PARTICLE ACCELERATION NEAR THE FARADAY SHIELD VIA CYCLOTRON HARMONIC INTERACTION DURING ICRF PLASMA HEATING

Satish Puri
MPI für Plasmaphysik, EURATOM Association, Garching bei München

Energy absorption in the edge region via cyclotron-harmonic interaction during ICRF heating of thermonuclear plasmas 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. Analytical expression for the particle acceleration rate, taking into account the radial evanescence of the perpendicular electric field, is derived. For the ASDEX fast wave ICRF heating parameters, it would be possible to accelerate the $Z = 3$ carbon impurities to energies in excess of $100\,eV$ in less than $10\,\mu S$. These observations have been confirmed through accurate numerical integration of the particle's equations of motion. The role of the plasma sheath is considered and a simple Faraday shield design capable of mitigating both the cyclotron-harmonic interaction and the sheath effects is suggested. Implications of direct impurity heating in the vicinity of the Faraday shield for the case of low-frequency heating schemes such as the Alfvén wave heating are examined.

1. CYCLOTRON HARMONIC INTERACTION

We consider the linearized motion of a particle in a uniform magnetic field B_0 and an electric field $E(\vec{r},t) = \int d\vec{k}\, E(\vec{k}) \exp\{i(\omega t - \vec{k}\cdot\vec{r})\}$, where $\vec{k} = k_x\,\hat{x} + k_y\,\hat{y} + k_z\,\hat{z}$ and the hats represent unit vectors. Let $E_{r,l} = E_x \pm iE_y$, $k_\perp^2 = k_x^2 + k_y^2 = k_0^2 - k_z^2$, $\tan\psi = k_y/k_x$, and $\vec{k}\cdot\vec{r} = k_\perp r_g \sin(\omega_c t + \psi) + k_z v_z t$, 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

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

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.

The electric field spectrum $E(\vec{k})$ in Eq.(1) is weighted by the modulation factor $\mathcal{M} = J_n(k_\perp r_g)\exp(-in\psi)$. Since, in the case of the ICRF antenna near field, k_x is imaginary while k_y is real by definition, ψ assumes imaginary values. One obtains $\exp(-2i\psi) = (k_x - ik_y)/(k_x + ik_y)$. Writing $k_x = i|k_x|$, and for the case $k_y < 0$, $\exp(-2i\psi) = (|k_x| + |k_y|)/(|k_x| - |k_y|)$. For $|k_y| \gg |k_x|$, $\exp(-2i\psi) = -4k_y^2/k_\perp^2$. Approximating the Bessel function as $J_n(k_\perp r_g) \approx (k_\perp^n r_g^n)/(2^n n!)$ gives $\mathcal{M} \approx (i|k_y|r_g)^n/n!$.

For 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, Eq.(1) yields

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

Upon integrating the differential equation obtained after replacing r_g by $v_\perp/\omega_c$ in Eq.(2), one obtains

$$t_{10} \approx 1.9\eta^{1/2} Z^{1/2} \frac{B_0^2}{k_y^2 E_l} T_i^{-1/2} \ , \tag{3}$$

where t_{10} is the time required for a tenfold increase in the kinetic temperaure T_i defined as $T_i = (1/2)MAv_\perp^2/e$, measured in electron volts.

For the ASDEX fast wave ICRF heating at the fundamental hydrogen cyclotron frequency $\omega = \omega_{cH}$, impurity harmonic resonances C_5^{3+}, C_3^{5+}, and O_4^{5+} (the subscripts denote the cyclotron harmonic number while the superscripts stand for the particle charge) occur at some location along the azimuthal arc spanned by the antenna. The dominant among these is the $Z = 5$, third harmonic carbon resonance C_3^{5+}. For the ASDEX parameters, $B_0 = 2.5\,T$, $|k_y| \approx 10\,cm^{-1}$, corresponding to a $3mm$ gap between the adjacent Faraday shield conductors and $E \approx 300\,V\,cm^{-1}$, it would take the carbon impurity atom approximately $5.0\,\mu S$ to be accelerated from $1\,eV$ to $10\,eV$. In further $2.9\,\mu S$ and $0.5\,\mu S$, respectively, the particle will attain energies corresponding to $100\,eV$ and $1\,keV$, respectively.

In the case of the second harmonic heating at $\omega = 2\omega_{cH}$, the deuterium resonance D_5^+ would be the dominant harmonic resonance. Starting with $100\,eV$ energy, the deuterium ion will require about $60\,\mu S$ to be accelerated to $1\,keV$. The initial $100\,eV$ will have to be supplied via the sheath acceleration process.

In the foregoing examples it was assumed that the particle orbit possesses the optimal phasing with respect to the electric field for maximum acceleration.

These results have been confirmed through accurate 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).

A simple solution to the problem presented by the cyclotron-harmonic interaction might consist in using a Faraday screen consisting of thin, inclined vanes in the form of a Venetian blind (Fig. 2). E_y in this case is substantially uniform, thereby effectively suppressing the cyclotron-harmonic acceleration.

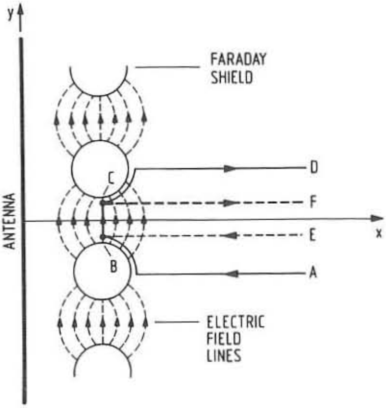

Fig.1 ASDEX antenna configuration

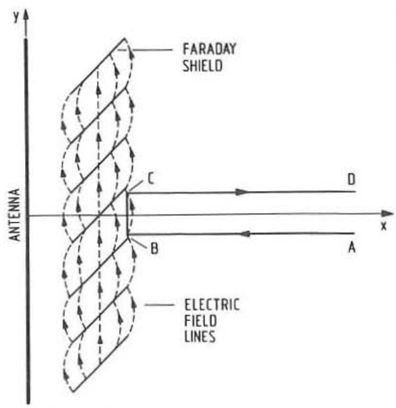

Fig.2 Venetian blind Faraday screen

2. PLASMA SHEATH EFFECTS

In the contour $ABCD$ (A, D, E and F extend to infinity) in Fig. 1, the electric field is primarily concentrated along BC and $\int E_{BC} \cdot dl \approx \int \mu_0 H \cdot da$, in the absence of a plasma sheath. If the contour $EBCF$ were to be used for estimating the electric field along BC, the diminished contribution of the magnetic induction is compensated for by the x-component of the electric field along EB and CF; which, of course, disappears in the presence of a plasma sheath, leaving only the magnetic induction component contributing to the field between BC, as was also the case in the absence of the Faraday shield. The missing electric field component along $ABCD$ reappears as the tangential electric field in the sheaths along the curved parts of the contour. Neglecting the small contribution to the magnetic induction from the induced Faraday shield currents [1], the following picture emerges in the presence of the sheaths:

(i) There is no material reduction in the electric field along BC in comparison with the field present in the absence of the Faraday shield.

(ii) The contributions from the contours ABE and FCD end up as sheath potentials (not necessarily symmetric). Together these potentials add up to the fields short-circuited by the Faraday shield conductors.

For the Venetian blind Faraday shield configuration of Fig. 2, since the short-circuited fields extend only over the thickness of the vanes, the sheath potentials would be correspondingly small. Thus the integration $\oint E \cdot dl$ along the contour $ABCD$ in Fig.2 is not materially affected by the introduction of the Faraday screen; the potential gradients making negligible contribution to the predominantly rotational electric fields.

3. IMPURITY ACCELERATION FOR LOW-FREQUENCY HEATING

For the low-frequency electric fields, the velocity gained by the particle in half a cyclotron period is given by $\Delta v_{\perp} \approx 2E_{\perp}/B_0$. This corresponds to an energy gain of

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

The energy gained in this case is independent of the degree of ionization and increases with A. Thus the low Z iron impurities could be accelerated to potentially damaging energies, unless care is exercised in limiting the electric field to

$$E_{\perp} \leq 7.1 \left(T_{max}/A\right)^{1/2} B_0 \, kV/m \; , \tag{5}$$

where T_{max} is the maximum admissible impurity ion energy. Assuming $T_{max} = 50\,eV$ corresponding to a sputtering yield of $< 1\%$ for the iron impurity ions, $E_{\perp} \leq 17\,kV/m$ for the ASDEX parameters, allowing a coupling of over $3\,MW$ per antenna. The recycling problem may be further alleviated by coating the Faraday screen with a low atomic weight material such as carbon.

4. DISCUSSION

Indirect evidence of cyclotron-harmonic acceleration is indicated by the selective etching of the Faraday shield at two symmetric azimuthal locations possibly corresponding to the third harmonic deuterium resonances for the case of $\omega = 2\omega_{cH}$ ICRF heating in ASDEX [2]. High energy deuterons, presumably generated in the edge region, have also been observed in ASDEX.

The large sheath potentials could also lead to a uniform sputtering of the Faraday shield by direct ion acceleration [3]. Under appropriate conditions, the sheaths could eject high energy ions which, in turn, would undergo rapid cyclotron-harmonic interaction. A better understanding of the role played by the sheaths must await availability of precise experimental data.

ACKNOWLEDGMENT

I am pleased to acknowledge the helpful suggestions offered by Prof. R. Wilhelm and Dr. D. W. Faulconer during the course of this work.

REFERENCES

[1] FAULCONER, D. W., J. App. Phys. **54** (1983) 3810.
[2] BEHRISH, R. (private communication)
[3] NEUHAUSER, J. (private communication)