Proposed physical model for very hot electron shell structures in electron cyclotron resonance–driven plasmas

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The localized shell-like hot electron layers in electron cyclotron resonance–driven plasmas are interpreted theoretically and justified experimentally as surfaces of absorption of Bernstein modes launched by the external microwave in the vicinity of upper hybrid resonance.

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I. INTRODUCTION

The appearance of very hot (10^3–10^6 eV) peripherical electron layers or shells during the electron cyclotron resonance (ECR) heating of plasmas in both axisymmetric [1,2] and nonaxisymmetric (minimum B) [3] magnetic mirrors has been well known for several decades. However, the physical nature of this specific phenomenon is not really understood. Efforts to give a physical interpretation of these extremely hot layers were typically made on the basis of the single particle model in which the plasma behavior is hoped to be understood by analyzing individual particle motion in the vacuum microwave and magnetic fields [4].

Indeed, such an approach is quite fruitful but only with the condition that the plasma density is so low that the internal collective fields do not perturb the vacuum fields. Typically this condition is not satisfied in actual plasma devices [5], so the single particle approach is difficult to justify. This paper aims to suggest a collective philosophy that is applicable in plasmas of any density [6,7] and for this reason is hopefully more appropriate for understanding the physical nature of the shell structures in the ECR-driven plasmas.

II. PHYSICAL MODEL

The main idea behind this approach consists of the following. The incident electromagnetic (EM) wave experiences a very strong retardation when approaching the resonant areas and, due to this retardation, enters into both temporal and spacial resonances with the electrostatic (ES) plasma waves, transferring to them their energy, and then practically disappears. The ES waves propagate in the plasma and are locally absorbed when approaching their own resonant areas, which generally do not coincide with the resonant areas for the incident EM wave. Due to the inhomogeneity of the plasma parameters, the absorption of the ES waves takes place on thin surfaces that are likely the shell-like figures, and results in the appearance of hot electron shell-like layers.

III. MODEL ANALYSIS

To justify this picture let us consider an extraordinary (X) EM wave entering a plasma and suppose the magnetic field to be inhomogeneous in the direction perpendicular to the magnetic lines. To couple with the ES waves, which also propagate across the magnetic lines [Bernstein (B) waves], the X wave should enter in the double resonance,

$$\omega=\omega_B , \tag{1}$$

$$k_X=k_B , \tag{2}$$

where ω and ω_B are frequencies, and k_x and k_B are wave numbers of the X wave and B wave, respectively.

Condition (1) is accomplished automatically because of the large spectrum of virtual plasma waves available to resonate with an external EM wave, but condition (2) is generally not satisfied because of the great difference between the phase velocities of the EM waves and ES waves. Indeed, the dispersion relation for X waves [8] and B waves [9] are, respectively,

$$1-(k_x c/\omega)^2=(\omega_p/\omega)^2(\omega^2-\omega_p^2)/(\omega_p^2+\omega_c^2-\omega^2) , \tag{3}$$

$$\begin{aligned}1+(k_B v_{\rm th}/\omega_p)^2=&\exp(-k_B^2 r_L^2)I_0(k_B^2 r_L^2)-2(\omega/\omega_c)^2\\ &\times\sum_q \exp(-k_B^2 r_L^2)\\ &\times I_q(k_B^2 r_L^2)/(q^2-\omega^2/\omega_c^2) .\end{aligned} \tag{4}$$

Here $v_{\rm th}$ is the electron thermal velocity, ω_p and ω_c are plasma and cyclotron frequencies, respectively, r_L is the electron Larmor radius, and I_q is the Bessel function of the first kind of imaginary argument, $q=1,2,\ldots$.

Since the ES-wave length is basically much shorter than the EM-wave length, condition (2) is likely to be satisfied if somewhere inside the plasma $k_B\to 0$ and $k_x\to\infty$ simultaneously. To verify whether such conditions are compatible with each other, we shall use the asymptotic expression for (4) at $k_B\to 0$, given by Bernstein [9], together with Eq. (3) in the form

$$k_x^2=(\omega/c)^2\{1+[1-(\omega_p/\omega)^2]/[1+(\omega_c/\omega_p)^2-(\omega/\omega_p)^2]\}\ , \qquad (5)$$

$$k_B^2=(\omega_c/v_{\rm th})^2[1+(\omega_c/\omega_p)^2-(\omega/\omega_p)^2]\ . \qquad (6)$$

It is seen from (5) and (6) that at the upper hybrid resonance (UHR) condition $(\omega/\omega_p)^2=1+(\omega_c/\omega_p)^2$ the X wave has a resonance ($k_x\rightarrow\infty$) while the B wave exhibits a cutoff ($k_B\rightarrow 0$). Thus, the necessary condition for the X-B coupling is perfectly satisfied near the UHR.

The condition for the X-B conversion is given by Eq. (2) so that we obtain from (5) and (6)

$$u^2=(k_{ox}r_L)^2(1+u-N)\ , \qquad (7)$$

where

$$u=1+(\omega_c/\omega_p)^2-(\omega/\omega_p)^2 \qquad (8)$$

is the UHR "detuning" for the optimum X-B conversion,

$$k_{ox}=\omega/c \qquad (9)$$

is the incident EM-wave number, and

$$N=n/n_{\rm co}\ , \qquad (10)$$

where c is the speed of light in free space, $n_{\rm co}$ is the cutoff density for a given ω.

In the case of nonrelativistic plasmas, $(k_{ox}r_L)^2\ll 1$. In this approximation at any plasma density, except for the values lying just around the cutoff density, the solution of Eq. (7) is

$$u=k_{ox}r_L(1-N)^{1/2}\ . \qquad (11)$$

Two interesting conclusions follow from the last equation. First, one concludes that the X-B conversion does not occur at densities exceeding the cutoff density. Second, the X-B conversion in underdense ($\omega_p<\omega$) plasmas occurs at magnetic fields larger than the value corresponding to the UHR but smaller than that for ECR. Thus, the incident EM wave, entering a plasma as an X wave, penetrates into the plasma until it reaches the gap between the ECR and UHR surfaces and then is converted into a B wave that is of purely electrostatic nature.

To determine the direction of propagation of the B wave that is born during the X-B conversion process, it is useful to examine the sign of the group velocity near the point of the X-B conversion. The group velocity can be derived from Eq. (6), since the conversion occurs near the UHR surface at which $k_B\rightarrow 0$. Then we have

$$v_{\rm gr}=-(\omega_p r_L)^2/v_{\rm ph}\ , \qquad (12)$$

where $v_{\rm ph}=\omega/k_B$ is the phase velocity of the B wave.

Since the group velocity is negative, one concludes that the B wave goes backward with respect to the incident X wave so that the UHR surface can be regarded as a reflecting barrier. However, as one knows from quantum mechanics, the reflecting barrier is efficient if it is thick, i.e., if the thickness of the barrier is much larger than the wavelength. In our case the situation is just the opposite: near the UHR the wavelength grows infinitely while the resonance zone is quite thin. In these conditions the B wave tunnels partially through the UHR surface so that the conversion area is an origin of two identical (but perhaps of different intensity) B waves: backward and forward waves, propagating in opposite directions. Let us now examine how the energy of these two B waves is transferred to the plasma electrons.

In our model the electrons are energized due to the B-wave dissipation in plasma. But, if a plasma is collisionless, as is the case in most ECR-driven plasmas, it is not obvious how the B waves transfer their energy to the electrons. As a matter of fact, as Bernstein has shown [9], the main collisionless mechanism of the ES-wave damping, the Landau damping, disappears if the wave is propagating across a magnetic field. However, Sagdeev and Shapiro have suggested [10] another collisonless mechanism that seems to be quite adequate in the case in which we are interested. The Sagdeev-Shapiro damping mechanism consists of an acceleration of the electrons in the direction perpendicular to the wave propagation direction across the magnetic field lines. Let us estimate the Sagdeev-Shapiro damping effect in our particular case.

The electrons that are trapped by the B wave move with the wave and experience some oscillations inside the potential well. For a rough estimate the oscillations can be neglected and only the averaged motion with the phase velocity of the wave $v_{\rm ph}$ must be taken into account. If the magnetic field is directed along the z axis and the wave propagates along the x axis, the electrons are accelerated along the y axis so that their motion is described by the equation

$$dv_y/dt=\omega_c v_{\rm ph}\ , \qquad (13)$$

from which we find the accelerated electron velocity

$$v_y=\omega_c v_{\rm ph}t \qquad (14)$$

and the acceleration electron energy

$$W=(mv_{\rm ph}{}^2/2)\omega_c^2t^2\ . \qquad (15)$$

We have supposed the initial velocity to be zero.

The acceleration lasts until the particle escapes from the potential well. To estimate this effect one should consider the oscillations of the particle along the x axis in the frame moving with the wave. These oscillations are described by the equation

$$dv_x/dt=-(e/m)E_0\sin k_B x-\omega_c v_y\ , \qquad (16)$$

where E_0 is the amplitude of the B wave.

The electrons that are trapped by the B wave are oscillating during the lapse of time while they are trapped. It means that they escape from the well when the right-hand side of Eq. (16) no longer changes its sign. It happens when the second term becomes equal to or larger than the amplitude of the first term, from where one obtains an estimate for the maximal attainable velocity

$$v_y^{\rm max}=eE_0/m\omega_c\ , \qquad (17)$$

the maximal attainable energy

$$W^{\max}=e^2E_0^2/2m\omega_c^2=\mathrm{mc}^2(4\pi P/v_{\mathrm{ph}}B^2)\ , \qquad (18)$$

and the time of acceleration

$$t_{\mathrm{acc}}=eE_0/m\omega_c^2 v_{\mathrm{ph}}=\mathrm{mc}^2(8\pi P/e^2B^4v_{\mathrm{ph}}^3)^{1/2}\ . \qquad (19)$$

Here we have expressed E_0 in terms of the energy flux density of the wave $P=E_0^2v_{\mathrm{ph}}/8\pi$.

It is seen from Eq. (18) that the Sagdeev-Shapiro damping should result in the appearance of electrons with the energies increasing "infinitely" if the wave is strongly retarded. This retardation occurs, as usual, around the surface where the wave experiences the resonances with the medium in which it propagates. To find the position of these resonant surfaces around which the energetic electron population is generated, one has to analyze the dispersion relation for B waves in its asymptotic form at $k_B\rightarrow\infty$. Using a standard development for the Bessel function we find from (4)

$$k_B^3v_{\mathrm{th}}^3=[\omega_p^2\omega_c/(2\pi)^{1/2}]\{1+2(\omega/\omega_c)^2 \times\sum_q[(\omega/\omega_c)^2-q^2]^{-1}\}\ . \qquad (20)$$

Equation (20) clearly shows that the B wave is strongly retarded when the cyclotron frequency is $1/q$ fraction of the wave frequency $q=1,2\ldots$. It means that both above B waves, which appeared as a result of the X-B conversion in the gap between the ECR and UHR surfaces, are propagating along the x axis in opposite directions and are each stopped at nearest ω/q-resonant surfaces. Due to the Sagdeev-Shapiro damping mechanism, as follows from Eq. (18), the very energetic electrons appear during this retardation. The result is the appearance of shell-like energetic electron layers. It is likely that in practice only two very energetic layers can be formed, even if several values of q are present in a given plasma. The reason is that a resonant surface is theoretically an impenetrable barrier for B waves, since both phase and group velocities, by definition ($k_B\rightarrow\infty$), are zero at the resonance [8].

The hot electron layers are quite thin because the electron acceleration, as follows from Eq. (18), takes place in the near vicinity of ω/q-resonant surfaces, and the diffusion of the accelerated electrons from the resonant surfaces is restricted by the magnetic field. Unfortunately, it is not possible in this work to compare $W^{\max}$ with the actual spectrum given in Fig. 3. The reason is that Eq. (18) contains two independent parameters: $W^{\max}$ and v_{ph}. Transforming (18) to the form $W^{\max}/mc^2=0.5(E_0/B)^2$ we conclude that the electrical field near the first Bernstein resonance amounts to about 200 kV/cm at the electron energy of around 100 keV when the magnetic field is about 1 kG.

An interesting physical effect can be expected as a result of the proposed model. Since the electrons are accelerated perpendicularly to both the magnetic field and the wave propagation direction, the accelerated electrons, in the case of the cylindrical geometry, form a strong azimuthal current that is diamagnetic or paramagnetic depending on which direction the B wave is propagating in. If several layers are produced, then the $B1$ layer rotates in the opposite direction to the others. Since the Sagdeev-Shapiro damping is the main mechanism of the incident EM energy coupling to the electrons, the energy accumulated in the hot layers is a major part of the energy infused in the plasma from the incident microwave. This is the reason why the use of the diagnostics based on the diamagnetic loops in the ECR-driven plasmas requires much precaution, because among shells there are diamagnetic ones and paramagnetic ones. The above picture is somewhat idealistic because the magnetic field in this case is homogeneous. When the magnetic lines are curved, for example, in the axisymmetric mirror traps, an effect such as hot electron rinds in the plasma should result and are observed [1,2].

IV. EXPERIMENT

The experiments have been performed in the negative ion ECRIS described elsewhere [11]. The ECR plasma was ignited in a vacuumated cylindrical cavity (128 mm in diam. and 84 mm long) under action of a cw microwave from a magnetron (2.45 GHz, 215 W). The experimental apparatus is schematized on Fig. 1.

Two disk shaped $SmCo_5$ magnets 55 mm in diam. were fixed on each side of the chamber coaxially with it to form a mirror structure inside the cavity. The mirror ratio was rather high ($R=3.2$) to create a strong radial inhomogeneity of the magnetic field within the cavity to form four well-resolved axially symmetric resonant surfaces corresponding to the ECR ($B1$ surface), the half ECR ($B2$ surface), the one third ECR ($B3$ surface), and the quarter ECR ($B4$ surface). The $B5$ surface was just near the wall. Figure 2 presents the shape of $B1$, $B2$, $B3$, and $B4$ surfaces (the numbers show the magnetic induction values in kG).

To detect hot electron shells we used an x ray and visible light produced by a small tungsten target (3×3 mm^2, 1 mm thick) which was movable along the radius in the midplane of the cavity. Both the x ray and visible light

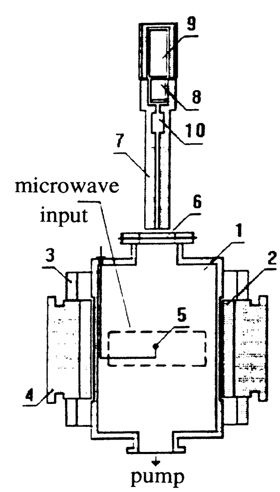

FIG. 1. Experimental apparatus: 1, microwave cavity (plasma chamber); 2, $SmCo_5$ magnets; 3, iron yoke; 4, magnet holder; 5, movable target; 6, plexiglass window; 7, x-ray telescope; 8, NaJ(Tl) scintillator; 9, photomultiplyer; 10, diffused x-ray trap.

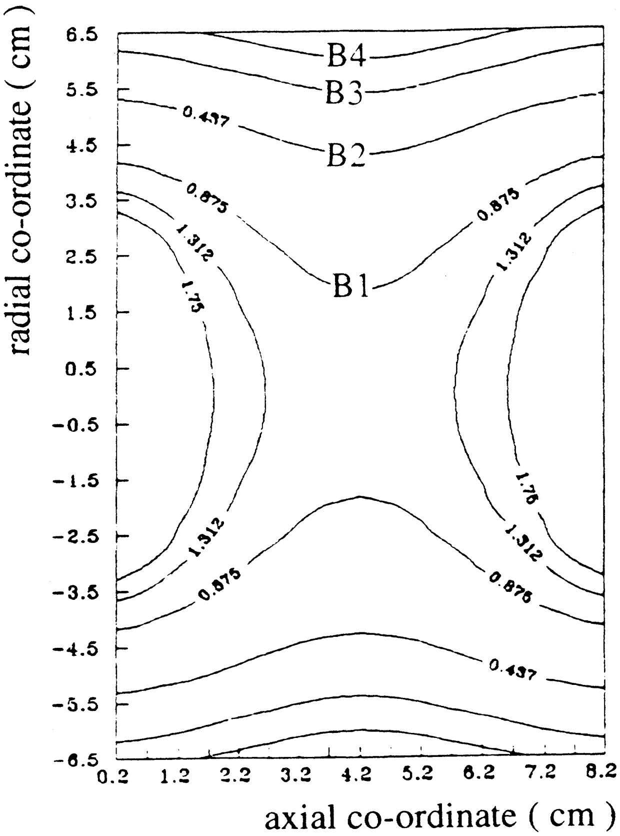

FIG. 2. Shape of $B1-B4$ surfaces. The midplane of the magnetic structure intersects the axis at 4.2 cm.

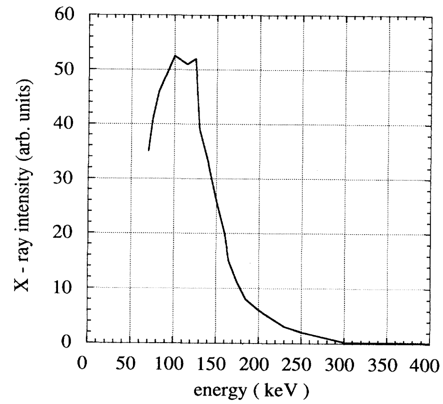

FIG. 3. Energy spectrum of bremsstrahlung from the target placed in the $B1$ shell.

were observed through the 5-mm-thick plexiglass sealed window. The x ray was detected and analyzed using a NaJ(Tl) scintillator followed by a 256-channel height-of-pulse analyzer. The visible light was observed visually or through a pyrometer, allowing an evaluation of the target temperature. The experiments were performed in hydrogen gas at a pressure of around 1.10^{-4} Torr.

Let us now describe the results of our observations and measurements. When the target is located exactly on the axis in the midplane of the cavity one observes the x-ray emission and a heating of the target up to about 1000 °C. However, when moving the target at a distance of 14 mm from the axis, the target is violently heated and destroyed during a fraction of a second. During this "explosion" of the target a strong x-ray emission with the energy centered around 100 keV is observed. This phenomenon always takes place when the target (its central point) is located between 14 and 18 mm from the axis. A typical x-ray spectrum obtained at a reduced microwave power (about 100 W) in this region is given in Fig. 3. Above 18 mm the x ray and the heating of the target become "normal": both are at a level slightly lower than on the axis.

When moving the target further along the radius, the x-ray level is low and the target remains cold. However, when reaching a distance of 38 mm from the axis the above phenomenon is reproduced. The x ray and the heating are also violent although slightly weaker: the x-ray spectrum is centered around 33 keV and the target is heated up to 2800 °C. The further displacement of the target towards the wall of the cavity results in a sharp decrease of the x ray and target heating at about 45 mm from the axis.

The next zone of the strong heating of the target is observed at a distance of 49 mm from the axis and lasts until the target touches the wall. The x ray is not observed in this case (which means that the energy of photons is lower than 10 keV: threshold determined by the plexiglass window) and the target temperature is 1400 °C.

Figure 4 shows the zones of very strong energy fluxes on the target when moving from the axis towards the wall. The radial distribution of the magnetic field is also given in this picture. One clearly sees that, in agreement

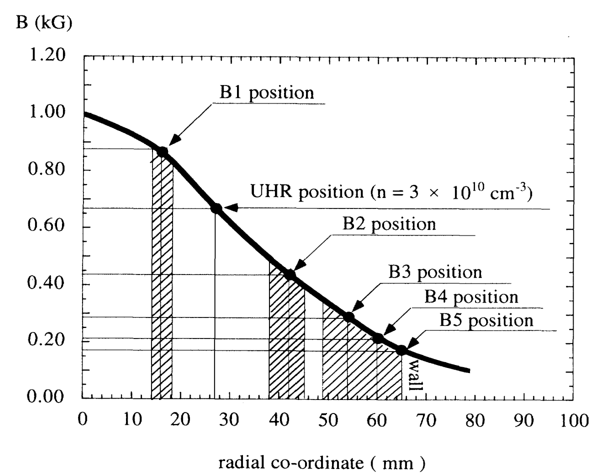

FIG. 4. Hot zones (dashed) detected by the target moving along the radius. The solid curve represents the radial distribution of the magnetic field in the midplane. The broken arrows show the points on the radius corresponding to 1st...5th cyclotron harmonics resonating with the incident frequency. The straight arrow shows the point on the radius where the UHR occurs.

with the above model, a high density of energy shells, which are produced on a background of cold plasma, are centered just around the cyclotron harmonics.

It was observed also that if the target is placed at 7–9 mm away from the external limit of the nearest to the axis hot zone, the hot shell structure disappears. The target in this case remains cold and the x ray is not observed. If one supposes that the upper hybrid resonance occurs in this place, then the plasma density in this region should be 3×10^{10} cm^{-3}. We have used the target as a Langmuir probe to measure plasma density in this region (in this case the target support was covered by a thin quartz layer, and the target was turned to be perpendicular to the field lines). The plasma density value yielded by the probe measurements was 2×10^{10} cm^{-3}. We consider this value as being in satisfactory agreement with the above estimated value.

Finally, we have attempted to observe the rotation of hot electron shells in the azimuthal direction. For this purpose we have constructed a sandwichlike probe, composed of two identical 3×3 mm^2 Tungsten plates separated by a thin layer of mica, which allowed us to measure electron current from each sandwich face independently. The measurement was made at reduced microwave power (<50 W) in order to reduce the probe heating.

Comparing electron current received by either probe face we have clearly observed that all the shells are in rotation around the axis. We have also determined that the $B1$ shell exhibits a rotation in the direction opposite to the direction of rotation of the rest of the shells, $B2$, $B3$, and $B4$.

V. CONCLUSIONS

The experimental results, taken as a whole, support the proposed collective model of coupling between the ECR plasma and the incident EM wave. In particular, the following theoretical conclusions from the collective model are in agreement with the experimental results:

(i) The incident EM wave entering ECR plasma across the magnetic field is absorbed in the vicinity of the UHR surface, but this area remains cold.

(ii) The energy deposited on the UHR surface is transported out of this area in the form of the Bernstein wave; this wave is absorbed on the surfaces on which the cyclotron harmonics, including the fundamental one, are in resonance with the incident microwave frequency.

(iii) The absorption of the Bernstein wave on the cyclotron harmonics surfaces is visibly the Sagdeev-Shapiro mechanism.

The adopted physical model predicts that an extraordinary EM wave is basically not able to heat a plasma in the volume. The ECR heating by an extraordinary wave, according to this model, results in the appearance of a series of very hot electron shells that are separated from the much colder bulk plasma by the magnetic field. In these conditions, the heating of the bulk plasma can only be provided by an EM wave entering the plasma along the magnetic lines. As was proposed earlier by one of the authors [12], such waves are converted near the ECR surface into the nonlinear Langmuir waves which, in turn, are heating the bulk plasma through the nonlinear mechanisms.

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