Minority Ion Current Drive during ICRH

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ABSTRACT

The RF induced diffusion in velocity and real space are tied together in a toroidal geometry. This gives rise to new ICRH current drive mechanisms, which are found to be the dominating ones for minority ion current drive with high power.

1. INTRODUCTION

Minority ion current drive, originally proposed by Fisch [1], is caused by diffusion mainly in $v_\perp$ for ions satisfying the resonance condition $\omega = n\omega_c + k_\parallel v_\parallel$. Here n denotes the multiple of the cyclotron frequency, ω_c the cyclotron frequency of the resonating minority species, $k_\parallel$ the parallel wave number, $v_\perp$ and $v_\parallel$ the velocity perpendicular and parallel to the magnetic field. Since the magnetic field is decreasing with major radius the wave will resonate with particles having $v_\parallel > 0$ on the low field side of the unshifted cyclotron resonance for positive $k_\parallel$ and for $v_\parallel < 0$ on the high field side. The main expected effect is therefore a current profile modification around the magnetic surface intersecting the cyclotron resonance in the mid plane. Whether a net ion current drive appears, depends on the geometry and the power deposition profile as well as on the $k_\parallel$ spectrum.

When finite orbit width effects are included the diffusion in velocity space is coupled to the diffusion in real space. This gives rise to new current drive mechanisms, for which the RF-induced radial drift plays an important role (with the orbit width we mean the radial deviation a drift orbit makes from a magnetic flux surface). Passing particles are turned into trapped, the trapped ions drift either inwards or outwards depending on the toroidal mode number, n_ϕ. In the former case as they approach the centre and become marginally trapped they will then pitch angle scatter preferentially into counter passing particles, because of the longer time spent on the counter leg. In the latter case they remain trapped and form a current profile which is parallel with the plasma current on the outside and anti-parallel on the inside.

2. ANALYSIS OF MINORITY ION CURRENT DRIVE

For simplicity we consider a plasma with a circular cross section and the current anti-parallel to the toroidal magnetic field. Trapped ions are moving parallel with the toroidal field on the inside leg and anti-parallel on the outside. An orbit can be expressed in the three invariants (E, P_ϕ, Λ), where E is the energy, P_ϕ the toroidal angular momentum and $\Lambda = \mu B_0/E$, where μ is the magnetic moment. The orbit topology of this invariant space is shown in Fig. 1 for constant energy [2]. During ICRH, in the absence of the finite orbit width effects, trapped and passing ions increase their $v_\perp$ so that they, while remaining on the same flux surface, turns into trapped particles with orbits having their turning point at the cyclotron resonance, the – · – · – lines in Fig. 1. When the finite orbit width effects are included for a directed wave spectrum an RF-induced radial drift appears [3]. Instead of staying on the same flux surface for $n_\phi < 0$ the trapped ions reduce their P_ϕ and drift downwards while approaching the – · – · — line. As the ions move towards the centre they become marginally trapped. Collisions will preferentially pitch angle scatter the trapped particles into counter-passing ones located close to the outer leg of the fat banana orbit. The trapped particles scattering into co-passing ones become located close to the inner leg. The RF-driven current is then dominated by passing particles. For $n_\phi > 0$ the particles drift outwards when approaching the line – · – · – and will become and remain trapped. The dominating current contribution comes then from trapped particles, with the current anti-parallel to the plasma current at smaller radii and parallel at larger radii. For large powers when the orbits become fatter a net current appears because the ions spend longer time on the outer leg than the inner one.

The RF-driven current profiles are calculated with the Monte Carlo code FIDO [4], which solves the velocity distribution expressed in the three invariants (E, P_ϕ, Λ). The following equilibrium is considered: a circular plasma with a magnetic field of 2.2 T at the magnetic axis, R_0=2.96 m, the plasma current 2 MA , 8 keV electron and ion temperatures constant in space and time, the density is also constant $n_H=1.5 \cdot 10^{18}\ m^{-3}$, $n_D=3.0 \cdot 10^{19}\ m^{-3}$. The wave resonates with the hydrogen and second harmonic absorption on deuterium is neglected. The $|E_+|^2$ is assumed to be proportional to $exp\text{-}(r/0.24)^2$ in the entire plasma. Positive n_ϕ represents waves with a phase velocity parallel with the toroidal magnetic field and anti-parallel with the plasma current. For these parameters the slowing down time is 0.8 s. The results presented here are taken at t=2 s when nearly steady state conditions are reached.

The sensitivity of the RF-driven current profiles to the position of the cyclotron resonance, R_c, can be seen by plotting the area integrated current $I(r) = \int 2\pi r j(r) dr$ in Fig. 2, where we have chosen the sign of the current such that a positive current is anti-parallel to the ohmic plasma current. For the cases shown in Fig. 2a with $n_\phi > 0$ the dominating minority current comes from trapped ions. For the cases shown in Fig. 2b with $n_\phi < 0$ the dominating minority current comes from passing particles except for heating at the low field side where they are trapped or lies in the region VIII of Fig. 1.

Off axis current drive at the high field side with $n_\phi > 0$ was used for sawtooth stabilisation in JET [4]. The RF-driven current density profiles calculated for $n_\phi = 15$ and $R_c = 2.66$ is shown in Fig. 3 for different powers. The current drive mechanism for passing particles found by Fisch [1] is only important for powers below 1 MW, for higher power the current drive is dominated by trapped particles according to the discussion above. For optimal reduction of the ohmic current gradient at the $q = 1$ surface, the inflection point of the RF-driven current density profile should be located at the $q = 1$ surface. As the power increases the inflection point which is near the current reversal point moves outwards. This is caused not only by orbit broadening but also by an outward drift of trapped high energy ions. Note that the cyclotron resonance intersects the mid plane at minor radius $r = 0.3$, which in the thin orbit width approximation becomes the current reversal surface.

The RF-driven current by counter passing particles described above, obtained by high field side heating with $n_\phi = -15$ and $R_c = 2.66$, is plotted versus power in Fig. 4. The current increases nearly linearly with power, ≈ 0.5A/W. The current is located essentially in the interval $0.3 < r < 0.5$, i.e. outside the intersection of the cyclotron resonance with the mid plane. The current profile can be varied by changing the position of the cyclotron resonance.

3. CONCLUSIONS AND DISCUSSIONS

Minority ion current drive during ICRH has been analysed taking finite orbit width effects into account. The thin orbit width results, where the RF-driven current is produced by passing particles, are found to be valid for low powers only. When finite orbit width is included two new current drive mechanisms appear, for which the RF-induced radial drift by an asymmetric toroidal wave spectrum plays an important role. For wave propagation parallel with the plasma current a large net current is obtained contrary to the thin orbit width approximation.

Current drive experiments on JET, with a spectrum of waves travelling anti-parallel to the plasma current, $n_\phi > 0$, for which the cyclotron resonance intersected the mid plane near the $q = 1$ surface showed an increased sawtooth period [4]. This was explained in accordance with the thin orbit width calculations by flattening of the total plasma current gradient near the $q = 1$ surface. The experiments also showed that as the power was further increased the sawtooth period was reduced. Our calculations show that for a wave propagating anti-parallel to the plasma current, absorbed on the high field side, an RF-driven current profile of the shape that can flatten the current density gradient at the $q = 1$ surface and thus provide sawtooth stabilisation can be obtained. But in contrast to the thin orbit width theory the currents now mainly comes from trapped ions. As the power increases the current reversal surface moves outwards and thus becomes less effective in flattening the current profile around the $q = 1$ surface.

To see whether the sawtooth stabilisation could have been obtained by high energy ions we calculate the energy density of the minority ions for off axis heating at $R_c = 2.66$ with $n_\phi = 15$ and $n_\phi = -15$. As can be seen in Fig. 5 due to the RF-induced outward drift for $n_\phi = 15$ the energy density is much lower in the centre and broader compared to $n_\phi = -15$. This supports that sawtooth stabilisation is not obtained by fast ions but by current profile modifications.

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REFERENCES

[1] Fisch N.J., Nuclear Fusion **21**(1981)15.
[2] Carlsson J., Eriksson L.-G. and Hellsten T., this conference.
[3] Chen L., Vaclavik J. and Hammett G., Nucl. Fusion **28**(1988)389.
[4] Start D.F.H., et al, International Conf. on Plasma Physics (Proc. Conf. Innsbruck, 1992) Vol. 16C, part II, EPS, Geneva 1992, 897.

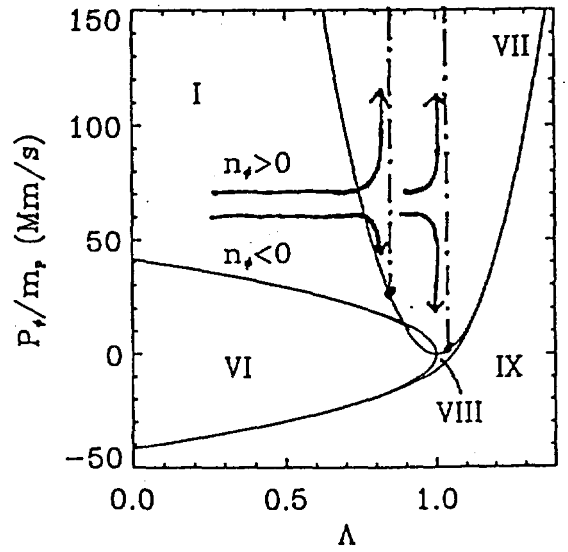

Fig. 1: The orbit topology in the invariant space (P_ϕ, Λ) for constant energy, the lines – · – represents orbits having turning point at the cyclotron resonance, (right) a line for low and (left) high field side heating are shown.

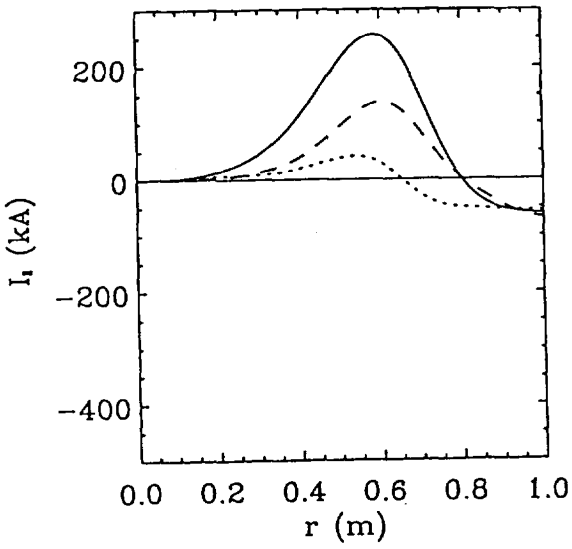

Fig 2a: Area integrated RF-driven current at t= 2 s and n_ϕ=15 for different position off the cyclotron resonance - - -R_c =2.66, ----- R_c =2.96 .... R_c =3.26m.

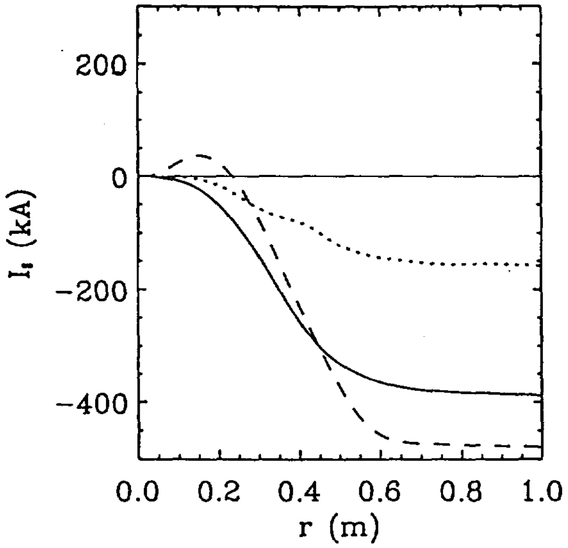

Fig. 2b: The same as for Fig. 2a with n_ϕ=-15.

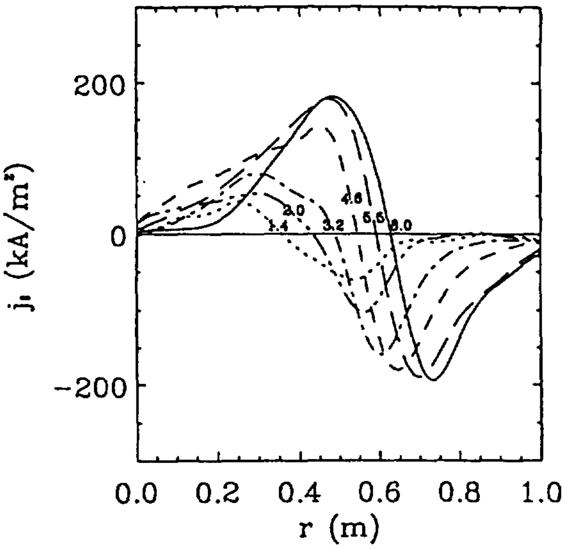

Fig. 3: RF-driven current profiles at t= 2s for different absorbed power in MW, n_ϕ=15 and R_c =2.66.

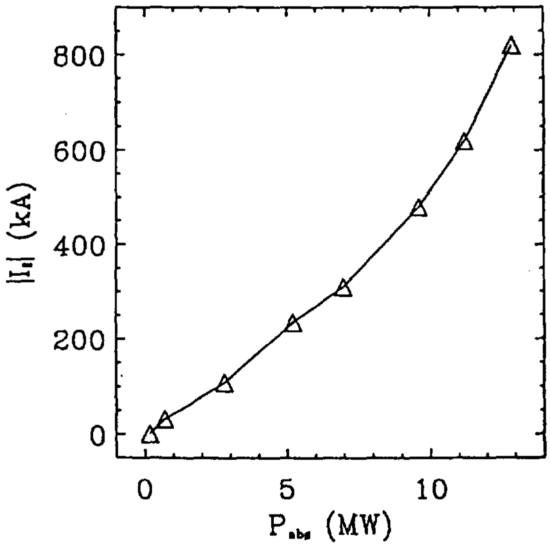

Fig. 4: The total RF-driven current versus power for R_c=2.66 and n_ϕ=-15.

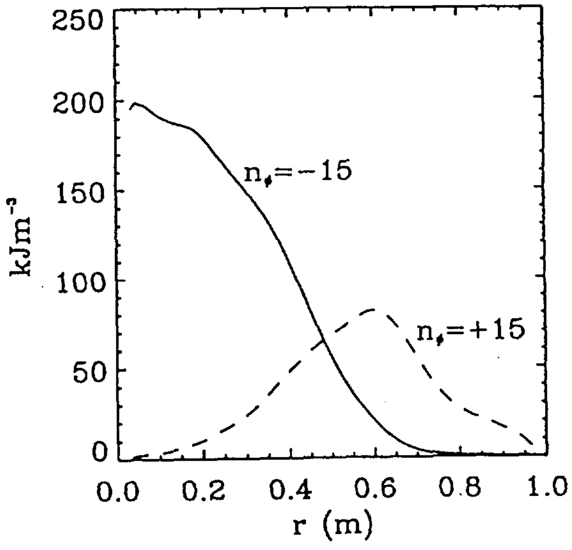

Fig. 5: Minority ion energy density for off axis heating with R_c=2.66.