Edge Plasma Heating via Cyclotron Harmonic Interaction

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Energy absorption in the edge region via cyclotron harmonic interaction during plasma heating with the ion-cyclotron range of frequencies is examined. It is shown that the electric field ripple caused by the closely spaced Faraday-shield conductors gives rise to large effective perpendicular wave numbers, resulting in strong cyclotron harmonic damping. For the parameters of the ASDEX tokamak, carbon impurity ions with $Z=5$ and an initial perpendicular energy of 1 eV could be accelerated to energies in excess of 1 keV in less than 10 μs (corresponding to about 100 cyclotron orbits).

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Ion-cyclotron range-of-frequencies (ICRF) plasma heating at high power levels is accompanied by edge heating, impurity production, and a rise in density. With use of two antennas with nickel- and chromium-coated Faraday screens, respectively, it has been demonstrated that the bulk of the metallic impurities originate from the Faraday shield of the excited antenna.[1] Large-scale sputtering of the Faraday-screen surface with enhanced etching at two azimuthally symmetrical localized regions has also been observed.[2] In this Letter I examine the possibility of the production of energetic ions in the vicinity of the Faraday shield via the cyclotron harmonic acceleration. A simple Faraday-shield design capable of mitigating the cyclotron harmonic acceleration will be presented.

Figure 1 shows the idealized antenna and the Faraday-shield configuration (the actual antenna is curved) used in the ASDEX ICRF heating experiments. The Faraday shield consists of 8-mm-diam cylindrical conductors separated by 3-mm gaps. The electric field vanishes along the conductor surfaces and is concentrated in the gaps between the conductors giving rise to a spatial modulation with the characteristic wave number $k_y \approx \pi/(3\ \mathrm{mm}) \approx 1000\ \mathrm{m}^{-1}$. The large k_y together with the large electric field ($E_{\mathrm{rms}} \approx 34$ kV/m, corresponding to an applied voltage of 17 kV across a 50-cm antenna section for the case of ASDEX) create the valid environment for the existence of cyclotron harmonic acceleration.

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

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

where $\mathbf{k}=k_x\hat{\mathbf{x}}+k_y\hat{\mathbf{y}}+k_z\hat{\mathbf{z}}$ and the carets 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

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

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

$$\Delta v_\perp=\tfrac{1}{2}\eta\exp(-i\omega_c t)\int d\mathbf{k}\textstyle\sum_n J_n(k_\perp r_g)\exp(-in\psi)$$
$$\times\int dt\,[E_r(\mathbf{k})\exp\{i(\omega+\omega_c-n\omega_c-k_z v_z)t\}+E_l(\mathbf{k})\exp\{i(\omega-\omega_c-n\omega_c-k_z v_z)t\}]\,, \tag{6}$$

where $\eta=Ze/MA$ is the charge-to-mass ratio and $J_n(k_\perp r_g)$ is the Bessel function of the first kind and order n. Equation (6) occurs in various contexts and is fundamental to the Bernstein[3] wave heating proposed earlier by the author[4] for the heating of toroidal plasmas. The present derivation parallels that of Hall and Sturrock.[5]

The electric field spectrum $E(\mathbf{k})$ 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[6] 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

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

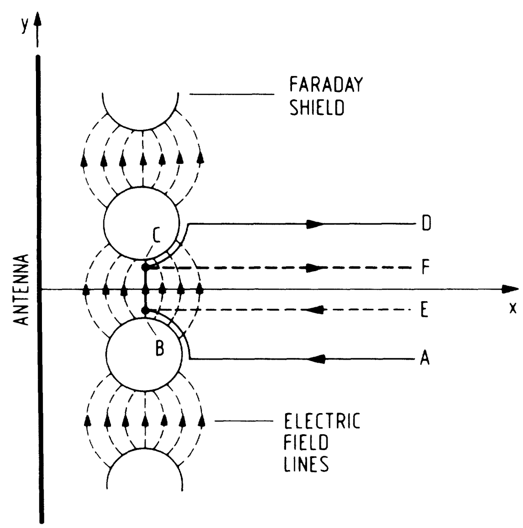

FIG. 1. Idealized antenna and Faraday-shield geometry for the ASDEX ICRF heating.

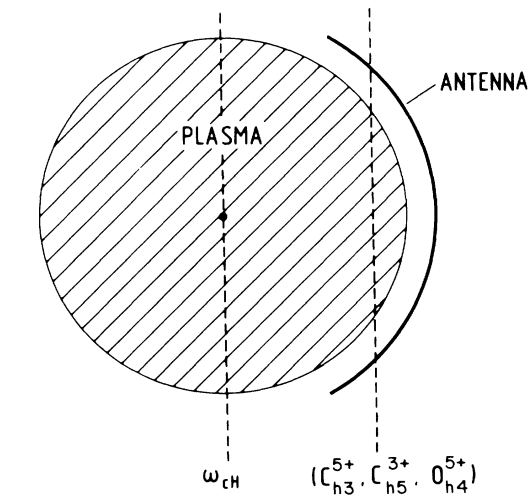

FIG. 2. Approximate location of the impurity harmonics near the outer plasma edge during the fundamental hydrogen cyclotron heating of ASDEX. The subscripts denote the cyclotron harmonic number while the superscripts stand for the particle charge.

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 y directions, respectively. For $|k_y| \gg |k_z|$, using Eq. (3) 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 occurring through $\exp(-k_x x)$ for $k_\perp \ll 1$ and the finite wavelength along y replace the role played by the perpendicular wave number 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

$$|\Delta v_\perp| \approx |0.25\eta(k_y r_g)^2 E_l|\Delta t. \tag{13}$$

Replacement of r_g with $v_\perp/\omega_c$ in Eq. (13) yields

$$\frac{dv_\perp}{v_\perp^2} = \frac{1}{4}\frac{k_y^2}{\eta B_0^2} E_l\, dt. \tag{14}$$

Integration of Eq. (14) gives

$$\frac{1}{v_{\perp i}} - \frac{1}{v_{\perp f}} = \frac{1}{4}\frac{k_y^2}{\eta B_0^2} E_l t, \tag{15}$$

where $v_{\perp i}$ and $v_{\perp f}$ are the initial and the final velocities, respectively. The above integration accounts for the changing gyroradius during the acceleration process. Upon substituting $v_\perp = (2eT/MA)^{1/2}$ and assuming that $T_f = 10T_i$, one obtains from Eq. (15)

$$t_{10} \approx 1.9\eta^{1/2} Z^{1/2} \frac{B_0^2}{k_y^2 E_l} T_i^{-1/2}, \tag{16}$$

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

I proceed to apply the result of Eq. (16) to the case of impurity acceleration during the fundamental hydrogen cyclotron frequency heating in ASDEX. The approximate locations of the impurity harmonic resonances C^{3+}_{h5}, C^{5+}_{h3}, and O^{5+}_{h4} (the subscripts denote the cyclotron harmonic number while the superscripts stand for the particle charge) are shown in Fig. 2. The dominant among these is the $Z=5$, third-harmonic carbon resonance C^{5+}_{h3}. For the 8-mm-diam Faraday-shield conductors with 3-mm gaps, $k_y \approx 1000$ m^{-1}. The static magnetic field near the plasma edge is approximately 2.5 T and the applied antenna field has the value $E_{\rm rms} \approx 34$ kV/m. The presence of the conducting Faraday-shield rods would tend to enhance the electric field in the gaps by the geometric factor $\gamma \approx (8+3)/3 = 3.67$. However, this geometric enhancement may be partly nullified by the plasma sheaths formed at the edge of the conductors. Because of the absence of any data, it is difficult to estimate the precise contribution from the sheaths. In the following estimates, I assume the electric field amplitude E_l to be 30 kV/m. For the case of third-harmonic acceleration, the carbon impurity atom with $Z=5$ would require approximately 5.0 μs to be accelerated from 1 to 10 eV. In a further 2.9 and 0.5 μs, respectively, the particle will attain energies corresponding to 100 eV and 1 keV, respectively. It has been 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 100 cyclotron orbits. The acceleration process could be readily initiated by particles with perpendicular energy ≥ 1 eV. Although no precise data exist, 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 ≈ 30 cm, the particles would require typically over 100 μs to traverse the antenna width.

These analytical results have been confirmed through accurate (checked by reverse integration) numerical integration of the particles' equations of motion in a steady, uniform magnetic field produced by application of a voltage across two infinite cylindrical conductors.

No direct experimental proof of the present theory exists. Indirect evidence, however, suggests that the impurities are produced at the Faraday shield in JET.[1] With use of two antennas with nickel- and chromium-plated Faraday shields, respectively, it is found that the metallic impurities originate from the Faraday shield of the excited antenna.[1] Examination of the ASDEX Faraday shield exhibits evidence of locally enhanced sputtering at two azimuthally symmetric locations possibly corresponding to the third-harmonic $Z=5$ carbon resonance.[2]

The severity of the cyclotron harmonic acceleration drops rapidly with the increasing impurity harmonic number and is of considerably less importance at the second-harmonic ($\omega = 2\omega_{c\rm H}$) heating. The problem will, however, return for the reactor relevant situations involving ICRF plasma heating at $\omega = 2\omega_{c\rm D}$ and $\omega = 2\omega_{c\rm T}$.

A simple solution to the problem created by the cyclotron-harmonic interaction would consist of our using the Venetian-blind Faraday-shield configuration of Fig. 3, provided the cooling problems could be resolved. Since the short-circuited fields extend only over the thickness

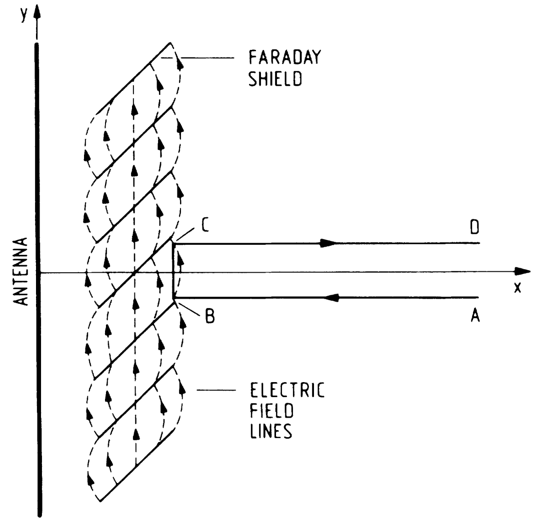

FIG. 3. Venetian-blind Faraday screen geometry.

of the vanes, the region available for the cyclotron harmonic interaction may be too narrow to support extended acceleration.

As already mentioned, plasma sheaths may modify these results in a significant fashion. Since the sheath thickness is of the order of the ion Larmor radius, sheath potentials would contribute an additional source of cyclotron harmonic acceleration because of the inevitable presence of strong electric fields with sharp gradients in the sheaths. k_y, in fact, could become large enough to support cyclotron harmonic interaction at higher harmonic numbers, thereby involving a much broader class of particles in the acceleration process.

Several processes, such as the nonresonant contributions to particle acceleration, stochastic effects due to phase randomization, collisions, guiding center drifts, 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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