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Excitation of chorus-like waves by temperature anisotropy in dipole research experiment (DREX): A numerical study*

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Due to their significant roles in the radiation belts dynamics, chorus waves are widely investigated in observations, experiments, and simulations. In this paper, numerical studies for the generation of chorus-like waves in a launching device, dipole research experiment (DREX), are carried out by a hybrid code. The DREX plasma is generated by electron cyclotron resonance (ECR), which leads to an intrinsic temperature anisotropy of energetic electrons. Thus the whistler instability can be excited in the device. We then investigate the effects of three parameters, i.e., the cold plasma density n_c, the hot plasma density n_h, and the parallel thermal velocity of energetic electrons, on the generation of chorus-like waves under the DREX design parameters. It is obtained that a larger temperature anisotropy is needed to excite chorus-like waves with a high n_c with other parameters fixed. Then we fix the plasma density and parallel thermal velocity, while varying the hot plasma density. It is found that with the increase of n_h, the spectrum of the generated waves changes from no chorus elements, to that with several chorus elements, and then further to broad-band hiss-like waves. Besides, different structures of chorus-like waves, such as rising-tone and/or falling-tone structures, can be generated at different parallel thermal velocities in the DREX parameter range.

Keywords: dipole research experiment (DREX), chorus-like waves, temperature anisotropy

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1. Introduction

Chorus waves are whistler mode emissions, which can be commonly observed in the inner magnetosphere and play dominant roles in the radiation belts dynamics.[1–7] The frequency of chorus waves is in the range of electron gyro-frequency in the radiation belts. Thus they can exchange energy with electrons effectively via cyclotron resonances. This mechanism may then explain the enhancement of relativistic electrons in the magnetic storm recovery phase.[8,9] Such waves are also believed to scatter electrons into the loss cone, which may lead to a precipitation of $\sim$ keV electrons.[10] Ni *et al.* have demonstrated that the formation of the diffuse and pulsating auroras is a result of such precipitation.[11,12] Besides, chorus waves are also supposed to be a cause of the formation of pancake-like electron distributions.[13]

A chorus spectrum generally consists of two bands separated by a gap near the half of the electron gyro-frequency with discrete chirping elements,[14,15] including rising and/or falling tone structures. The two bands have different propagation properties. For example, the lower band is dominated by electromagnetic waves along the ambient magnetic field lines, while the upper band is highly oblique quasi-electrostatic waves.[16,17]

Chorus waves are under further investigation in observations, simulations, as well as ground experiments. Various theoretical and simulation models have been proposed to explain their characteristics in recent decades. A linear theory proposed by Kennel described the amplitude in the initial stage of the whistler instabilities,[18] and nonlinear models were then offered for the nonlinear evolution of these instabilities. For example, Omura *et al.* obtained the nonlinear wave growth rate in a parabolic ambient magnetic field.[19] They also carried out a series of simulations to explain the formation of the falling tone and the gap. Schriever *et al.* suggested that the lower band chorus might be the result of wave–wave coupling while the upper band was driven by anisotropic electrons in hundreds of eVs.[20] Liu *et al.* demonstrated that the two bands were excited by two distinct anisotropic electron populations via a two-dimensional (2D) particle-in-cell (PIC) simulation.[21] However, these models need to be further validated by observations or experiments. Actually some experiments were attempted to excite whistler waves in near-earth space environments. In such an experiment carried out by Helliwell in 1983,[22] coherent very low frequency (VLF) signals were launched into the Earth's magnetosphere, and amplified by about 30 dB with narrow-band whistler mode emissions being triggered. It was indicated that the results were

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caused by wave–electron cyclotron resonance. Also in the high-frequency active auroral research program (HFAARP), extremely-low-frequency (ELF)/VLF waves were generated in the magnetosphere,[23] and the triggered emissions were mostly observed under the quiet magnetospheric conditions.

On the other hand, additional to satellite/ground observations and numerical simulations, ground experiments also play an important role in the investigation of chorus waves. Various types of laboratory simulation devices have been built to investigate the fundamental physical processes in the magnetosphere plasmas, such as the large plasma device (LAPD) at University of California, Los Angeles (UCLA) and the collisionless terrella experiment (CTX) at Columbia University. In LAPD experiments, a beam of electrons was launched into the device to generate chorus-like waves with rapid frequency chirping.[24] With different plasma parameters, the spectra of the chorus-like waves showed various structures. In CTX experiments, radial and azimuthal mode structures of plasma waves were excited either by hot electron instabilities or by a broad-band antenna, while a population of energetic electrons was created using electron cyclotron resonance heating.[25]

An experimental device specially designed for simulating radiation belt physics, dipole research experiment (DREX), is under construction at Harbin Institute of Technology (HIT) in China,[26–28] as an important component of China major state facility for fundamental research, space environment simulation research infrastructure (SESRI). It is designed to simulate the basic physical processes in the near-earth space environment by scaling plasmas in laboratory with that in space, and aims to study wave–particle interaction of energetic particles in the radiation-belt-like plasmas. Since chorus-like waves are crucial for such processes, numerical simulations are needed to predict whether the waves can be excited under the designed parameters of DREX. In this paper, we carry out a numerical research with DREX parameters and designed experiment conditions using a hybrid code to study chorus-like waves' excitation process and their characteristics.

The rest of the paper is organized as follows. We describe the simulation code, DAWN, and simulation setup in Section 2. Numerical results are then presented in Section 3. The paper is summarized in Section 4.

2. Simulation setup

We here use a hybrid code named DAWN[29] to simulate the wave excitation in DREX. The ions are assumed to be fixed due to their slower time scale compared to that of electrons. The cold electrons are modeled by a group of linearized fluid equations, and the hot energetic electron populations are handled by PIC schemes. The distribution of the hot electrons is assumed to be bi-Maxwellian with a number density $n_{\rm h}$

$$f(u_{\parallel},u_{\perp}) = \frac{n_{\rm h}}{(2\pi)^{3/2}w_{\perp}^{2}w_{\parallel}}\,{\rm e}^{-0.5(u_{\parallel}^{2}/w_{\parallel}^{2}+u_{\perp}^{2}/w_{\perp}^{2})},$$

where $w_{\perp}$ ($w_{\parallel}$) is the thermal velocity perpendicular (parallel) to the background magnetic field, which is assumed parabolic as $B_{0z}(z) = B_{0z}(1+\xi z^{2})$, where $\xi = 4.5/(RL)^{2}$ is the inhomogeneity factor for a dipole magnetic field, R is the radius of the "planet", and L is the distance to the center of the planet on the equatorial plane. RL has a typical scale of $\sim$2 m in DREX. $u_{\parallel}$ ($u_{\perp}$) is the parallel (perpendicular) relativistic velocity of energetic electrons and f is the distribution function. A mirror-like field is applied as a reasonable approximation to the dipole field of DREX near the magneto-equator where our simulation is concentrated. The x and y components of the ambient field are chosen as $B_{0x} = -x({\rm d}B_{0z}/{\rm d}z)/2$ and $B_{0y} = -y({\rm d}B_{0z}/{\rm d}z)/2$ to make it divergence-free. Absorbing boundary condition is applied in our simulations, and the detailed description of the DAWN code can be found in Ref. [29].

The plasma in DREX is designed to be generated by an electron cyclotron resonance (ECR) source as well as a biased cold cathode discharge, which gives the energetic electrons an essential temperature anisotropy represented by the anisotropy factor A ($\equiv T_{\perp}/T_{\parallel}-1$). By varying the power of the ECR source, one can control the temperature anisotropy A in a wide range (e.g., from 1 to 20 or higher). The collisional frequency of the electrons with neutral particles is $\sim 10^{5}$ s^{-1} while the gyro-frequency of the electron is $\sim 10^{10}$ s^{-1}, which is much larger than the collisional frequency. Thus the plasma can be treated as collisionless in at least $\sim 10^{5}$ gyro-periods, while the simulation time in this work is $\sim$ 5000 gyro-periods (which is about the designed experiment duration). Therefore the electron is collision-free and the temperature anisotropy can be held in the simulation period to drive the whistler instability. There are mainly 3 parameters that can significantly influence the whistler instability, namely, the cold and hot plasma densities, as well as the parallel thermal velocity, according to Kennel.[23] Satellite observations have indicated that chorus waves have a higher occurrence rate outside the plasmasphere where the plasma density is lower. So the background cold plasma density may play a significant role in the generation of chorus waves. Under the DREX designed parameters, the gyro-frequency of electrons $\Omega_{\rm e0}$ is about 7.025×10^{9} s^{-1}, and the cold plasma density can be in the range of 10^{17}–10^{18} m^{-3}, with the plasma frequency $\omega_{\rm pe}$ of 2.5–8 $\Omega_{\rm e0}$. The maximum linear wave growth rate $\gamma_{\rm max}$, a significant parameter in the generation process of chorus wave, largely depends on $n_{\rm h}$ and $w_{\parallel}$. $\gamma_{\rm max}$ increases with the hot plasma density $n_{\rm h}$. The parallel thermal velocity can determine the frequency of the maximum wave growth rate $\omega(\gamma_{\rm max})$ and the number of electrons that are resonated with the waves. Effects of the three parameters will be investigated separately in the simulation by varying one while fixing the other two. The DREX plasma parameters and the simulation parameters are listed in Tables 1 and 2, where c is the speed of light.

Table 1. The plasma parameters in DREX.

Parameter	Value
Plasma density (n_e)	10^{17}–10^{18} m^{-3}
Radius (RL)	~ 2 m ($\sim 50c\,\lvert\Omega_{e0}\rvert^{-1}$)
Electron temperature (T_e)	1–100 eV
Magnetic field at the equator (B_0)	~ 0.05 T
Electron beta (β_e)	~ 0.1

Table 2. Common simulation parameters.

Parameter	Value
Cell size	$0.05c\,\lvert\Omega_{e0}\rvert^{-1}$
Number of cells	6554 ($\sim$300 $c\,\lvert\Omega_{e0}\rvert^{-1}$)
Number of masking cells	300
Time step	0.02 $\lvert\Omega_{e0}\rvert^{-1}$
Number of time steps	250000
Number of particles per cell	2000
Cold plasma frequency ω_{pe}	3–8 $\lvert\Omega_{e0}\rvert$
The inhomogeneity parameter ζ	$2.0457\times10^{-3}c^{-2}\Omega_{e0}^2$

3. Simulation results

3.1. Effects of the cold plasma density

In this subsection, we will discuss the temperature anisotropy threshold (A_T) that is needed to excite chorus-like waves in the DREX under different cold plasma densities (corresponding to different ω_{pe}). Generally, the chorus waves are more frequently observed in the radiation belts out of the plasmasphere where the plasma density is much lower. Can chorus-like waves be generated more easily with lower plasma densities in DREX? To study this issue, we carry out a series of simulations to investigate the relation between temperature anisotropy threshold A_T and the plasma density. In our simulations, the parallel thermal velocity and density of the energetic electrons are fixed and their perpendicular thermal velocities

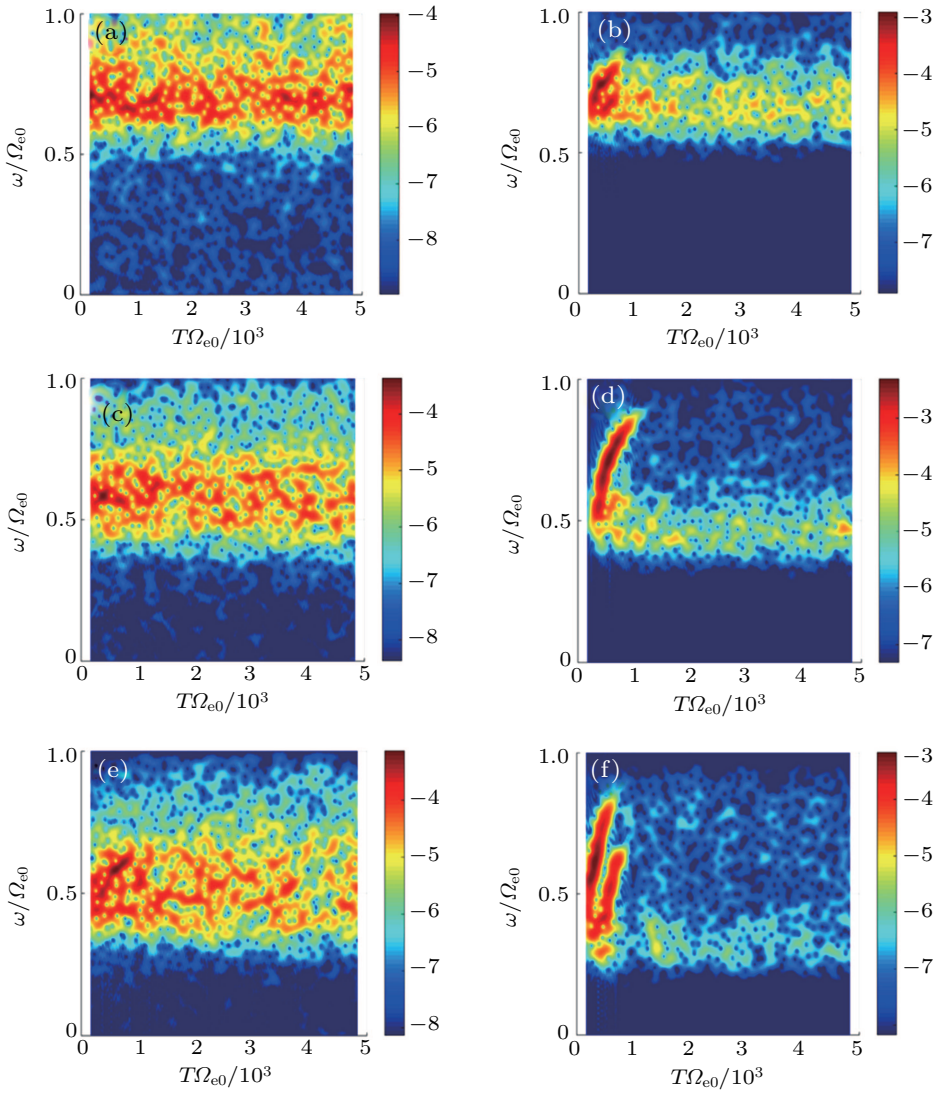


Fig. 1. (color online) Normalized power spectrum densities which vary in the frequency domain with different cold plasma densities. The parallel thermal velocity $w_{\parallel}=0.05$ and hot plasma frequency ω_{ph}=1 are the same for all cases. Other parameters are: $w_{\perp}=0.15$, $\omega_{pe}=3$ for panel (a); $w_{\perp}=0.17$, $\omega_{pe}=3$ for panel (b); $w_{\perp}=0.17$, $\omega_{pe}=6$ for panel (c); $w_{\perp}=0.2$, $\omega_{pe}=6$ for panel (d); $w_{\perp}=0.2$, $\omega_{pe}=8$ for panel (e); and $w_{\perp}=0.25$, $\omega_{pe}=8$ for panel (f).

change in a wide range until chorus-like waves are generated at a certain ω_{pe}. Thus the temperature anisotropy threshold A_T can be obtained. The simulation results are shown in Fig. 1 and the simulation parameters of all the cases in this work can be found in Table 3, where $\omega_{ph} = \omega_{pe}\sqrt{n_h}$ is the hot energetic plasma frequency, and n_h in the simulation is normalized by n_c. The power spectrum densities (PSD) in this paper can be obtained by the wave magnetic field $\delta B_\perp$ recorded at the location $Z = 4c|\Omega_{e0}|^{-1}$, where the characteristic length $L_B \equiv (1/B_0)(dB_0/dz)$ is roughly $61c|\Omega_{e0}|^{-1}$ (about 2.6 m), the same order as that in LAPD.[24] In Fig. 1, $w_\parallel$ (scaled by c) is fixed to be 0.05, ω_{pe} (scaled by Ω_{e0}) is set to be 3 for panels (a) and (b), 6 for panels (c) and (d), and 8 for panels (e) and (f). In Fig. 1(a), $w_\perp = 0.15$, only broad band whistler waves in the frequency range 0.6–0.8 can be seen without obvious chorus-like elements. When $w_\perp$ increases to 0.17, there is a discrete rising-like element which is excited between $t = 0$ and 800 (scaled by $|\Omega_{e0}|^{-1}$), though the frequency sweeping range of this element is very narrow. However, we can conclude that A_T is between 8 and 10.56 for $\omega_{pe} = 3$. Similarly, when $w_\perp$ of the energetic electrons is small (thus A is small), we see only whistler waves in Fig. 1(c). With the increase of $w_\perp$ (A), we obtain a rising-like element in Fig. 1(d) with $A = 15$. This element has a larger frequency sweeping range of 0.5–0.9, which indicates a larger frequency sweep rate than that in Fig. 1(b). Then we can find that A_T is in the range of 10.56 to 15 for $\omega_{pe} = 6$. Simultaneously, A_T can be found between 15 and 24 from Figs. 1(e) and 1(f) by the same method for $\omega_{pe} = 8$.

The results of Fig. 1 can be explained by calculating the linear wave growth rate as shown in Fig. 2. The dashed lines indicate the cases without chorus elements being excited, while the solid lines represent the cases with chorus elements in the PSD pictures. When ω_{pe} increases, a higher A is needed to keep the maximum linear wave growth rate to be at an adequate level. Besides, we find that the starting frequency is about $\omega(\gamma_{max})$, which is coincident with the previous works on chorus generation in space.[29–31]

From the above results we can conclude that with a lower ω_{pe}, corresponding to a lower cold plasma density, chorus-like waves can be generated with a much smaller A_T, which indicates that smaller power is needed to drive this temperature anisotropy. In other words, chorus waves can be more easily excited in low density plasmas with other parameters fixed. It is coincident with the observations that chorus waves have a high occurrence rate outside the plasmasphere where the plasma density is low. Besides, according to the linear theory, the width of the linear wave growth rate peak is larger with a higher plasma density. Thus more free energy is needed to generate chorus-like waves in high density plasmas. To excite chorus-like waves in future DREX experiments, low plasma density should be applied.

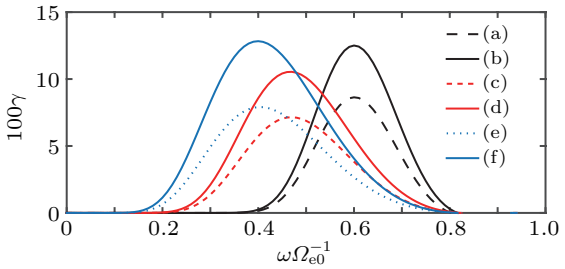


Fig. 2. (color online) The linear wave growth rate γ in different cases (corresponding to those in Fig. 1), where γ is normalized by $|\Omega_{e0}|$ in this paper.

3.2. Effect of the hot plasma density

As predicted by the linear theory, the linear wave growth rate increases with the hot plasma density. In this subsection, we demonstrate the influence of the hot plasma density on the generation of chorus waves in DREX. First, we study A_T under different hot plasma densities in four simulations, and the results are shown in Figs. 3(a)–3(d), where ω_{pe} is fixed to be 8 and $w_\parallel$ is 0.025. In Figs. 3(a) and 3(b), the hot plasma frequency ω_{ph} is fixed to be 1. In Fig. 3(a), $w_\perp$ is 0.125, and there are only whistler waves above $0.55\Omega_{e0}$. In Fig. 3(b), $w_\perp$ increases to 0.15, we can see that two rising-like elements are generated with the starting frequency of ~ 0.6. Thus A_T is between 24 and 35 in this case. In Figs. 3(c) and 3(d), the hot plasma frequency ω_{ph} is 2. There is no chorus being excited when $w_\perp = 0.07$ (as shown in Fig. 3(c)), but a strong chorus element is generated when $w_\perp = 0.08$ (as shown in Fig. 3(d)). Therefore, A_T is between 6.84 and 9.24 in this case when $\omega_{ph} = 2$, much smaller than that in the case of $\omega_{ph} = 1$. Thus, a larger hot electron density can lower the threshold of temperature anisotropy for exciting the chorus waves.

Then we continue to increase the hot plasma density on the basis of Fig. 3(b), and the results are shown in Fig. 3(e). In this case, ω_{ph} increases to 2 while the other parameters are the same as those in Fig. 3(b). It can be seen that broadband hiss-like waves are generated in Fig. 3(e) without the discrete element. Thus, with the increase of the hot electron density, the generated waves change from chorus-like to broad band hiss-like waves. Although large hot plasma density is good for the excitation of chorus, if the temperature anisotropy is fixed in a certain range, the hot energetic plasma with too high density can excite hiss-like waves only.

We calculate the linear wave growth rate for the cases in Fig. 3, as shown in Fig. 4. The maximum growth rates of the two cases without chorus are about 0.07 and the maximum growth rates of the two cases with chorus elements are about 0.1. However, the growth rate corresponding to Fig. 3(e) is about 0.4, which is much larger than that of the other cases. As a moderate maximum growth rate is essential for the generation of chorus elements, we can conclude that the hot plasma density should be moderate for chorus generation.

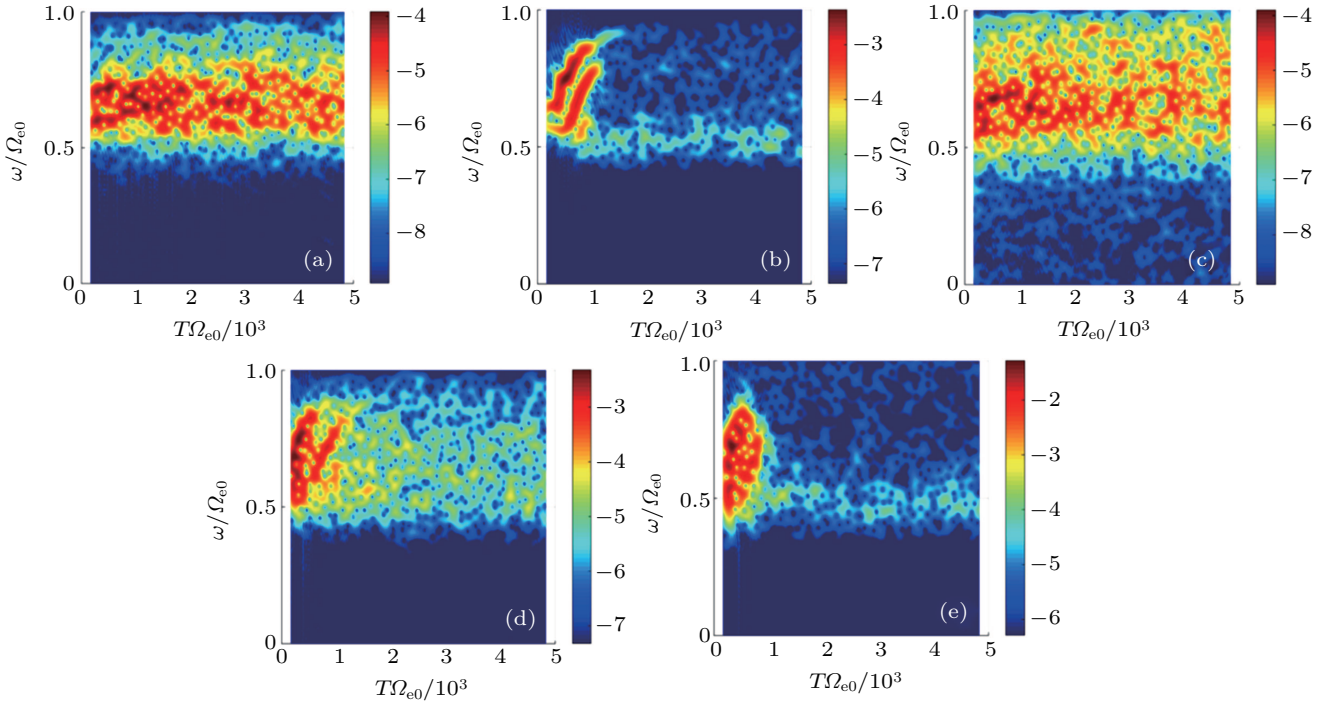


Fig. 3. (color online) Normalized power spectrum densities varying in the frequency domain with different hot electron densities. The parallel thermal velocity $w_{\parallel} = 0.025$ and cold plasma frequency $\omega_{pe} = 8$ are the same for all cases. Other parameters are: $w_{\perp} = 0.125$, $\omega_{ph} = 1$ for panel (a); $w_{\perp} = 0.15$, $\omega_{ph} = 1$ for panel (b); $w_{\perp} = 0.07$, $\omega_{ph} = 2$ for panel (c); $w_{\perp} = 0.08$, $\omega_{ph} = 2$ for panel (d); and $w_{\perp} = 0.15$, $\omega_{ph} = 2$ for panel (e).

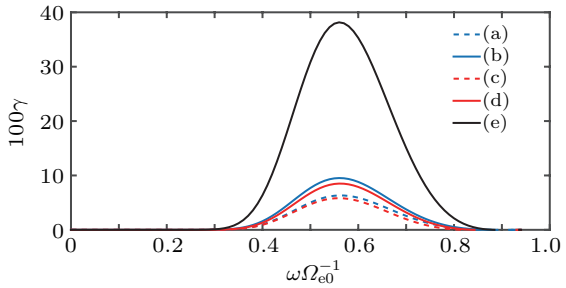


Fig. 4. (color online) The linear wave growth rate in different cases (corresponding to those in Fig. 3).

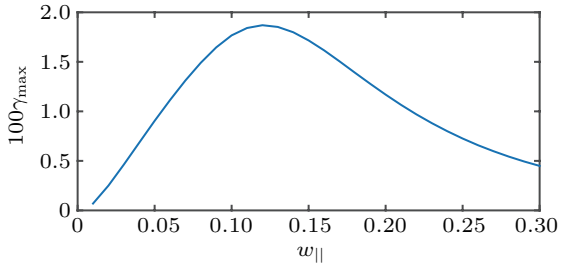


Fig. 5. (color online) Maximum linear wave growth rate as a function of the parallel thermal velocity.

3.3. Effect of the parallel thermal velocity

In this subsection, we study the influence of the parallel temperature on the excitation of chorus-like waves. As mentioned above, A_T is between 24 and 35 in the case of $\omega_{ph} = 1$, $w_{\parallel} = 0.025$, and $\omega_{pe} = 8$, as shown in Figs. 3(a) and 3(b), larger than that in the case of $\omega_{ph} = 1$, $w_{\parallel} = 0.05$, and $\omega_{pe} = 8$, as shown in Fig. 1(f). So is the starting frequency, and this is consistent with the linear theory. According to the resonant condition $\omega - k_{||}v_{||} = \Omega_{ce}$, a lower $v_{||}$ can resonate with the wave with higher frequency. We plot the maximum linear wave growth rate as a function of the parallel thermal velocity in Fig. 5, where the anisotropy is fixed at 8, and the cold plasma frequency is $5\Omega_{e0}$. The results show that the parallel thermal velocity can influence the maximum linear growth rate, then influence the generation of chorus waves. Therefore, the parallel temperature is crucial on the generation of the chorus waves.

Simulation results of the normalized electron power spectrum densities varying in the frequency domain with different parallel thermal velocities, as well as the spatial profile and time evolutions of the wave amplitude with different parallel thermal velocities, are shown in Fig. 6 for three typical cases. In these simulations, ω_{pe} is fixed to be 8, the energetic electrons density proportion is fixed at 1.56%, and $w_{\parallel}$ is adjustable to study the parallel thermal velocity effect on the excitation of chorus-like waves. In Fig. 6(a), the parallel thermal velocity is 0.05, the perpendicular thermal velocity is 0.25, the same as that in Fig. 1(f). Rising-like chorus can then be generated, and the starting frequency in Fig. 6(a) is about 0.4. Then we increase $w_{\parallel}$ in Fig. 6(c) to 0.1, and the corresponding $w_{\perp}$ is chosen as 0.4. Both falling-like and rising-like structure waves are generated together in this case. We continue to increase $w_{\parallel}$ to 0.2 in Fig. 6(e), then only falling-like structures are found in this case. The wave propagating characteristics of the three cases are correspondingly plotted in the right hand

side of Fig. 6, showing that the waves are generated near the magneto-equator. In Fig. 6(b), the waves are excited between $t = 0$ and 1000 (scaled by $|\Omega_{e0}|^{-1}$), then the free energy is consumed rapidly. However, in Fig. 6(d), the free energy of the isotropic electrons is released by the generation of waves at $t \sim 1000$, and then accumulated between $t = 1000$ and 2000. This accumulation contributes to the wave's excitation again at $t = 2000$. Although absorbing boundary condition is applied in our simulations, the wave will not be completely absorbed. There are always weak reflected waves left in the boundary of the simulation domain when the wave amplitude is large. In Fig. 6(f), the reflected waves can be found during the wave propagation. The magnetic field energy is plotted in Fig. 7 for the three cases in Fig. 6. It can be seen in Fig. 7 that the wave energy peaks are matched one-by-one with the wave elements well. But the detailed generation mechanism of these falling-like structure needs further studies.

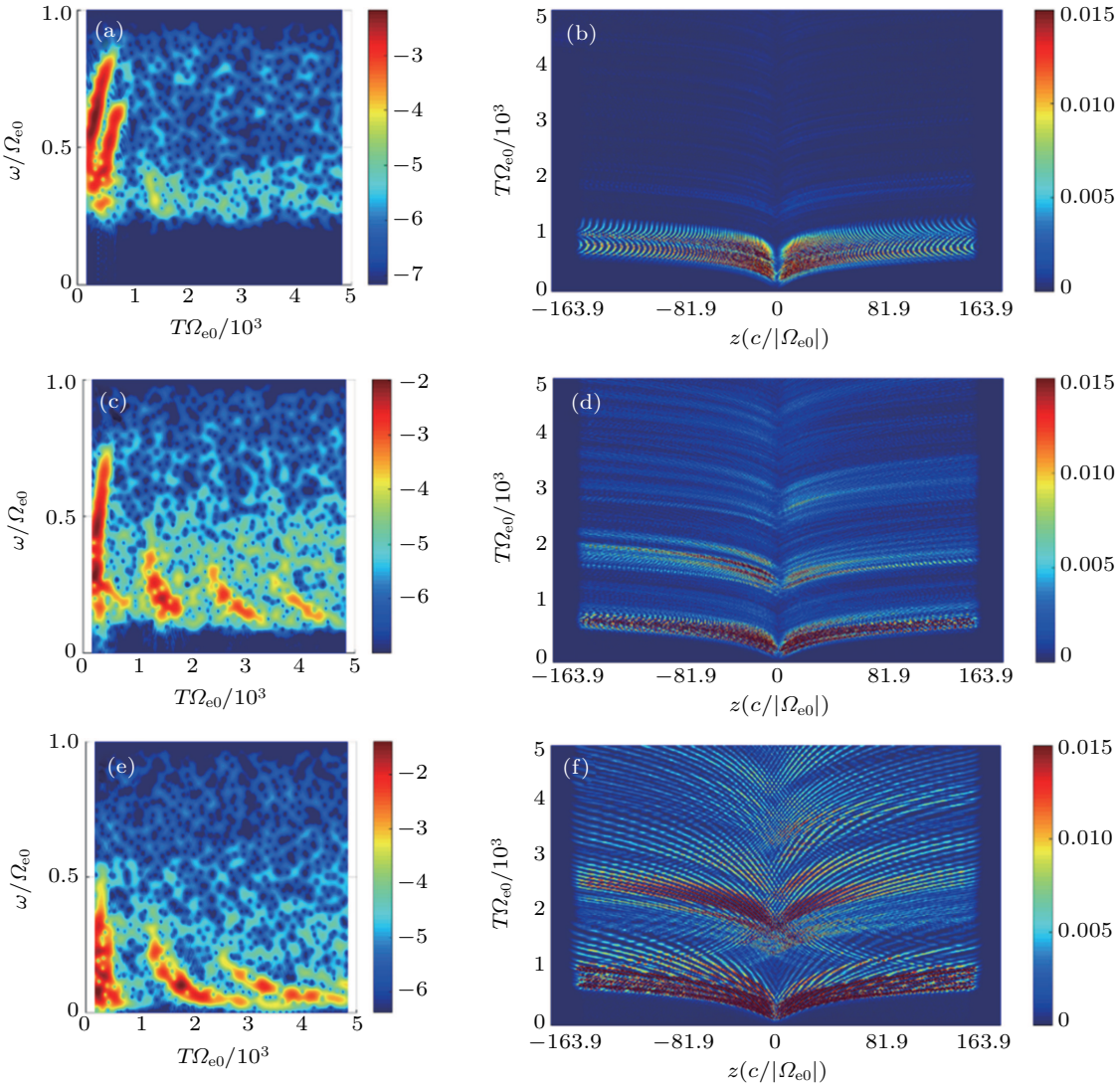


Fig. 6. (color online) (a), (c), (e) Normalized power spectrum densities varying in the frequency domain with different parallel thermal velocities. (b), (d), (f) Spatial profile and time evolutions of the wave amplitude with different parallel thermal velocities, respectively. The hot plasma frequency $\omega_{ph} = 1$ and the cold plasma frequency $\omega_{pe} = 8$ are the same for the three cases. Other parameters are: $w_{\parallel} = 0.05$, $w_{\perp} = 0.25$ for panel (a); $w_{\parallel} = 0.1$, $w_{\perp} = 0.4$ for panel (c); and $w_{\parallel} = 0.2$, $w_{\perp} = 0.75$ for panel (e).

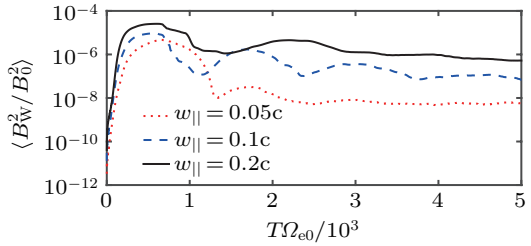


Fig. 7. (color online) Wave intensity at different parallel thermal velocities.

As a brief summary, the simulation parameters and wave properties of the cases in this paper are listed in Table 3.

Table 3. Simulation parameters and wave properties of all the cases in this work.

Case	ω_{ph}	$w_{\parallel}$	$w_{\perp}$	ω_{pe}	Wave properties
Fig. 1(a)	1	0.05	0.15	3	whistlers
Fig. 1(b)	1	0.05	0.17	3	rising-tone
Fig. 1(c)	1	0.05	0.17	6	whistlers
Fig. 1(d)	1	0.05	0.2	6	rising-tone
Fig. 1(e)	1	0.05	0.2	8	whistlers
Fig. 1(f)	1	0.05	0.25	8	rising-tone
Fig. 3(a)	1	0.025	0.125	8	whistlers
Fig. 3(b)	1	0.025	0.15	8	rising-tone
Fig. 3(c)	2	0.025	0.07	8	whistlers
Fig. 3(d)	2	0.025	0.08	8	rising-tone
Fig. 3(e)	2	0.025	0.15	8	hiss-like waves
Fig. 6(a)	1	0.05	0.25	8	rising-tone
Fig. 6(c)	1	0.1	0.4	8	rising-tone and falling-tone
Fig. 6(e)	1	0.2	0.75	8	falling-tone

4. Conclusion

A hybrid simulation is used to study the generation of chorus-like waves in the establishing device DREX. Besides the temperature anisotropy, there are also three other main parameters that significantly influence the generation of chorus, i.e., the cold plasma density (n_c), the hot plasma density (n_h), and the parallel thermal velocity of energetic electrons. We demonstrate the effect of the three parameters on the generation of chorus-like waves by three groups of simulations, and the main conclusions are as follows. (i) In the designed DREX parameter regime, different structures of chorus-like waves, the rising-like, the falling-like, and the mixed, can be generated. (ii) A low ω_{pe} which corresponds to a low cold plasma density can generate chorus-like waves with very small anisotropy threshold A_T. (iii) A high hot electron density can lower the threshold. However, for certain temperature anisotropy, only hiss-like waves are excited at a very high hot electron density.

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