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SIMULATION OF ION CYCLOTRON RESONANCE HEATING THROUGH RESONANT ABSORPTION IN TWO-ION SPECIES PLASMA

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Abstract

Particle simulation of two-ion hybrid cyclotron resonance heating (ICRH) of a magnetized hydrogen plasma with deuteron minority by magnetosonic waves launched from the low magnetic field side is reported. Depending on the minority concentration, partial transmission and partial reflection of the incoming waves off the two-ion hybrid resonance layer occur, in contrast to the mode conversion mainly taking place during incidence from the high field side. Preferential minority heating is observed, as the minority cyclotron resonance is close to the two-ion hybrid resonance layer.

I. Introduction

We study a numerical simulation of two-ion hybrid resonance heating that plays an important practical role in many experiments of ion cyclotron resonance heating in tokamaks and stellarators [1,3]. In a paper [4], which discussed the results of numerical study of two-ion hybrid resonance heating, Riyopoulos and Tajima observed mode conversion of magnetosonic wave that is excited by a current sheet and is propagating across the magnetic field into the two-ion electrostatic modes. The interaction of plasma ions with strong electrostatic oscillations leads to efficient heating of plasma ions. The results of Ref. [4] were obtained with hydrogen ion (H) as minority and deuteron (D) as majority. In the case of fast magnetosonic wave excitation from the high magnetic field side, the electromagnetic wave attains the ion-ion hybrid resonance region before the minority cyclotron resonance, being mode-converted to the ion-ion short-wavelength electrostatic mode. In this case efficient heating of both majority (D) and minority (H) ions is observed. The rates of heating depend mainly on relative concentrations and the ion plasma to cyclotron frequency ratios, but in fact are not very different for both ion species. The plasma fluctuations excited through the complete mode conversion of the incoming magnetosonic mode to the ion-ion electrostatic mode cause strong velocity space diffusion for both ion species. The wave incidence from the low field side, on the other hand, shows preferential minority heating and much smaller heating of majority ions. This is because for the case of low field side excitation the wave encounters the minority cyclotron resonance layer *before* the ion-ion resonance layer. In this case, consequently, effective minority heating connected with usual ion cyclotron resonance absorption takes place. A reflection of the incoming magnetosonic mode takes place at the cut-off layer, located between the minority cyclotron resonance and the ion-ion hybrid resonace, instead of a mode conversion to the ion-ion-hybrid mode.

II. Low-field Side Excitation of ICRH

In the present paper, we consider an experimentally created scenario of low field side excitation during recent ion-cyclotron resonance heating (ICRH) experiments in the T-10 tokamak [3]. The wave propagates perpendicular ($k_{\|} \simeq 0$) to the magnetic field in a two-ion species plasma with hydrogen, as a majority and deuteron as a minority. This case differs from to the low field side launching of Ref. [4] in that the heavy ion (D), rather than the light (H), is now the minority and that, therefore, the sequence between ion-ion hybrid and minority cyclotron layers is reversed. The profiles of the majority and minority cyclotron frequencies across the varying magnetic field are shown in Fig. 1. The ion-ion hybrid frequency curve is given by

$$\omega_{ih} = \Omega_\alpha \left(\frac{\omega_\beta^2}{\omega_\alpha^2} + \frac{\Omega_\beta^2}{\Omega_\alpha^2} \right)^{1/2} \left(1 + \frac{\omega_\beta^2}{\omega_\alpha^2} \right)^{-1/2}, \qquad (1)$$

where ω_α, ω_β are the ion plasma frequencies and Ω_α, Ω_β are the ion cyclotron frequencies of the majority (α) and minority (β) ion species, respectively. According to Eq. (1) the ion-ion-hybrid frequency lies between the cyclotron frequencies for each ion species and falls much closer to the minority cyclotron frequency $\Omega_\beta \left(\omega_{ih} \to \Omega_\beta \text{ as } \frac{n_\beta}{n_\alpha} \to 0 \right)$. The ion hybrid layer x_{ih} and the cyclotron resonance x_β (x_D for the present case) are defined by $\omega_{ih}(x_{ih}) = \omega_p$ and $\Omega_\beta(x_\beta) = \omega_p$ respectively, with ω_p the pump frequency. Consequently during propagation from the low field side x_β is encountered before or after x_{ih}, depending on whether $\Omega_\beta = \Omega_H > \omega_{ih}$ or $\Omega_\beta = \Omega_D < \omega_{ih}$, respectively

According to the WKB theory [5] including the finite Larmor radius effects to the lowest order, the wave launched from the low field side (on the right in Fig. 1) encounters a cut-off layer x_c close to but before the ion-ion hybrid layer x_{ih}. A complete treatment [5,6] through the differential equation for propagation including warm plasma and inhomogeneity effects reveals that an almost total reflection of the incoming magnetosonic wave off the resonant regime and back towards the exciting antenna will occur in case $k_{\|} \cong 0$. Transmission and mode conversion into the ion-ion hybrid mode can be very small depending on the effective width of the non-propagation region between the cut-off and the resonance. This region gets narrower with decreasing minority content and a considerable tunneling-through may occur for small minority percentage. This aspect of the low field side incidence differs from the high field side incidence where mode conversion of the incoming radiation into the ion-ion hybrid mode rather than reflection or tunneling is the dominant outcome. It also implies that the wave does not reach the exact minority cyclotron resonance in the case with relatively high percentage of deuteron as minority.

III. Electromagnetic Particle Simulation

The present investigation is based on the fully self-consistent electromagnetic particle code with electrons treated as guiding centers in order to eradicate the excessive noise that would otherwise arise due to electron thermal motions [4]. The full ion dynamics is followed in our simulation. The system is 1-$\frac{1}{2}$ dimensional (one spatial and two velocity space coordinates) with absorbing boundaries in the x-direction [7]. We investigate two cases of relatively large and small minority concentration.

Figure 2(a) represents time dependence of Poynting vector for the following set of parameters:

$$B(x) = \frac{B_0}{a+x} \quad , \quad \frac{m_{\text{maj}}}{m_{\text{min}}} = 0.5 \quad , \quad \frac{T_{\text{majo}}}{T_{\text{mino}}} = 1 \quad , \quad \frac{n_{\text{maj}}}{n_{\text{min}}} = 9,$$

corresponding to $\omega_p = 1.076\Omega_D$ at the ion hybrid layer x_{ih}. From this picture an almost complete reflection of the incoming electromagnetic flux near the ion-ion resonance-cut-off region is observed. No significant conversion to the ion-ion hybrid mode is observed as the electrostatic field profiles indicate no activity significantly above noise levels. The increase of the electromagnetic energy tapers off at time $t \cong 180\omega_{pH}^{-1}$, which is the arrival time of the wave near the hybrid layer, as shown in Fig. 3(a)-3(b). Beyond this time the stored energy changes a little bit slower, since the wave can not penetrate further to the left and the net incoming flux is balanced by particle heating. The electrostatic energy keeps increasing in accordance with the increasing level of thermal fluctuations caused by the increasing temperature. There is only a small amount of electromagnetic transmission through the middle as shown in Fig. 2(a). The phase space plots v_x *vs.* x at the end of the run (Fig. 3(e)-3(f)) show the ion response to the pump wave. There is little activity on the left of the resonance-cut-off layer as expected. The heating rate for the ions is shown in the energy versus time plots in Fig. 3(c)-3(d) in comparison with the field energy density history. In spite of the near total reflection ion heating takes place. The relative increase in deuteron temperature is 50% over a time span of 10 cyclotron periods. We observe a relative increase in temperature ($\Delta\varepsilon_D/\varepsilon_D \simeq 1.5$) rate three times faster for deuteron than for hydrogen, although more absolute amount of energy goes into majority ions. A physical interpretation of this phenomenon is the following: Nonlinear particle trapping combined [4] with quasilinear diffusion due to enhanced turbulence heats the minority (D) more effectively than majority as the wave frequency near the hybrid resonance is close to the minority cyclotron frequency.

We show the results of a similar case of lower minority concentration $n_{\mathrm{maj}}/n_{\mathrm{min}} = 39$ in Figs. 2(b) and 4(a)-4(d). It is obvious from the electromagnetic Poynting flux plot of Fig. 2(b) that a significant wave penetration to the left of the cut-off region takes place with the wave propagating all the way to the left boundary. The stored electromagnetic energy does not saturate until $t \sim 300\omega_{pH}^{-1}$, roughly the arrival time at the left boundary. The majority and minority phase plots 4(c) and 4(d) at the end of the run $t = 418\omega_{pH}^{-1}$ verify propagation to the left half, as opposed to Figs. 3(e) and 3(f). As the wave now reaches the deuteron cyclotron layer, it causes intense selective heating of the minority. The relative increase in deuteron temperature is $\Delta\varepsilon_D/\varepsilon_D = 2.5$ over ten cyclotron periods, much larger than in the previous case. The total (combined) ion energy absorption however is not significantly different in both cases. In contrast, in case of hydrogen minority in a deuteron background when the minority cyclotron resonance always falls to the low field side of the two ion hybrid layer, similar, but even stronger, preferential minority heating has been observed numerically.

IV. Discussion

It has been suggested that buildup of temperature difference, combined with the local counter-drifting between the two ion species under the influence of the wave, may trigger velocity space instabilities [8] when T_D/T_H becomes large. This will result in an effective redistribution of the deuteron energy into the hydrogen ions on a time scale much faster than the Coulomb collision time scale.

The anomalous heating of plasmas containing two ion species has been observed to date in stellarators [1,2] and tokamaks [3] during generation of intense ICRH and fast magnetosonic waves; in a rotating plasma under the conditions of crossing electric and magnetic fields [10]; in mirrors during the buildup of ion-ion instabilities [11,12]. Considerable enhancement in neutron production, attributed to the heating of the minority ions of the beam, was recently reported in combined beam – ICRH heating experiments in JET [13].

The experiments on Uragan [1,2] were designed to study the heating of $H + D$ plasmas with Alvén waves of moderate power coupling ($\sim$ 300 kW). The plasma density $(4 + 10) \times 10^{12}\mathrm{cm}^{-3}$ was achieved by resonant wave excitation across a broad range of the longitudinal magnetic field strength $B_0 = (5 + 20)$kG. Provided that the conditions are met for IC-resonance of deuterium ions ($\omega \approx \omega_{CD}$, $B_0 = 13$kG), the ions of hydrogen ($T_H < 1$ keV at $\tilde{n} \sim 10^{12}\mathrm{cm}^{-3}$) were found to heat up anomalously fast (less than 1 ms). The measured times of proton heating were less than those of energy exchange between the ions of H and D by far on account of Coulomb collisions ($t_0 \sim 4$ ms at $\tilde{n} \sim 4 \times 10^{12}\mathrm{cm}^{-3}$, $T_D \geq$300 keV). The fluctuational magnetic field strength in the IC-resonance region being 15G, the deuterons in the wave field picked up the directional speed $\varphi_{\perp D} = \kappa_{\|} c\tilde{B}/4\pi n_D e \sim 4 \times 10^7$cm/sec in excess of the thermal one $v_{tD} \sim 10^7$cm/s). Such conditions are conducive to growth of a microscale ion-ion instability whose phase of saturaton is peculiar for high level turbulent pulsations. Scatter of both the ion species upon pulsations leads to an effective collisionless heating of the ions.

The paper [11] gives the results of experiment on growth and saturation of the ion-

ion instability in a mirror ($\emptyset = 60$ cm, $L = 120$ cm). The plasma volume is separated with a double negative potential mesh (tandem mirror). The experiments were run in a cold ($T_0 \sim$ 7 eV) low density ($\bar{n} \sim 10^8$ cm^{-3}) plasma. Changing the potential sign of the guiding mesh brought the beam of ions into the "target" plasma with a velocity close to the ion acoustic one. Such procedure discovered density wells of the space scale $L \sim (5 + 10)$ cm$\sim 100\lambda_{pi}$ and associated long time-of-life structures (vortices) ($D \sim 50\omega_{pi}^{-1}$) localized in phase space which is indicative of trapping of the bulk of ions by the unstable wave electric field. The measurements of the ion velocity distribution function is a direct experimental evidence of ion trapping, bringing to light a rise in the velocity range corresponding to the central part of the cortex.

Worth specific reference are the results of experimental program on rotating plasma [10] and a triple mirror [12] which also attested to ion-ion instability growth and anomalous heating of ions.

Acknowledgments

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Figure Captions

Fig. 1 The one-dimensional plasma model in our simulations. Shown are the ion cyclotron frequency profiles and the two-ion hybrid frequency ω_{ih} profile as a function of the distance x/L. The line $\omega{=}\omega_{\rm pump}$ matches the local ω_{ih} at $x{=}0$. The deuteron cyclotron resonance point is also within the simulation system ($x{=}x_D$).

Fig. 2 The x component of the Poynting vector $S_x{=}cE_y \times B_z$ as a function of x at time $t{=}418\omega_{pH}^{-1}$. The antenna is located at $x{=}950\Delta$ and the compressional Alfvén wave is launched from the weak field side. (a) Case of higher minority concentration $n_D/n_H{=}1/9$ shows almost complete reflection. The cut-off point x_c would be at $x_c{=}658\Delta$ according to the WKB theory, very close to $x_{ih}{=}614\Delta$. (b) Lower minority concentration $n_D/n_H = 1/39$ shows significant tunneling and partial reflection. $x_c{=}627\Delta$ by the WKB theory, while $x_{ih}{=}614\Delta$.

Fig. 3 Time history of field energies and ion temperatures during ICRH ($t{=}0 - 400\omega_{pH}^{-1}$) for $n_D/n_H{=}1/9$. (a) The electrostatic field energy $E_L^2/4\pi$. (b) the transverse electric field energy $E_{\rm tra}^2/4\pi$. (c) majority (hydrogen) ion kinetic energy ε_H. (d) minority (deuteron) ion kinetic energy ε_D. (e) (p_x, x) phase space plot hydrogen at $t{=}418\omega_{pH}^{-1}$. (f) (p_x, x) space plot of deuteron at $t{=}418\omega_{pH}^{-1}$.

Fig. 4 Time history of ion temperatures during ICRH ($t{=}0 - 400\omega_{pH}^{-1}$) for $n_D/n_H{=}1/39$. (a) majority (hydrogen) ion kinetic energy ε_H. (b) minority (deuteron) ion kinetic energy ε_D. (c) (p_x, x) space plot of hydrogen at $t{=}418\omega_{pH}^{-1}$. (d) (p_x, x) space plot of deuteron at $t{=}418\omega_{pH}^{-1}$.

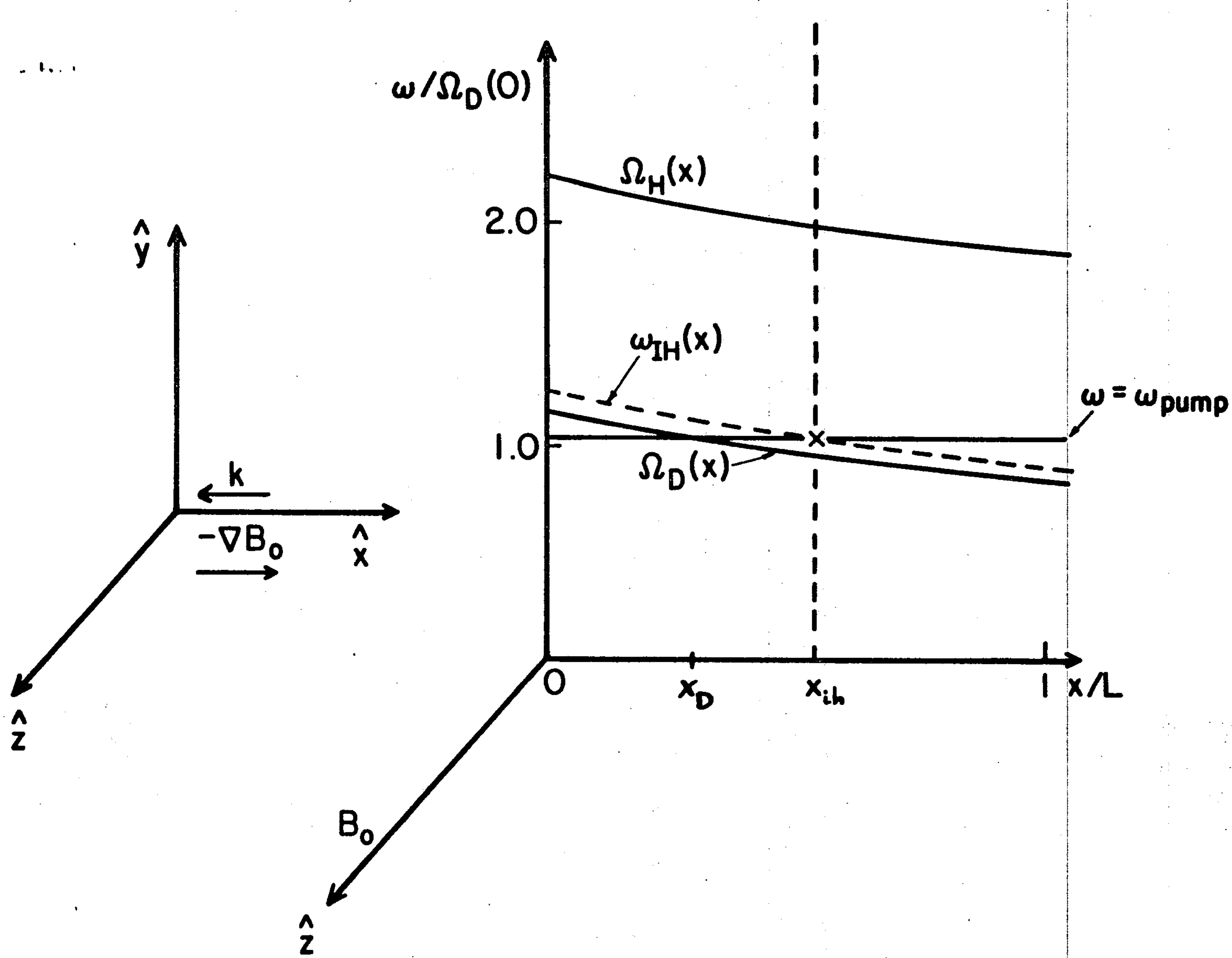


Fig. 1

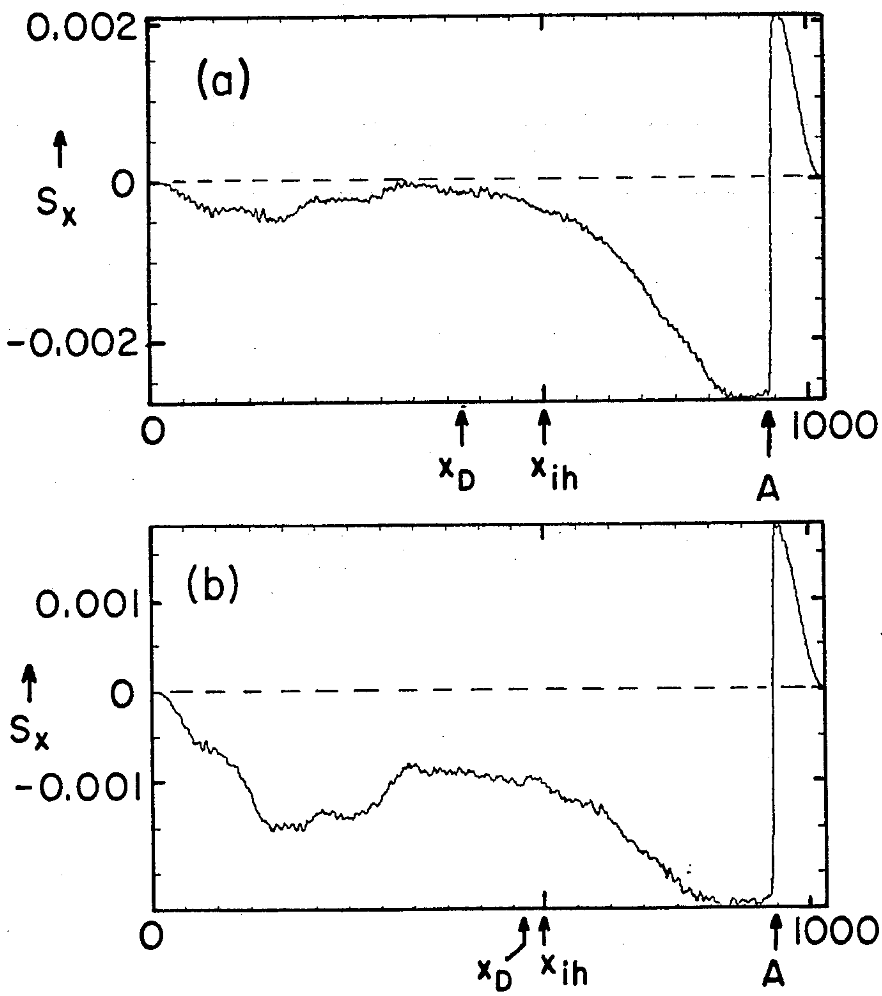


Fig. 2

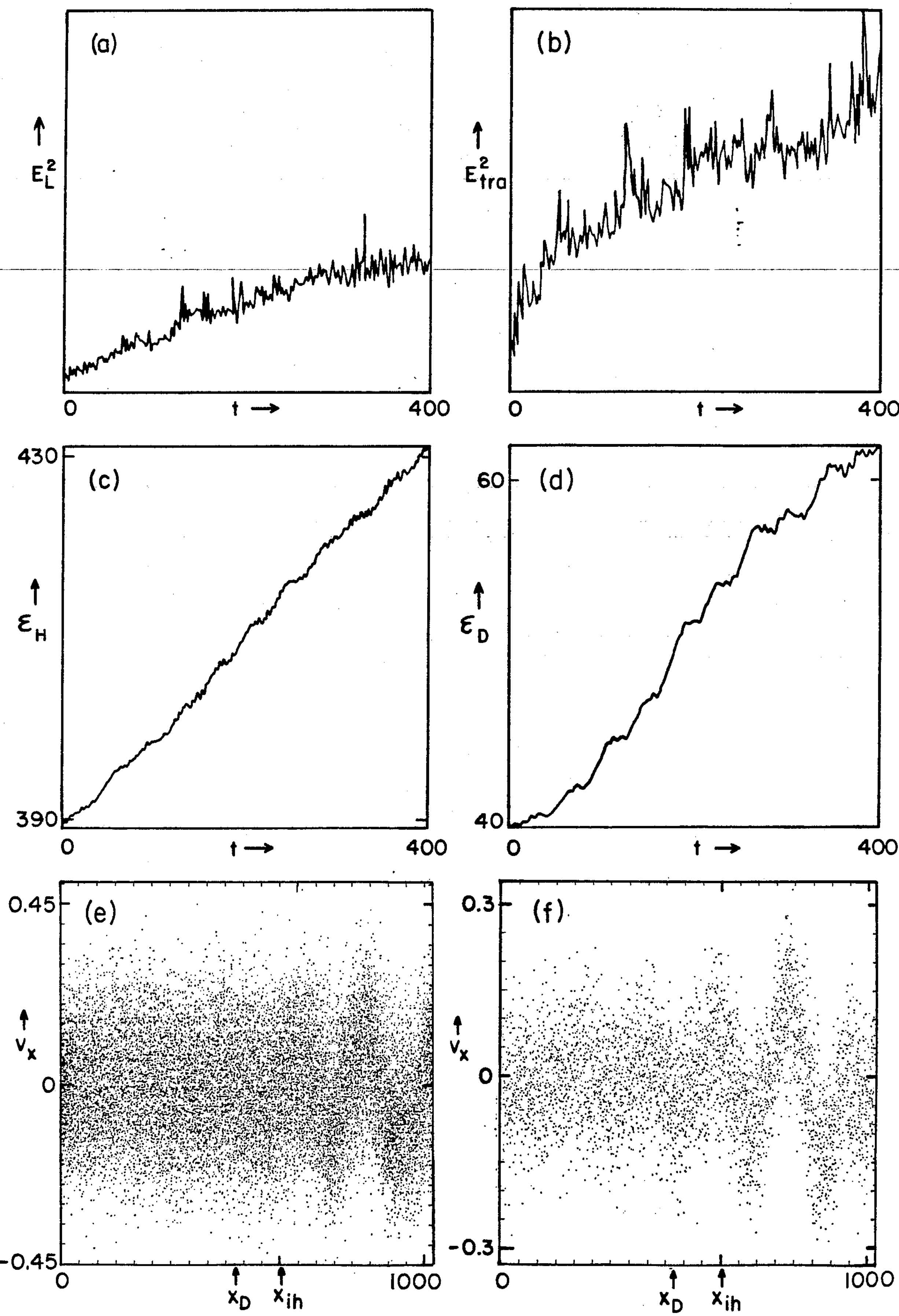
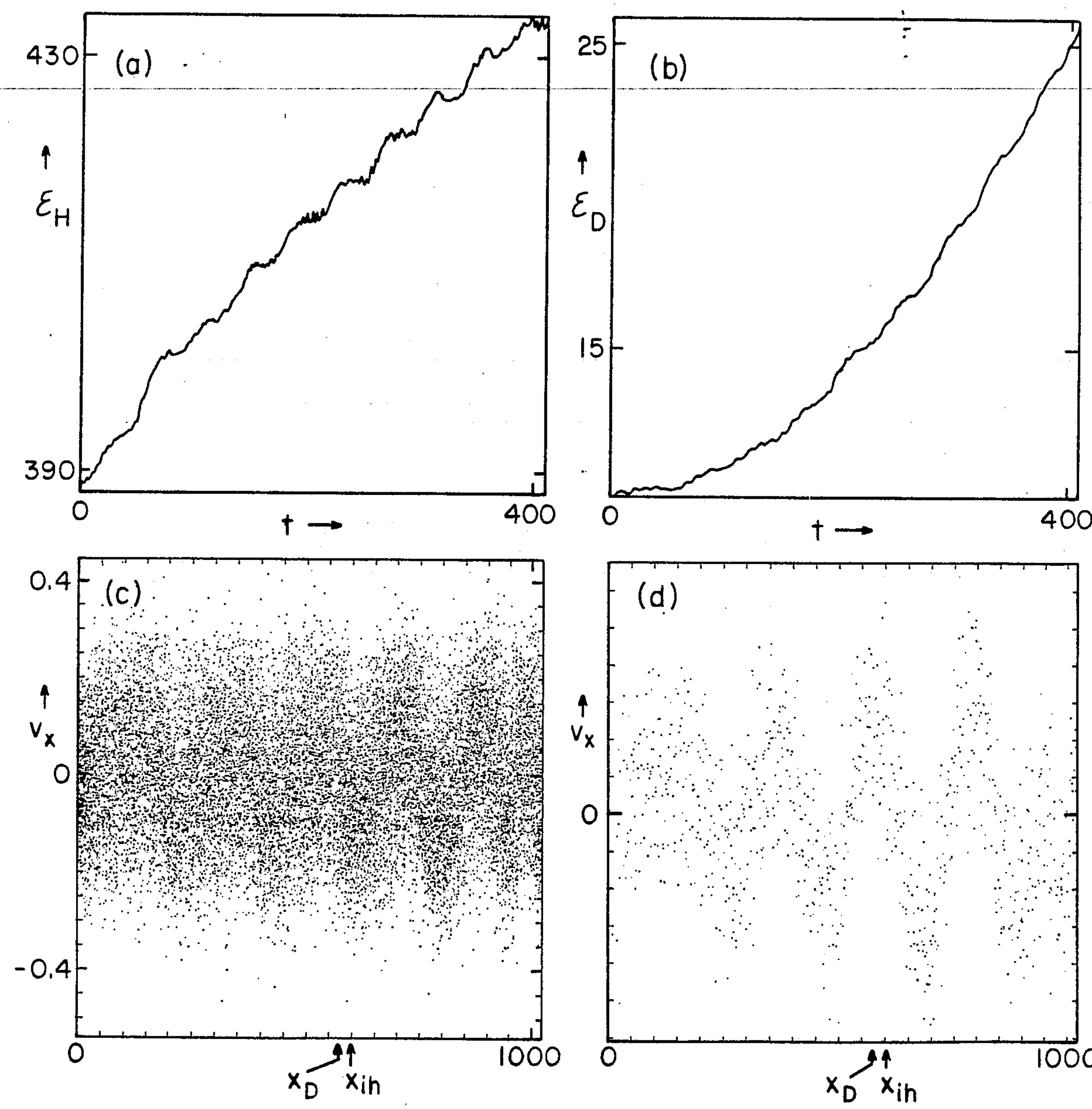

(a)
E_L^2
0
t →
400
(b)
E_{tra}^2
0
t →
400
430
(c)
ε_H
390
0
t →
400
60
(d)
ε_D
40
0
t →
400
0.45
(e)
v_x
0
-0.45
0
x_D
x_{ih}
1000
0.3
(f)
v_x
0
-0.3
0
x_D
x_{ih}
1000

Fig. 3



430
390
(a)
$\mathcal{E}_H$
0
t
400
25
15
(b)
$\mathcal{E}_D$
0
t
400
0.4
0
-0.4
(c)
v_x
0
1000
x_D
x_{ih}
(d)
v_x
0
0
1000
x_D
x_{ih}

Fig. 4