down from above) and the plasma current in the counter-clockwise direction, this vertical drift is downward towards the divertor. If the time required for the ion to grad-B and curvature drift downward across the separatrix is less than the time required for the ion to $E_r \times B_\phi$ drift across the $B_\theta \ll \varepsilon B_\phi$ x-region near the X-point, the ion will be lost across the separatrix, a form of ion orbit loss due to the presence of a divertor X-point.

The time required for an ion entering the X-region at radius r to grad-B and curvature drift downward a distance Δr is

$$\tau_{\nabla B} = \frac{\Delta r}{V_{\nabla B,c}} = \frac{\Delta r}{(W_\perp + 2W_\parallel)/eRB} = \frac{eRB}{W(1+\zeta^2)}\Delta r, \qquad (10)$$

where ζ is the cosine of ion direction with respect to the magnetic field and W denotes the ion energy. During this time the ion is also $E_r \times B_\varphi$ drifting through a poloidal arc distance

$$r\Delta\theta = V_{E\times B}\tau_{\nabla B} = \frac{E_r(r)}{B_\phi}\frac{eRB}{W(1+\zeta^2)}\Delta r. \qquad (11)$$

These expressions were used to numerically calculate the minimum energy, $W_{\min}(\bar{r}', \bar{r}_{\rm sep})$ for which an ion entering the x-region at $\bar{r}'$ must have in order to escape across the separatrix, with the x-region represented as a vertical wedge of angular width $\Delta\theta = 0.15$ rad, as discussed in [13]. The minimum energy so calculated was comparable to and usually greater than the minimum loss energy for 'normal' ion orbit loss calculated in the previous section, from which we conclude that the lost cone for X-loss would be empty due to ion orbit loss at smaller radii flux surfaces. We note that this may not always be the case and that X-loss could potentially affect the distribution of ions crossing the separatrix into the SOL in some plasmas by concentrating ions, ion energy and momentum in the vicinity of the X-point [8].

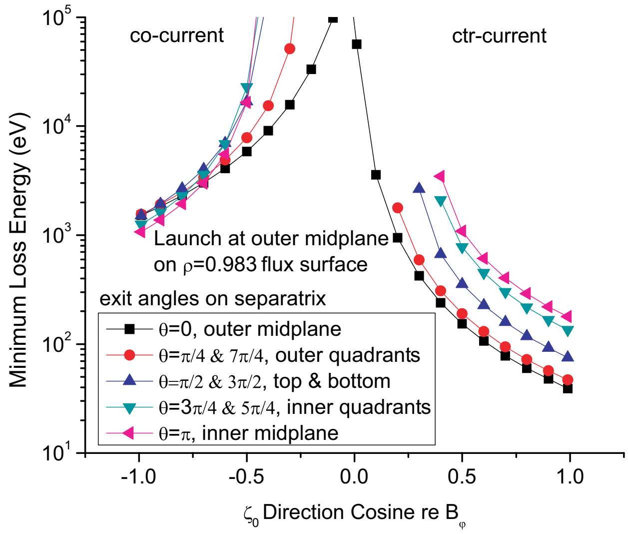

Figure 9. Minimum loss energies for particles launched at the outer midplane to escape across the separatrix at various locations.

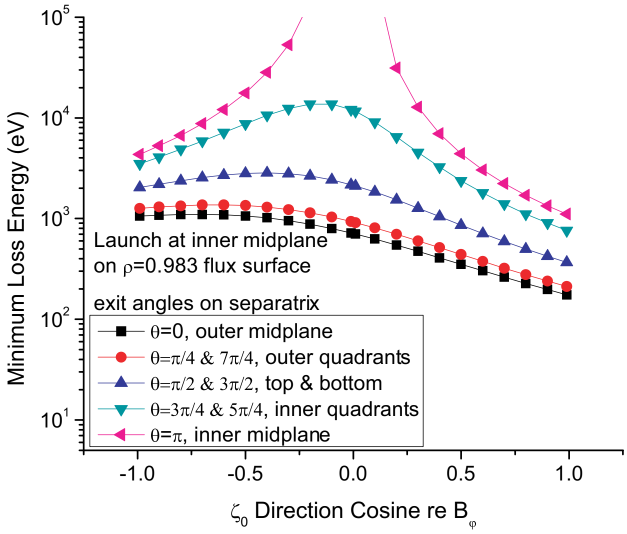

Figure 11. Minimum loss energies for particles launched at the inner midplane to escape across the separatrix at various locations.

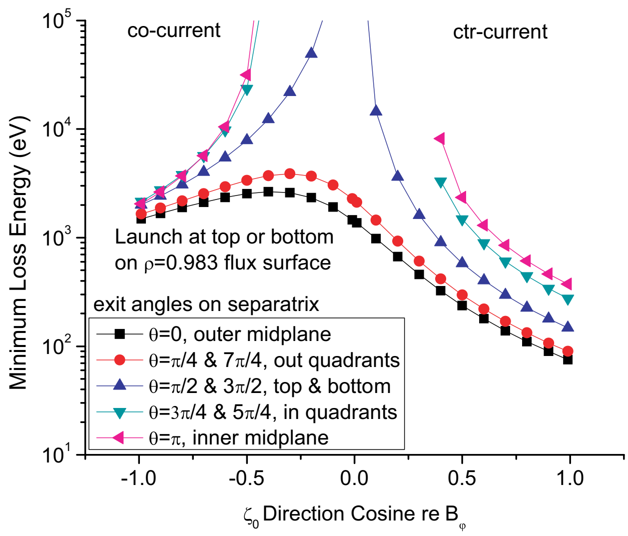

Figure 10. Minimum loss energies for particles launched at the top or bottom to escape across the separatrix at various locations.

5. Distribution of ion-orbit-loss particles and energy over the SOL

One of the purposes of this paper is to examine where in the SOL the ions lost from internal flux surfaces are deposited. Figures 9–11 show the minimum loss energies for ions to be deposited in each of the eight octants of the SOL, for ions launched from the outer midplane, from the top or bottom, and from the inner midplane, respectively. For the ions launched from near the outer midplane, counter-current ions with $\zeta_0 > -0.7$ have the lowest minimum energy requirements for exiting across the separatrix near the outer midplane, and ions with $\zeta_0 < -0.7$ have the lowest minimum energy requirements for exiting across the separatrix at the inboard midplane, as may be seen from figure 9. Ions launched from the top or bottom or inner half of the plasma require the lowest minimum energies to escape across the separatrix on the outboard midplane of the plasma, as shown in figures 10 and 11.

These results suggest that a preponderance of ions and energy loss into the separatrix by ion orbit loss is distributed into the outboard SOL near the midplane.

Considering that the speeds of ions moving along the field lines within the flux surface ($\sim 10^5\,\mathrm{m\,s^{-1}}$) are much greater than the speed of 'radial' motion across flux surfaces (1–$10\,\mathrm{m\,s^{-1}}$ in the plasma edge), ions with a given direction cosine ζ_0 and speed V_0 will quickly traverse all locations θ_0 on the flux surface before they are transported radially across the flux surface. At the first location θ_0 for which $V_0 \geqslant V_0^{\min}(\zeta_0)$ for some location θ_D on the separatrix (or other loss surface), the ion will be lost. At each successively outward flux surface, the minimum energy required for ion orbit loss decreases (at least for the H-mode radial electrostatic potential structure shown in figure 1), for all values of the directions cosine of ion velocity with respect to the toroidal magnetic field, ζ_0 (e.g. as in figure 3). The implication is that the high-energy 'hole' in the ion distribution function increases down to lower energy monotonically with increasing ρ. This lower energy for the 'hole' is different for every location on the flux surface and for every direction cosine ζ_0. Thus, the ion orbit loss over any radial interval $\Delta\rho$ will correspond to those ions in the energy interval $E_{\min}(\rho + \Delta\rho, \zeta_0) - E_{\min}(\rho, \zeta_0)$, and the location at which these ions escape into the SOL corresponds to the smallest value of $E_{\min}(\rho, \zeta_0)$ for escape over any point on the separatrix, which in this calculation is at the outboard midplane. Thus, we would expect ion orbit loss to cause a strong peaking of the particle and energy fluxes into the SOL in the vicinity of the outboard midplane.

There are (at least) three other factors which could enter into an ion orbit loss calculation of the poloidal distribution of fluxes into the SOL—scattering, the inward return current necessary to maintain charge neutrality against the ion orbit loss, and the effect of turbulence on the drift orbits. The deuterium-carbon 90° scattering frequencies for the parameters shown in figure 1 are a few hundred per second, which is comparable to the inverse residence time for ions with radial velocities of about $10\,\mathrm{m\,s^{-1}}$ in the 10 cm edge region where ion orbit loss of thermal ions is important. So scattering could have the effect of changing a particle direction from a value of ζ_0 for which its energy is too small to be lost to a value of ζ_0 for which its energy is above the minimum required for ion orbit loss, i.e. to scatter a particle into a loss cone. Thus, scattering would increase the ion-orbit-loss rates above the values calculated without taking scattering into account.

The loss of ions from the plasma in the ion-orbit-loss process must be compensated by the divergence of a return current in order to maintain charge neutrality. Based on the argument (e.g. 14) that this return current is most probably an inward ion current from the SOL, this return current ion source must exactly balance the ion orbit loss in the particle continuity equation, at least in a flux surface average sense. Thus, the combined effect of the ion-orbit-loss and return current processes would remove inward cooler ions distributed around the SOL to produce the inward return current in the plasma and add energetic ions at the same rate, but near the outboard midplane, by ion orbit loss, resulting in a redistribution of ions and a heat source in the SOL concentrated about the outboard midplane. While the ions lost from the plasma by ion orbit loss do not constitute a current flowing in the plasma, the return current from the SOL is an electric current flowing in the plasma and exerts a $j \times B$ torque on the plasma which affects plasma rotation and the radial electric field in the edge plasma. We believe that using the above experimental radial electric field and rotation velocities to evaluate the ion orbit loss of particle and energy and the intrinsic rotation due to ion orbit loss implicitly takes such compensating effects into account, at least insofar as return current effects on the radial electric and rotation velocities used to evaluate the ion orbit loss are concerned.

Ion orbit loss of ions with directed momentum from an internal flux surface constitutes a transfer of rotation angular momentum into the SOL (concentrated near the outboard midplane), and the inward return current of ions with directed momentum from the SOL into the plasma also constitutes a transfer of rotation angular momentum into the plasma from the SOL.

We further note that there are other factors besides ion orbit loss that affect the poloidal distribution of the particle and energy flux across the separatrix and into the SOL—flux surface expansion/contraction and edge-localized modes (ELMs) being two. The conductive heat and diffusive particle fluxes should be distributed poloidally in the same way as the radial gradients of temperature and density, as determined by the compression and expansion of the separation between flux surfaces, which results in steeper spatial gradients and fluxes on the outboard side of the plasma into the outboard SOL (e.g. 15). ELMing plasmas seem to have a larger fraction of the particles going into the SOL on the outboard side that do non-ELMing discharges [16], which indicates that ELMs may cause fluxes preponderantly into the outboard SOL also.

Most experimental observations are made for H-mode plasmas with ELMs, e.g. [17, 18]. Thus, the above calculations of the poloidal distributions of ions and ion energy into the SOL due to ion orbit loss are consistent with experimental observation, but there are also other mechanisms which can produce a preponderance of the particle and energy fluxes into the outboard SOL.

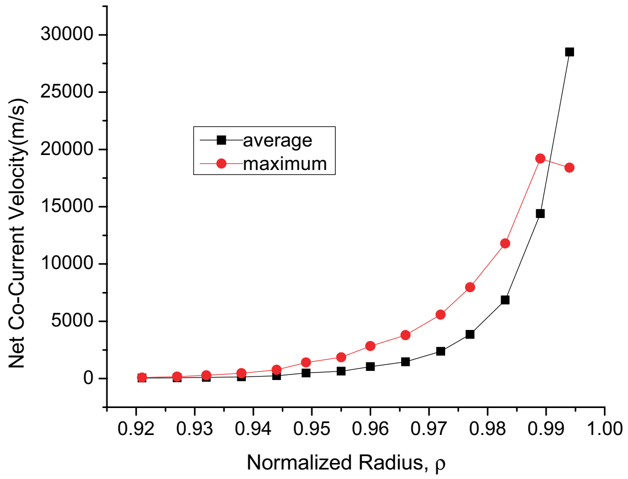

Figure 12. Net co-current parallel fluid velocity in plasma edge produced by preferential ion orbit loss of counter-current ions (average—average of loss fractions for different poloidal launch, maximum—largest loss fraction for any poloidal launch).

6. Distribution of momentum into the SOL and intrinsic rotation in the edge pedestal

The preferential ion orbit loss of ions with positive velocity components along the direction of the toroidal magnetic field (counter-current in the configuration of this paper) produces a counter-current source of parallel momentum into the SOL. This positive (with respect to the direction of toroidal magnetic field) parallel momentum source is deposited into the SOL near the outboard midplane for ions lost from flux surfaces with $\rho < 0.98$, but for flux surfaces with $0.98 < \rho < 0.99$ the deposition in the SOL shifts towards the top and bottom of the plasma. For $\rho > 0.99$, the predominantly co-current lost ions are deposited in the SOL near the outboard midplane as a negative parallel momentum source.

The preferential loss of counter-current ions also causes a residual co-current intrinsic rotation in the edge plasma due to the preferential retention of co-current direction ions [8–11]. The net co-current rotation velocity at any flux surface is determined by the cumulative net counter-current directed ion orbit loss that has taken place inside of that flux surface to determine the loss cone in the plasma ion velocity distribution at that flux surface

$$\begin{aligned}\Delta V_{\parallel}(\rho) &= \int_{-1}^{1} \mathrm{d}\zeta_0 \left[\int_{V_{\min}(\zeta_0)}^{\infty} (V_0\zeta_0) V_0^2 f(V_0)\, \mathrm{d}V_0\right]_\rho \\ &= 2M_{\mathrm{orb}}(\rho)\left[\int_0^{\infty} (V_0) V_0^2 f(V_0)\, \mathrm{d}V_0\right]_\rho \\ &= \frac{\Gamma(2)}{\pi^{3/2}} M_{\mathrm{orb}}(\rho) V_{\mathrm{th}}(\rho) = \frac{2}{\pi^{3/2}} M_{\mathrm{orb}}(\rho)\sqrt{\frac{2kT_{\mathrm{ion}}(\rho)}{m}}.\end{aligned} \tag{12}$$

This ‘intrinsic rotation’ produced by ion orbit loss is plotted in figure 12. The downturn at $\rho > 0.99$ is caused by the preferential loss of co-current ions in this region. This result is generally consistent with results of deGrassie *et al* [9, 11], except for the $\sim T_{\mathrm{ion}}^{1/2}$ scaling implied by equation (12) instead of the $\sim T_{\mathrm{ion}}$ scaling reported in these references. However, M_{orb} also has a positive T_{ion} dependence, so the scaling expected from equation (12) is stronger than $\sim T_{\mathrm{ion}}^{1/2}$.

7. Summary and conclusions

Conservation of energy and angular momentum causes some thermalized ions in the plasma edge to execute drift orbits that cross the separatrix and are lost from the plasma. We have investigated the effect of this ion orbit loss on the distribution of ions, ion energy and ion parallel momentum fluxes into the scrape-off layer from the confined plasma. Our principal finding is that there is a large peaking of the particle and energy fluxes in the vicinity of the outboard midplane as a result of ion orbit loss. We also find that there should be some high-energy ions in the SOL that have escaped from internal flux surfaces and confirm the previous prediction of [9, 13] that ion orbit loss in an H-mode plasma with oppositely directed toroidal field and current produces an intrinsic co-current rotation in the edge plasma that has a stronger dependence on ion temperature than $\sim\sqrt{T_{\rm ion}}$.

We note that the quantitative results presented in this paper are based on parameters for a H-mode discharge in the DIII-D tokamak and would be expected to differ for other radial electric field, ion temperature, magnetic field and size.

Acknowledgments

An email exchange with Tom Petrie on the experimental evidence related to poloidal asymmetries of particle fluxes into the SOL is gratefully acknowledged. This work was supported by the USDoE under Grant No. DE-FG01-ER54538 with the Georgia Tech Research Corporation.

Appendix: physics of ion orbit loss in the plasma edge

The calculation of ion orbit loss of thermalized plasma ions flowing from the core plasma core across the plasma edge into the scrape-off layer is different than the usual calculation of ion orbit loss from a stationary plasma distribution in at least two respects. First, the loss cone increases with radius as the ions flow outward. Second, the lost ions are replenished by a source of ions flowing outward from the core.

Ions on a given magnetic flux surface with a given orientation (specified by the cosine of their direction with respect to the toroidal magnetic field direction, ζ_0) execute drift orbits required by conservation of energy, magnetic moment and canonical angular momentum. In the absence of sufficient collisions, such orbits cross the separatrix or LCFS, if they have sufficiently large energy as calculated from equations (4*a*) and (4*b*). On the interior magnetic flux surfaces this energy is so large that the number of ions in the 'thermalized' ion distribution with this energy or greater is negligible for all direction cosines, and the loss of ions from interior flux surfaces across the separatrix is practically zero.

However, for the exterior flux surfaces in the plasma edge the minimum ion energy determined from equations (4*a*) and (4*b*) for a given direction cosine, $E_{\rm min}(\zeta_0)$, that is sufficient for the ion to cross the separatrix becomes smaller and the number of ions in the 'thermalized' ion distribution with that direction cosine which can be lost becomes significant. If we neglect collisions of these ions that would scatter such ions out of these loss orbit before they cross the separatrix, then we conclude that all ions with direction cosine ζ_0 which have energy $E \geqslant E_{\rm min}(\zeta_0)$ will be lost, leaving the plasma with a distribution of ions which, for each direction cosine ζ_0, is empty above $E = E_{\rm min}(\zeta_0)$. Using such a distribution, the fraction of ions on flux surface ρ with direction cosine ζ_0 that have energy $E \geqslant E_{\rm min}(\zeta_0)$, $f_{\rm orb}(\rho, \zeta_0)$, can be calculated.

If ρ_1 is the innermost flux surface for which ion orbit loss is significant and $\Gamma(\rho_1, \zeta_0)$ is the outward flux of ions with direction cosine ζ_0 being transported in the plasma at flux surface ρ_1, resulting from ion sources at all $\rho < \rho_1$, then an ion orbit loss flux $\Gamma_{\rm iol}(\rho \geqslant \rho_1, \zeta_0) = f_{\rm orb}(\rho_1, \zeta_0)\Gamma(\rho_1, \zeta_0)$ is created which, in the absence of collisions, passes unattenuated through all flux surfaces with $\rho > \rho_1$ and across the separatrix. The outward flux of ions being transported in the plasma is reduced by the number escaping on loss orbits across the separatrix, $\Gamma_{\rm plas}(\rho_1, \zeta_0) = \Gamma(\rho_1, \zeta_0) - \Gamma_{\rm iol}(\rho_1, \zeta_0) = (1 - f_{\rm orb}(\rho_1, \zeta_0))\Gamma(\rho_1, \zeta_0)$.

At the next incrementally outward flux surface $\rho_2 = \rho_1 + \Delta\rho$ there is an ion orbit loss flux of ions escaping of orbits that originated on flux surface ρ_1 and a flux of ions being transported in the plasma, $\Gamma_{\rm plas}(\rho_2, \zeta_0) = \Gamma_{\rm plas}(\rho_1, \zeta_0) + S\Delta\rho$ where S represents any sources or sinks of ions with direction cosine ζ_0 in the interval $\rho_1 < \rho < \rho_2 = \rho_1 + \Delta\rho$. Because of the closer proximity to the separatrix of ρ_2, the minimum energy for ion orbit loss of an ion with direction cosine ζ_0 at ρ_2, as determined by equations (4*a*) and (4*b*), will generally be less than the minimum energy for escape at ρ_1, i.e. $E_{\rm min}(\rho_2, \zeta_0) < E_{\rm min}(\rho_1, \zeta_0)$, in which case the outward ion orbit loss flux for $\rho > \rho_2$ includes not only those ions with energies greater than $E_{\rm min}(\rho_1, \zeta_0)$ on loss orbits originating atρ_1, but also those ions with energies $E_{\rm min}(\rho_2, \zeta_0) < E < E_{\rm min}(\rho_1, \zeta_0)$, or $\Gamma_{\rm iol}(\rho \geqslant \rho_2, \zeta_0) = \Gamma_{\rm iol}(\rho \geqslant \rho_1, \zeta_0) + f_{\rm orb}(\rho_2, \zeta_0)\Gamma_{\rm plas}(\rho_1, \zeta_0)$. Again, the outward flux of ions transported in the plasma is reduced by the number escaping across the separatrix $\Gamma_{\rm plas}(\rho_2, \zeta_0) = \Gamma_{\rm plas}(\rho_1, \zeta_0) - \Gamma_{\rm iol}(\rho_2, \zeta_0) = (1 - f_{\rm orb}(\rho_2, \zeta_0))\Gamma_{\rm plas}(\rho_1, \zeta_0)$.

Repeating this line of argument for each subsequent incrementally outward flux surface ρ_3, ρ_4 etc, leads to the result of ions with energies in the intervals $E_{\rm min}(\rho_3, \zeta_0) < E < E_{\rm min}(\rho_2, \zeta_0)$, $E_{\rm min}(\rho_4, \zeta_0) < E < E_{\rm min}(\rho_3, \zeta_0)$, etc being lost across the separatrix at each subsequent outward flux surface.

Thus, there is an outward flux of ions in the plasma produced by interior ion sources. As this ion flux reaches the edge flux surfaces, the higher energy ions in the distribution can access loss orbits that cross the separatrix. The minimum energy for accessing such loss orbits depends on the direction of the particle velocity relative to the toroidal magnetic field. As the plasma flux flows further outward, the minimum energy for accessing a loss orbit decreases, more ions are able to access loss orbits, the outward flux of ions on loss orbits increases and the outwards flux of ions being transported in the plasma decreases.

The procedure described above for calculating ion orbit loss has been combined with three assumptions made for the sake of computational tractability in the formalism presented in the body of the paper. The first assumption, used in the above discussion, is that scattering can be neglected. The observation that $\nu_{\rm iz}^{*} < 0.02$ throughout the edge region for the discharge examined in this paper supports the assumption that most ions predicted by equations (4*a*) and (4*b*) to escape across the separatrix will do so before being scattered out of the escape drift orbit. The other neglected effect of scattering is the transfer of ions with direction cosines ζ_0 and energy $E < E_{\min}(\zeta_0)$ to another direction cosine ζ_0' for which $E > E_{\min}(\zeta_0')$, i.e. an ion can scatter from a direction for which its energy is too low to access a loss orbit to a direction for which its energy is high enough to access a loss orbit. Taking scattering into account would decrease the ion orbit loss via the first mechanism but would increase it via the second mechanism. Estimating the first effect to be of order 2% because $\nu_{iz}^* < 0.02$ in the shot examined, it is likely that including scattering would increase the calculated ion orbit loss via the second mechanism.

The second assumption made in evaluating the above ion orbit formalism in the body of the paper is that the distribution function of the outward flowing ions is isotropic in direction and Maxwellian in energy inside of the minimum radius at which ion orbit loss is significant, and the third assumption is that ions which escape across the separatrix are lost and do not return to the plasma. The anisotropy assumption allows integrals over direction to be evaluated readily, and the Maxwellian assumption allows integrals over energy to be evaluated readily. Both assumptions could easily be removed if the direction and energy dependences of the ion distribution function were known.

We plan to investigate corrections to the formalism to relax these three assumptions in future work.

References

[1] Hinton F.L. and Chu M. 1985 *Nucl. Fusion* **25** 345
[2] Miyamoto K. 1996 *Nucl. Fusion* **36** 927
[3] Shaing K.C. and Crume E.C. 1989 *Phys. Rev. Lett.* **63** 2369
[4] Shaing K.C., Crume E.C. and Houlberg W.A. 1990 *Phys. Fluids* B **2** 1492
[5] Shaing K.C. 1992 *Phys. Fluid* B **4** 171
[6] Shaing K.C. 2002 *Phys. Plasmas* **9** 1
[7] Matthews G.F., Corrigan G., Erents S.K., Fundamenski W., Kallenbach A., Kurki-Suonio T., Sipila S. and Spence J. 2002 *JET Report* EFDA-JET-CP(02)01-02
[8] Chang C.S. *et al* 2002 *Phys. Plasmas* **9** 3884
[9] deGrassie J.S., Groebner R.J., Burrell K.H. and Solomon W.M. 2009 *Nucl. Fusion* **49** 085020
[10] Stacey W.M. 2011 *Phys. Plasmas* **18** 102504
[11] deGrassie J.S., Muller S.H. and Bodeo J.A. 2012 *Nucl. Fusion* **52** 013010
[12] Luxon J. 2002 *Nucl. Fusion* **42** 614
[13] Stacey W.M. 2011 *Phys. Plasmas* **18** 122504
[14] McClemente K.G. and Thyagaraja A. 2006 *Phys. Plasmas* **13** 042503
[15] Callen J.D. *et al* 2010 *Nucl. Fusion* **50** 064004
[16] Petrie T.W., Watkins J.G., Lao L.L. and Snyder P.B. 2003 *Nucl. Fusion* **43** 910
[17] Petrie T.W. *et al* 2003 *J. Nucl. Mater.* **313–316** 834
[18] Petrie T.W. *et al* 2005 *J. Nucl. Mater.* **337–339** 216