Minority Ion Cyclotron Current Drive in Tokamaks

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Current profile control by minority ion cyclotron current drive is a method to stabilize sawtooth instabilities in future tokamak reactor experiments. Ion cyclotron current drive has previously been treated as a diffusion in velocity space only. In a toroidal plasma, the waves induce diffusion in real space as well as in velocity space. In combination with the finite deviation of the drift orbits from a magnetic flux surface, this gives rise to new current drive mechanisms. These mechanisms are found to be the dominating ones for minority ion current drive with high power and at high temperature.

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The confinement of a plasma in a tokamak relies on the generation of a toroidal plasma current. To sustain a steady state Wort proposed to drive the plasma current with radio frequency (RF) waves [1]. Later Fisch proposed a method to drive a current by heating either minority ions with a toroidally directed wave spectrum at a frequency equal to the ion cyclotron frequency or majority ions at harmonics of the cyclotron frequency [2]. This method has turned out to be useful for plasma current profile modifications in order to stabilize sawteeth. Experimental verification of the theory is difficult, since it produces only a small variation of the plasma current profile. However, at Joint European Torus (JET) the minority ion current drive has been indirectly demonstrated through the influence on the sawtooth period [3].

Minority ion cyclotron resonance heating has been extensively studied theoretically in the limit of the thin orbit width approximation, i.e., assuming the drift surface of an ion to coincide with a magnetic flux surface, and neglecting the RF-induced diffusion and drift [4]. In this approximation ion cyclotron heating and current drive are caused by diffusion mainly in $v_\perp$ for ions satisfying the resonance condition $\omega = n\omega_c + k_\| v_\|$, where n is an integer, ω_c the cyclotron frequency of the resonating species, $k_\|$ the parallel wave number, and $v_\perp$ and $v_\|$ the velocity perpendicular and parallel to the magnetic field, respectively. Since the magnetic field is decreasing with major radius the waves will resonate with particles having $v_\| > 0$ on the outboard side of the unshifted cyclotron resonance for positive $k_\|$ and for $v_\| < 0$ on the inboard side. The main expected effect is therefore a current profile modification around the magnetic surface intersecting the cyclotron resonance in the midplane. Whether a net driven ion current appears depends on the geometry, the power deposition profile, and the $k_\|$ spectrum.

When finite orbit width effects and the RF diffusion in real space as well as in velocity space are included, new current drive mechanisms appear in addition to the one proposed by Fisch [2]. For the new current drive mechanisms the RF-induced drift associated with an asymmetric spectrum will be shown to play a crucial role. Ion cyclotron heating and current drive can be analyzed from a single particle picture where the collisions mainly take place with a background of Maxwellian electrons and ions; self-collisions are assumed to be negligible. In the absence of collisions and RF interactions a drift orbit in an axisymmetric plasma can be described by three invariants, exact or adiabatic, e.g., energy W, magnetic moment μ, and toroidal angular momentum P_ϕ, where $P_\phi = Rmv_\phi + eZ\psi(r), eZ$ is the charge of the ions and ψ is the poloidal magnetic flux. The orbit invariants are affected by Coulomb collisions and wave particle interactions. The latter are obtained by integrating the equation of motion, including the wave field, across the resonance. An ion absorbs both energy and toroidal angular momentum from the wave. The change in toroidal angular momentum ΔP_ϕ due to RF interaction is correlated with the change in energy $\Delta W \approx \Delta W_\perp$ [5],

$$\Delta P_\phi = \frac{n_\phi}{\omega}\Delta W, \tag{1}$$

where n_ϕ is the toroidal mode number. The change in v_ϕ at the cyclotron resonance leads to a displacement of the turning point of a trapped ion Δr_T [5],

$$\Delta r_T = -\frac{n_\phi \Delta W}{eZ\omega\, \partial\psi/\partial r}. \tag{2}$$

Thus, if a toroidally directed wave spectrum is applied, the trapped ion turning point will drift radially inwards or outwards, depending on the sign of n_ϕ. The radial drift velocity of the turning point due to RF interaction (in minor radius) is given by

$$v_T = -\frac{n_\phi p q}{eZ\omega B_\phi r}, \tag{3}$$

where we have used that $\partial\psi/\partial r = RB_\theta$ and the safety factor $q = rB_\phi/R_0B_\theta, p$ is the RF-power density, and B_ϕ and B_θ are the toroidal and poloidal components of the equilibrium magnetic field, respectively. This drift will modify the dynamics of the heated ions as follows.

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As the resonating ions gradually are heated, the velocity component perpendicular to the magnetic field increases, and the orbits become trapped with their turning points gradually moving towards the cyclotron resonance and, at the same time, they drift outwards or inwards in accordance with Eq. (3). To illustrate this effect we have followed a test particle in time applying only the drift contributions for RF interaction and the Coulomb collision drift emanating from the slowing down of fast ions on electrons. The particle is initialized at $R = 3.36$ m in the midplane at $t = 0$ with $v_\parallel^2/v^2 = 0.3$, $v_\parallel < 0$, and $W = 50$ keV. The cyclotron resonance is located at 0.26 m out on the high-field side; the other parameters are given below. The different orbits are shown in Fig. 1(a) for $n_\phi = 15$ and in Fig. 1(b) for $n_\phi = -15$. If the test particle in Fig. 1(b) is followed slightly longer the orbit becomes marginally trapped. A small perturbation could then make it either copassing or counterpassing.

The minority ion distribution function and the RF-driven ion current are calculated with the Monte Carlo code FIDO [6] which includes the effect of the finite orbit width and

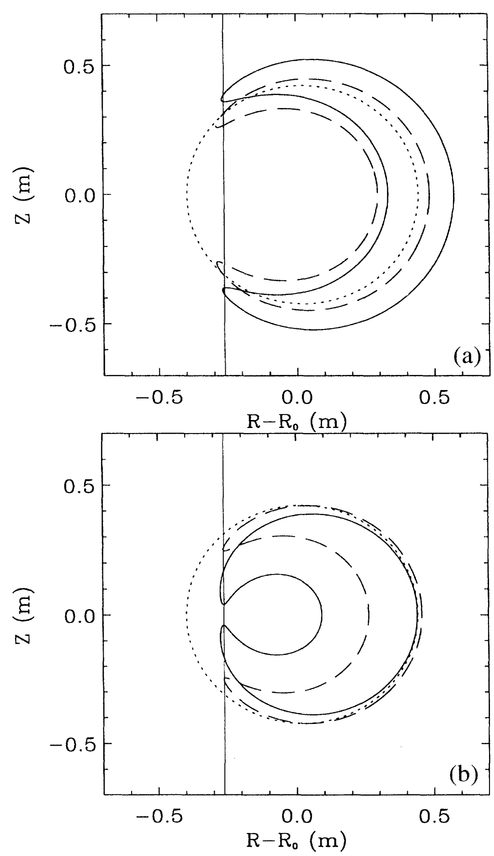

FIG. 1. (a) A drift orbit after 0 s (dotted), 0.2 s (dashed), and 1.3 s (full) of heating. $P = 10$ MW and $n_\phi = 15$. The thin vertical line is the cyclotron resonance. (b) Same as (a) but with $n_\phi = -15$.

the spatial RF diffusion. To investigate the current drive mechanism we have used the following parameters: a circular plasma with a magnetic field of 2.2 T at the magnetic axis, major radius $R_0 = 2.96$ m, minor radius $a = 1.25$ m, plasma current 0.84 MA with constant current density, and 8 keV electron and ion temperatures constant in space and time; the density is also constant $n_D = 3.0 \times 10^{19}$ m^{-3}. The toroidal magnetic field and the current are directed in opposite directions with the direction of the magnetic field being the positive one. Note that this implies negative Ohmic current, a copassing orbit has $\mathbf{v}\cdot\mathbf{B}_\phi > 0$ and a counterpassing one has $\mathbf{v}\cdot\mathbf{B}_\phi < 0$. Also, the currents and current densities in Figs. 2–6 are, if positive, antiparallel to the Ohmic current and vice versa. The wave resonates with hydrogen ions at their fundamental cyclotron frequency; the second harmonic absorption on deuterium is neglected. The temperature and density of the resonating ions are initially constant in space 8 keV and $n_H = 1.5 \times 10^{18}$ m^{-3}, respectively. The momentum slowing down time which is the characteristic time for reaching steady state is 0.8 s. The wave absorption in the examples presented here is proportional to $|E_+|$, which is the wave field component rotating with the ions; the E_- component is thus neglected and would not qualitatively change the analysis. We assume $|E_+|^2$ to be proportional to $\exp[-(r/0.24a)^2]$ in the entire plasma. Positive n_ϕ represents waves with a phase velocity parallel with the toroidal magnetic field and antiparallel to the plasma current.

For off-axis heating at the high-field side of the magnetic axis with $n_\phi > 0$ the trapped ions move outwards. Because of their finite orbit width the trapped ions contribute to the current profile. On the outer leg of a trapped drift orbit the ion moves nearly antiparallel to the magnetic field and on the inner leg parallel. This gives rise to a current similar to the diamagnetic source current for the neoclassical bootstrap current [7]. This current appears in addition to the one predicted by Fisch [2]. The relative importance of these effects is studied by separating the current contributions from the trapped and the passing ions. For the parameters used here we find that the trapped current contribution typically dominates for

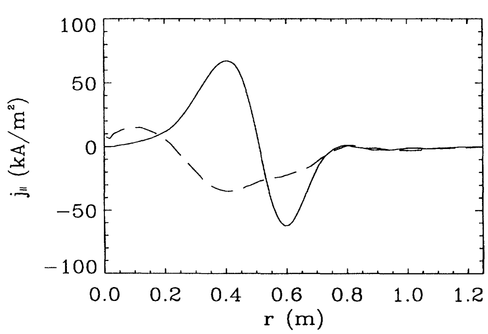

FIG. 2. Contributions to the current density from passing ions (dashed) and trapped ions (full) after 0.8 s of heating.

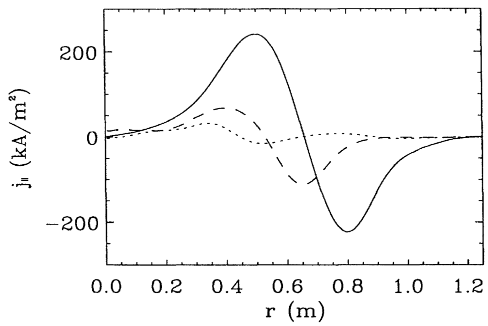

FIG. 3. Current density for $n_\phi = 15$. $P = 1$ MW (dotted), $P = 3$ MW (dashed), and $P = 8$ MW (full).

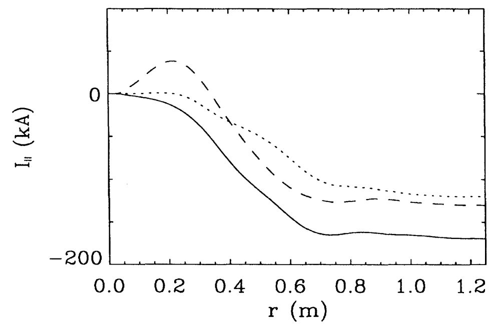

FIG. 5. Area integrated current $I(r)$ as a function of minor radius at $t = 2$ s, $P = 4$ MW, and $n_\phi = -15$, $R_c = 2.70$ m (dashed), 2.96 m (full), and 3.28 m (dotted).

absorbed power above 1 MW. The profiles can be seen in Fig. 2 for 3 MW, $n_\phi = 15$ and $R_c = 2.70$ m, where R_c is the major radius where the cyclotron resonance intersects the midplane. The modification of the current is thus a reduction on the inner part of the orbit and an increase on the outer part. This results in a reduction of the total current density gradient near the inflection point of the driven current density profile, in case of a centrally peaked Ohmic current density profile. If the inflection point is close to the $q = 1$ surface stabilization of sawteeth can occur provided the resulting current gradient is sufficiently small [8]. In the thin orbit width approximation only the passing ions contribute to the current. For low power, the current profiles for passing and trapped ions look similar. The current reversal point of the passing current is close to the minor radius r_c. As the power increases the trapped ions dominate the current profile and the reversal point moves outwards. This is caused not only by orbit broadening but also by an outward drift of trapped high energy ions. Thus, if the current reversal surface coincides with the $q = 1$ surface for low powers, it will not do so at higher power or after a longer time. The current density profiles for different powers are shown in Fig. 3 after 2 s of heating. The current reversal surface also moves continuously outwards with time until a steady state is reached. Off-axis current drive at the high-field side with $n_\phi > 0$ was used for sawtooth stabilization at JET [3], with the same directions of the magnetic field and current as used for the code calculations. However, these experiments were made with much higher minority concentrations for which the current drive mechanism proposed by Fisch [2] is still expected to play an important role. It was observed that below 5 MW the sawtooth period increased with power and above a threshold of ~5 MW the sawtooth period was reduced. This threshold depended on the minority density. This behavior of the sawtooth period was understood through the change in the current gradient near the $q = 1$ surface [3,8]. The reduction in the observed stabilization for high powers was explained by the creation of trapped ions, which in the thin orbit approximation do not carry any current. A more plausible explanation is the outward drift of the current reversal point with increasing power. If a stronger modification of the current gradient is needed at the $q = 1$ surface, the RF-driven current density can be increased by increasing the minority density. However, if the concentration increases too much the damping by electron Landau damping and transit time magnetic pumping of the fast wave increases and the current drive efficiency will

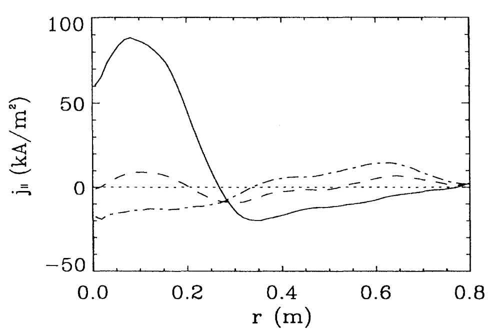

FIG. 4. The current density profile for $n_\phi = -15$ and $P = 4$ MW at $t = 0$ s (dotted), 0.01 s (dash-dotted), 0.03 s (dashed), and 0.08 s (full).

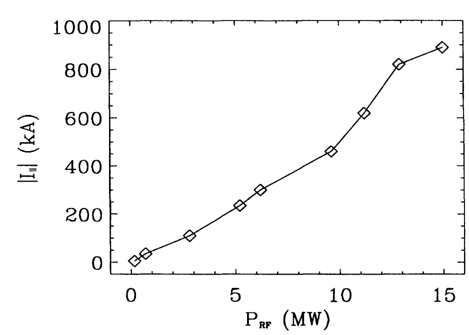

FIG. 6. The total driven current versus power for $R_c = 2.70$ and $n_\phi = -15$ at $t = 2$ s.

go down. The largest currents are obtained by positioning the resonance at the high-field side. However, this does not come from the fact that less trapped ions are created as in the thin orbit width approximation [3], but from the fact that the banana orbits become wider and the averaged parallel velocity becomes larger. The larger parallel velocity comes from the fact that the turning points move towards the high-field side.

For $n_\phi < 0$ the turning point of the trapped ions drifts inwards towards smaller minor radii. As a result, the turning points become located close to the midplane and the ions become marginally trapped in accordance with Fig. 1(b). Because of the finite orbit width ions following trapped orbits preferentially scatter into ions with counter orbits, such that the new orbit follows close to the outer leg of the trapped orbit. The trapped ions scattering into copassing ones will closely follow the inner leg of the trapped orbit. The counter orbits will then be located at minor radii $r > r_c$ and the co-orbits at $r < r_c$, where r_c is the minor radius at which the cyclotron resonance intersects the midplane. Thus, a cocurrent will be produced in the center and a counter one further out. The time evolution of the current density is shown in Fig. 4. Transiently a current profile similar to that expected from Fisch theory is obtained with a countercurrent for $r < r_c$ and a cocurrent for $r > r_c$. As time increases more trapped ions are formed which drift inwards and become passing and the driven current profile reverses so that the countercurrent appears at larger radii and the cocurrent at smaller radii. The final driven current profile flattens a peaked Ohmic current profile around $r = r_c$. If $r = r_c$ coincides with the $q = 1$ surface stabilization of sawteeth could appear. However, the reversal of the current profile could affect the dynamics of the sawteeth. The experiments at JET showed reduced sawtooth periods for this case. The current is dominated by passing ions formed as described above. The preferential scattering into counterpassing ions leads to a net counter current, i.e., a net current parallel with the plasma current. In addition, a diamagnetic current arising from the trapped particles appears but is comparatively small. When the cyclotron resonance intersects the midplane at the low-field side of the magnetic axis the trapped ions become counterpassing, with orbits located at the low-field side of the magnetic axis. In Fig. 5 we have plotted the area integrated current $I(r) = \int_0^r 2\pi r' j(r')\,dr'$ for different locations of the cyclotron resonance R_c. The lowest current is obtained for waves absorbed on the low-field side. The variation of the total current versus power with the cyclotron resonance at the high-field side can be seen in Fig. 6. In this case the current increases faster than linearly.

In the study presented here we have not included the current caused by the momentum transfer to the electrons, which partially cancels the ion current depending on the charge ratio between the minority ions (Z) and the background ion species (Z_{eff}). If $Z_{\mathrm{eff}} > Z$ a local net current, dominated by ions, is produced. If $Z_{\mathrm{eff}} < Z$ the current is dominated by electrons and reverses. In the case studied above a typical value would be $Z_{\mathrm{eff}} \approx 1.4$, yielding a net ion current. One can straightforwardly correct for this by using Eq. (42) in Ref. [9].

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