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Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Max-Planck-Institut für Plasmaphysik und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.

Edge Plasma Heating via Cyclotron Harmonic Interaction

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ABSTRACT

Energy absorption in the edge region via cyclotron harmonic interaction during ICRF plasma heating is examined. It is shown that the electric field ripple caused by the closely spaced Faraday shield conductors gives rise to large effective perpendicular wavenumbers, resulting in strong cyclotron harmonic damping. For the parameters of the ASDEX tokamak, carbon impurity ions with $Z = 3$ and an initial perpendicular energy of $1\,eV$ could be accelerated to energies in excess of $100\,eV$ in less than $10\,\mu S$ (corresponding to about 100 cyclotron orbits).

We consider the linearized motion of a particle in a uniform magnetic field B_0 and an electric field

$$E(\vec{r},t) = \int d\vec{k}\, E(\vec{k}) \exp\left[i(\omega t - \vec{k}\cdot\vec{r})\right] \;, \tag{1}$$

where $\vec{k} = k_x\,\hat{x} + k_y\,\hat{y} + k_z\,\hat{z}$ and the hats represent unit vectors. Let

$$E_{r,l} = E_x \pm iE_y \;, \tag{2}$$

$$k_\perp^2 = k_x^2 + k_y^2 = k_0^2 - k_z^2 \;, \tag{3}$$

$$\tan\psi = k_y/k_x \;, \tag{4}$$

and

$$\vec{k}\cdot\vec{r} = k_\perp r_g \sin(\omega_c t + \psi) + k_z v_z t \;, \tag{5}$$

where r_g is the gyroradius, ω_c is the cyclotron frequency and v_z is the particle's velocity along B_0. Change in the perpendicular velocity $v_\perp = v_x + iv_y$ may be expressed in the form

$$\begin{aligned} \Delta v_\perp = -\frac{1}{2}\eta \int d\vec{k} \sum_n J_n(k_\perp r_g) \exp(-in\psi) \\ \times \int dt \left[E_r(\vec{k}) \exp\{i(\omega + \omega_c - n\omega_c - k_z v_z)t\}\right. \\ \left. + E_l(\vec{k}) \exp\{i(\omega - \omega_c - n\omega_c - k_z v_z)t\}\right] \;, \end{aligned} \tag{6}$$

where $\eta = Ze/MA$, is the charge to mass ratio and $J(k_\perp r_g)$ is the Bessel function of the first kind and order n. Equation (6) occurs in various contexts and is fundamental to the Bernstein[1] wave heating proposed earlier by the author[2] for the heating of toroidal plasmas. The present derivation parallels that of Hall and Sturrock[3].

The electric field spectrum $E(\vec{k})$ in Eq.(6) is weighted by the modulation factor $\mathcal{M}$ defined as

$$\mathcal{M} = J_n(k_\perp r_g) \exp(-in\psi) \;. \tag{7}$$

For propagating waves[4] both k_x and k_y are real, $|\exp(-in\psi)| \equiv 1$, so that $|\mathcal{M}|$ is solely determined by the J_n. However, in the case of the ICRF antenna near field, k_x becomes imaginary while k_y is real by definition, and ψ in Eq.(4) assumes imaginary values. One obtains

$$\exp(-2i\psi) = \frac{k_x - ik_y}{k_x + ik_y} \ . \tag{8}$$

For $k_x = i|k_x|$ and $k_y < 0$, Eq.(8) gives

$$\exp(-2i\psi) = \frac{|k_x| + |k_y|}{|k_x| - |k_y|} \ . \tag{9}$$

The asymmetry with respect to $\pm k_y$ is presumably due to the additive or the subtractive contributions to the particle acceleration from the electric field inhomogeneities in the x and the y directions, respectively. For $|k_y| \gg |k_x|$, one obtains from Eq.(9)

$$\exp(-2i\psi) = -4k_y^2/k_\perp^2 \ . \tag{10}$$

Approximating the Bessel function as

$$J_n(k_\perp r_g) \approx \frac{k_\perp^n r_g^n}{2^n n!} \ , \tag{11}$$

and using Eqs.(7), (10) and (11) yields

$$\mathcal{M} \approx \frac{i^n}{n!}(|k_y| r_g)^n \ . \tag{12}$$

The right hand side of Eq.(12) resembles that of Eq.(11) with $k_\perp$ replaced by $2i|k_y|$. This is not surprising, since the combination of the electric field evanescence along x occuring through $\exp(-k_x x)$ for $k_\perp \ll 1$ and the finite wavelength along y, replace the role played by the perpendicular wavenumber for complex $k_\perp$. The form of the result of Eq.(12) may be anticipated intuitively, since the necessary ingredient for the existence of the cyclotron harmonic interaction is the presence of the perpendicular electric field gradients. Furthermore, it can be shown that Eq.(12) represents the minimum value attained by $|\mathcal{M}|$ for a given negative k_y.

For the case of fast wave ICRF antennas, large electric field gradients with correspondingly large $|k_y|$, occur directly in front of the Faraday shield. Assuming $n = 2$, $\omega = 3\omega_c$ and Δt the time available for acceleration, one obtains

$$|\Delta v_\perp| \approx |.25\eta (k_y r_g)^2 E_l| \Delta t \ . \tag{13}$$

Upon integrating the differential equation obtained after replacing r_g by $v_\perp/\omega_c$ one obtains from Eq.(13)

$$t_{10} \approx 2.7\eta^{1/2} Z^{1/2} \frac{B_0^2}{k_y^2 E_l} T_i^{-1/2} \quad , \tag{14}$$

where t_{10} is the time required for a tenfold increase in the kinetic temperaure T_i expressed in eV. For a given charge to mass ratio η, the particles with the least Z experience the fastest acceleration.

For the ASDEX fast wave ICRF heating at the fundamental hydrogen cyclotron frequency ($B_0 = 2.5\,T$, $|k_y| \approx .1\,cm^{-1}$, $E \approx 300\,V cm^{-1}$), it would take a carbon impurity atom with $Z = 3$ approximately $5.5\,\mu S$ to be accelerated from $1\,eV$ to $10\,eV$. In further $1.7\,\mu S$ and $0.6\,\mu S$, respectively, the particle will attain energies corresponding to $100\,eV$ and $1\,keV$, respectively. For the case of the second harmonic ($\omega = 2\omega_{cH}$) heating, the deuterium impurity atoms at the edge will be heated at a still faster rate. For these estimates it was assumed that a region could be found for the exact resonance condition to be fulfilled. This may not be difficult, since the fast wave antenna spans a large arc along the azimuth and samples a correspondingly large variation in B_0. We have also assumed that the particle orbit possesses the optimal phase with respect to the electric field for maximum acceleration and that the phase is preserved for the duration of the interaction lasting over approximately 150 cyclotron orbits. The acceleration process could be readily initiated by particles with perpendicular energy $\geq 1\,eV$ and parallel energy $\leq 1\,eV$. Although no precise data exists, such a group of particles is likely to occur in the region of the Faraday shield. Once the sputtering and outgassing mechanisms are triggered, there would be no dearth of further candidates to exponentiate the edge heating process. For the lateral antenna extension of $\approx 30\,cm$, the particles would require approximately $100\,\mu S$ to traverse the antenna width.

In the approximate estimation of the acceleration rates, we have neglected the contributions from the non-resonant ($n \neq 2$) harmonics. For the time scales of $1-10\,\mu S$, however, comparable contributions accrue from the non-resonant spectrum components. The much larger values of J_n for smaller n, substantially compensate for the $(\omega - \omega_c -$

$n\omega_c - k_z v_z$) factor in the denominator of the integrand of Eq.(6), especially in the critical initial stages of acceleration.

These observations have been confirmed through accurate (checked by reverse integration) numerical integration of the particle's equations of motion in a steady, uniform magnetic field and an electric field produced by applying a voltage across two infinite cylindrical conductors (Fig. 1). Parameters appropriate to the ASDEX fast wave ICRF heating experiments were chosen. Departures from the exact resonance condition by as much as $0.03\,\omega_c$ still results in over a tenfold energy increase within a few μS. Due to the interference among the harmonics, large oscillatory fluctuations in the velocity are observed. This fact may assume importance in the presence of stochasticity due to the irregularities in the close vicinity of the Faraday shield. Since cyclotron harmonic interaction is a differential process balancing much larger contributions, introduction of stochasticity would most likely result in larger net energy gains by the particles.

The stochastic effects will be even more pronounced in the case of ion-Bernstein wave heating where the relatively large longitudinal antenna extension would allow a particle to gain energy in several independent steps. For this case $|k_y/k_x| \ll 1$, $\psi \to 0$ and $|\exp(-in\psi)| \approx 1$. Also since $k_z \gg k_0$, $k_\perp^2 \approx -k_z^2$ while the continuity condition $\nabla \cdot \vec{E} = 0$ provides $|E_\perp| \approx |E_z|$. The relatively large longitudinal electric field E_z would tend to produce parametric modifications in Eq.(6), though not of a sufficient magnitude to affect the results significantly.

Removing the Faraday screen may not be a valid solution to the problem because similar acceleration conditions prevail near the coaxial antenna ports. Equation (14) shows that the impurity heating problem could be mitigated by increasing the magnetic field B_0 or the effective perpendicular wavelength $2\pi/k_y$.

Though not directly applicable to the low frequency schemes such as Alfvén wave heating, these results carry sobering implications regarding sputtering and outgassing from the Faraday shield (or the antenna itself in the absence of the Faraday shield) upon the application of large amplitude electric fields. The velocity gained by the particle in half a cyclotron period is given by

$$\Delta v_{\perp} \approx 2\frac{E_{\perp}}{B_0} \ . \tag{15}$$

This amounts to an energy gain of

$$\Delta T_i \approx 4 \times 10^{-8} \left(\frac{E_{\perp}}{B_0}\right)^2 A \ . \tag{16}$$

The energy gained in this case is independent of the degree of ionization and increases with A. Thus the low Z iron impurities (almost certainly to be found in the vicinity of an *untreated* Faraday screen surface) would be accelerated to potentially damaging energies with telltale gas and impurity production, unless care is exercised in limiting the electric field amplitude in keeping with the ambient B_0. Alternatively, for the low frequency plasma heating schemes, the edge heating problem may be alleviated by coating the Faraday screen with a low atomic weight material such as carbon.

One practical solution of general applicability would consist in introducing suitable barriers that would reduce the particle flux in front of the Faraday shield. Such a modified Faraday shield would also act as a diagnostic tool for gaging the relevance of the cyclotron harmonic interaction in the edge heating processes.

Several processes such as the residual plasma and sheath effects, collisions, guiding center drifts (rf induced drifts, for example, could force the accelerated particles onto the Faraday screen surface), as well as the rf magnetic fields are not included in this idealized analysis. However, the ideas presented in this paper are pertinent to the ICRF heating schemes and deserve careful attention.

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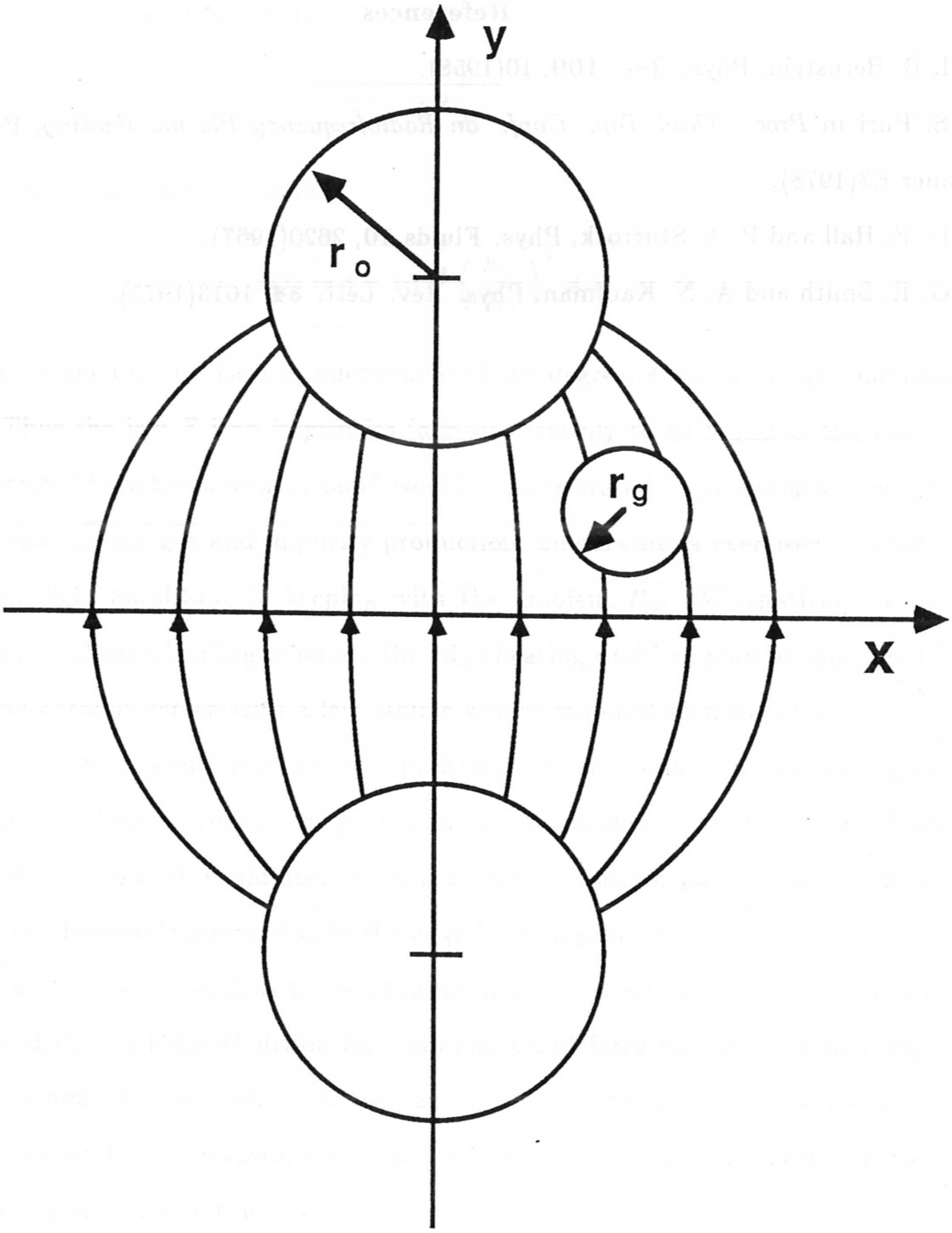

Fig.1 Electric field produced by applying a voltage across two parallel cylindrical conductors used for the numerical simulation of the cyclotron harmonic interaction