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Effects of Magnetic Field Line Stochasticity on Resonant Ion Behaviour in ICRF-Heated Tokamak Plasmas

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1-Introduction

ION CYCLOTRON RESONANCE HEATING (ICRH) via the magnetosonic wave, one of the main additional heating methods of Tokamak plasmas, has received considerable theoretical attention in recent years[1], especially in connection with the wave propagation problem and dynamics of tail formation process. The understanding of the wave absorption mechanisms by the plasma requires a precise description of the particle individual trajectories. The Hamiltonian mechanics, through a set of canonical variables, allow this description, and make the computation of the wave-particle interaction easier. In this analysis, we consider the collisionless behaviour of ions treated as test particles moving through a maxwellian plasma whose properties are not changed on the short time-scale of the ion heating, and subject to the usual resonance condition within a confining stochastic magnetic field configuration. The test particle experiences a net non adiabatic change in its magnetic moment and a net change in energy as it passes through the wave-particle resonance during its transit of the torus.

2- Hamiltonian Formulation of Guiding Center Motion

The formalism described here is Hamiltonian in character and agrees to first order in ρ with the usual guiding center treatment. Higher-order corrections are beyond the scope of the work. Unfortunately, magnetic coordinates are well defined in toroidal geometry only when magnetic surfaces exist. Even the presence of small islands greatly complicates these coordinates. However, the simplicity and elegance of the magnetic coordinate representation of drift motion can be preserved in the analysis of motion in stochastic fields if it is assumed that a neighboring magnetic configuration with nested surfaces exists. More precisely, we assume the exact magnetic field $\mathbf{B_e}$ is given by

$$\vec{B}_e = \vec{B} + \delta\vec{B} = \vec{B} + \vec{\nabla}\times\left(\alpha\vec{B}\right)$$

where **B** having exact nested, magnetic surfaces and α giving the magnetic perturbation.

The guiding center drift motion in the presence of an ambient perturbed magnetic field B_e can be parameterized in terms of four convenient canonical variables $P_\vartheta, \vartheta, P_\phi, \phi$ [2]

$$\dot{P}_\phi = -\frac{\partial H_0}{\partial \phi},\quad \dot{\phi} = \frac{\partial H_0}{\partial P_\phi},\quad \dot{P}_\vartheta = -\frac{\partial H_0}{\partial \vartheta},\quad \dot{\vartheta} = \frac{\partial H_0}{\partial P_\vartheta}$$

Where P_ϑ, P_ϕ are the canonical momenta with ϑ the poloidal angle, ϕ the toroidal angle and the dot represents the time derivative.

$$H_0 = \frac{1}{2}\rho_{//}{}^2 B_e{}^2 + \mu B_e + \Phi_{MHD}$$

is the Hamiltonian with $\rho_{//}$ the parallel gyro-radius, μ the magnetic moment and Φ_{MHD} the static electric potential of MHD activities.

The function $$\alpha(\psi,\phi,\theta) = \sum_{n,m} \alpha_{nm}(\psi)\cos(n\phi + m\theta + \phi_{nm})$$

which has units of length, is used to represent the islands and ergodic regions of the magnetic field. The harmonic perturbing fields α_{nm} were chosen to be of equal amplitude, and well localized about their rational surfaces

$$\alpha_{nm}(\psi) = \alpha_0 \exp[-(\psi - \psi_{nm})^2 / b]$$

where $q(\psi_{nm}) = m/n$, ϕ_{nm} are fixed random phases; b and α_0 were taken to be $2\cdot 10^{-4}$ and 10^{-5} respectively. ψ represents the toroidal flux function. Note that the poloidal coordinate θ is not identical to the usual poloidal angle ϑ, but we chose θ to increase from 0 to 2π if ϑ completes a poloidal rotation.

The unperturbed magnetic field used in this work is the simplest solution to the Grad-Shavranov equation with a zero β, large-aspect-ratio toroidal equilibrium.

3- Single Particle Response to the ICRF Field

The cyclotron resonance is confined to a very small layer of the plasma (lying in a cylindrical shell of constant radius) so a reasonable approximation is to represent the RF field as a plane, left handed circularly polarized wave of the form

$$\vec{E} = E_+ \cos(k_\perp x_\perp)[\cos(k_{//} x_{//} - \omega t)\vec{e}_2 + \sin(k_{//} x_{//} - \omega t)\vec{e}_3]$$

where $(\vec{e}_1, \vec{e}_2, \vec{e}_3)$ are unit vectors of the local orthogonal coordinate system with $\vec{e}_1$ along the magnetic field. The effect of ICRH is considered through the Hamiltonian

$$H = H_0 + \tilde{H}$$

where the wave-ion interaction occurs through the perturbative Hamiltonian $\tilde{H}$ written in the form $$\tilde{H} = -e\vec{v}\cdot\vec{A}$$

e is the ionic charge,

$$\vec{v} = v_{//}\vec{e}_1 + v_\perp(\cos\xi\,\vec{e}_2 + \sin\xi\,\vec{e}_3)$$

is the unperturbed particle velocity, ξ the gyro-phase and $\vec{A}$ the vector potential of the magnetosonic wave, assumed to be perpendicular to the magnetic field and with null-scalar-potential gauge condition. With an RF electric field $\vec{E}$ oscillating at a frequency ω near the local cyclotron frequency, the non-adiabatic change in μ, which may either be positive or negative depending on the gyro-phase compared to the phase of the wave, as the guiding center passes through a cyclotron resonance can be found from the following normalized equations

$$\dot{\mu} = -\frac{\partial H}{\partial \xi} = \frac{E_+}{\omega}\sqrt{2\mu B}\begin{pmatrix} k_\perp\sqrt{\frac{2\mu}{B}}\cos\xi\sin(k_\perp x_\perp)\sin(k_{//}x_{//}-\omega t-\xi)- \\ \cos(k_\perp x_\perp)\cos(k_{//}x_{//}-\omega t-\xi) \end{pmatrix}$$

$$\dot{\xi} = \frac{\partial H}{\partial \mu} = B - \frac{E_+}{\omega}\sin(k_{//}x_{//}-\omega t-\xi)\left(\sqrt{\frac{2B}{\mu}}\cos(k_\perp x_\perp)+2k_\perp\sin\xi\sin(k_\perp x_\perp)\right)$$

4- Numerical Results

The main part of the numerical analysis consists of solving the equations of motion for various initial conditions and different values of the relevant parameters. These equations are integrated numerically using a standard fourth order Runge-Kutta Algorithm. As a check for accuracy, we demand that the collisionless drift orbits conserve energy in the abscence of the RF electric field. Solving these equations yields the particle motion in a six-dimensional phase space. A two-dimensional, graphical representation of this solution can be obtained by plotting the phase point (ψ,θ) or (μ,θ) whenever ϕ or ξ becomes equal to some constant ϕ_0 or ξ_0 .

The form of the electric field is chosen to be gaussian

$$E_+(\phi) = E_0\exp\left(-\frac{(\phi-\pi)^2}{2\delta^2}\right)$$

with $\delta = \frac{\pi}{20}$ to model the finite toroidal extension of the wave field.

For $E_0 = 3\cdot10^{-5}$, the interval of variation of the magnetic moment [$4.73\cdot10^{-7}$, $1.93\cdot10^{-6}$] modifies to [$4.88\cdot10^{-7}$, $6.36\cdot10^{-7}$] in the presence of the magnetic perturbation with $\alpha_0 = 10^{-5}$. The interval of variation of ψ [0.01329, 0.01531] (after 24 tours the long way around the torus and 22000 gyro-periods) modifies to [0.01416 , 0.01606] (after 25 tours the long way around the torus and 22000 gyro-periods) in the presence of magnetic perturbation .

5- Conclusion

A Numerical code based on the Hamiltonian guiding center drift orbit formalism is used to analyze the effects of magnetic field line stochasticity (*MFLS*) on the ion cyclotron range of frequencies heating in a collisionless Tokamak plasma. Numerical calculations reveal large changes in magnetic moment and drift orbit of the RF-heated ion. The results show that *MFLS* effects can have important consequences for the heating efficiency and may deeply modify its impact on transport processes.

References

[1] Bécoulet A 1996 *Plasma Phys. Control. Fusion* **38** A1

[2] White R B and Boozer A H 1995 *Princeton Plasma Physics Laboratory Report,* PPPL-3094

α=0, E_0=3·10^{-5} α=10^{-6}, E_0=3·10^{-5}