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11 Influence of field and geometric configurations on the mode $\frac{11}{12}$ Influence of field and geometric configurations on the mode $\frac{77}{78}$ ¹³ conversion characteristics of hybrid waves in a magnetoplasma slab 10^{13} 14

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²² ARTICLE INFO ABSTRACT ⁸⁸

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Mode conversion Hybrid wave

33 99 Field configuration effects

²⁴ Article history: **Action** 2008 **Starface Conversion** characteristics of electrostatic hybrid surface waves due to the magnetic ⁹⁰ ⁹⁵ Received 1 June 2016 **Started in the symmetric and Startegie of the symmetric and Startegie of the symmetric and ⁹¹** 26 Received in revised form 27 September **anti-symmetric modes of hybrid surface waves** for two different magnetic field configurations: parallel ⁹² 27 and perpendicular. For the parallel magnetic field configuration, we have found that the symmetric 33 28 Avertual acceptomage of the propagates as upper- and lower-hybrid waves. However, the hybrid characteristics disappear and 94 29 Communicated by F. Porcelli **communicated by F. Porcelli** servey two non-hybrid waves are produced for the anti-symmetric mode. For the perpendicular magnetic field se 30 96 configuration, however, the anti-symmetric mode propagates as the upper- and lower-hybrid waves and 31 *Keywords:* Superveys the symmetric mode produces two non-hybrid branches of waves.

Mode conversion and the second of the se

³⁷ The investigation of surface waves in a plasma has drawn much in a magneto dusty plasma including the effects of slab thickness ¹⁰³ ³⁸ interest since the dispersion relation since it provides useful in- as well as the magnetic field strength and orientation. The depen- ¹⁰⁴ ³⁹ formation on various plasmas spatially separated from their sur- dence on the field orientation of the waves for the symmetric and ¹⁰⁵ ⁴⁰ roundings such as a vacuum or dielectrics [1–10]. In recent years, anti-symmetric modes in a dusty slab plasma has not been known ¹⁰⁶ ⁴¹ there has been a great deal of interest in waves in bounded yet. In this work, we choose the frequency range above the ion 107 ⁴² dusty plasmas [11–14] as well as in bulk plasmas [15–18] since cyclotron frequency but less than the electron cyclotron frequency. ¹⁰⁸ 53 a plasma slab can support propagation for the symmetric and in an isotropic plasma slab represented by [21] 119 ⁵⁴ anti-symmetric modes depending on wave conditions on the two **the example of the symmetric modes** depending on wave conditions on the two **and the symmetric modes** depending on wave conditions on the two **and the symm** 55 boundary surfaces of the slab $[2,20]$, the dispersion relations for ∞ and ∞ and ∞ in the surfaces of the slab $[2,20]$, the dispersion relations for ⁵⁶ both modes can be derived for each boundary condition. In this pa- $1+\frac{1}{2} \int \frac{dk_x k_z}{\sqrt{1+e^{ik_x k_z}}} \left(\frac{1+e^{ik_x k_z}}{1+e^{ik_x k_z}}\right) = 0$ (1) ¹²² The investigation of surface waves in a plasma has drawn much formation on various plasmas spatially separated from their surroundings such as a vacuum or dielectrics [\[1–10\].](#page--1-0) In recent years, there has been a great deal of interest in waves in bounded dusty plasmas $[11–14]$ as well as in bulk plasmas $[15–18]$ since tence of electrostatic hybrid oscillations was previously reported for the surface wave propagation in the semi-bounded (semiof the electrostatic upper- and lower-hybrid resonance oscillations entation of the external magnetic field but those frequencies can be enhanced by the increase of the magnetic field strength. However, the propagation of surface waves in the plasma slab would be quite different from the case of semi-bounded plasma. Since

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as well as the magnetic field strength and orientation. The depen-

 43 dust grains are often found in space and laboratory. The exis- We consider a dusty plasma slab with the sharp bound- 109 ⁴⁴ tence of electrostatic hybrid oscillations was previously reported aries at $x = 0$ and $x = L$ such that the characteristic length of 45 for the surface wave propagation in the semi-bounded (semi- plasma is much greater than the scale length of the inhomo- 111 ⁴⁶ infinity) magnetized dusty plasma [\[19\].](#page--1-0) In Ref. [\[19\],](#page--1-0) the frequencies geneity. Then, the specular reflection condition in which the par-
 ⁴⁷ of the electrostatic upper- and lower-hybrid resonance oscillations ticles undergo a mirror reflection such that $f_1(v_x, v_y, v_z, t)|_{x=0} = 113$ ⁴⁸ in a semi-bounded plasma are found to be independent of the ori-
 $f_1(-v_x, v_y, v_z, t)|_{x=0}$ and $f_1(v_x, v_y, v_z, t)|_{x=L} = f_1(-v_x, v_y, t)$ ⁴⁹ entation of the external magnetic field but those frequencies can v_z , t) $|x=L|$, where f_1 is the perturbed plasma distribution function, $\frac{115}{2}$ ⁵⁰ be enhanced by the increase of the magnetic field strength. How- can be used as the boundary condition for the study of surface 1^{16} ⁵¹ ever, the propagation of surface waves in the plasma slab would waves [\[1,2\].](#page--1-0) This boundary condition yields the dispersion equa- 117 52 be quite different from the case of semi-bounded plasma. Since tion for electrostatic surface waves propagating in the *z* direction 118 We consider a dusty plasma slab with the sharp boundgeneity. Then, the specular reflection condition in which the par $f_1(-v_x, v_y, v_z, t)|_{x=0}$ and $f_1(v_x, v_y, v_z, t)|_{x=L} = f_1(-v_x, v_y, t)$ in an isotropic plasma slab represented by [\[21\]](#page--1-0)

$$
\begin{array}{ll}\n\text{55} & \text{boundary surfaces of the slab [2,20], the dispersion relations for} \\
\text{56} & \text{both modes can be derived for each boundary condition. In this par-} \\
\text{57} & \text{per, we are motivated to investigate the surface waves propagating} \\
\text{58} & \text{1 + } \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{dk_x k_z}{k^2 \varepsilon_l(\omega, k)} \left(\frac{1 \pm e^{ik_x L}}{1 \pm e^{ik_x L}} \right) = 0, \\
\text{58} & \text{124} \\
\text{59} & \text{124} \\
\text{100} & \text{135} \\
\text{111} & \text{146} \\
\text{126} & \text{137} \\
\text{147} & \text{148} \\
\text{158} & \text{158} \\
\text{169} & \text{160} \\
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\text{191} & \text{192} \\
\text{100} & \text{106} \\
\text{111} & \text{107} \\
\text{122} & \text{124} \\
\text{133} & \text{125} \\
\text{144} & \text{126} \\
\text{155} & \text{128} \\
\text{166} & \text{128} \\
\text{177} & \text{128} \\
\text{188} & \text{129} \\
\text{199} & \text{120} \\
\text{100} & \text{121} \\
\text{111} & \text{122} \\
\text{131} & \text{123} \\
\text{142} & \text{124} \\
\text{153} & \text{125} \\
\text{166} & \text{126} \\
\text{178} & \text{128} \\
\text{189} & \text{129} \\
\text{190} & \text{120} \\
\text{101} & \text{122} \\
\text{112} & \text{124} \\
\text{131
$$

59 125 60 $\frac{1}{\sqrt[3]{\frac{1}{2}}\sqrt[3]{\frac{1}{2}}\sqrt[3]{\frac{1}{2}}\sqrt[3]{\frac{1}{2}}\sqrt[3]{\frac{1}{2}}\sqrt[3]{\frac{1}{2}}\sqrt[3]{\frac{1}{2}}\sqrt[3]{\frac{1}{2}}\sqrt[3]{\frac{1}{2}}\sqrt[3]{\frac{1}{2}}\sqrt[3]{\frac{1}{2}}\sqrt[3]{\frac{1}{2}}\sqrt[3]{\frac{1}{2}}\sqrt[3]{\frac{1}{2}}\sqrt[3]{\frac{1}{2}}\sqrt[3]{\frac{1}{2}}\sqrt[3]{\frac{1}{2}}\sqrt[3]{\frac{$ 61 Bionanotechnology, Hanyang University, Ansan, Kyunggi-Do 15588, South Korea. ² 127 Bionanotechnology, Eq. 13 Luc 10131 (127 Bionanotechnology, Eq. 13 Luc 10131 (127 Bionanotechnology, Eq. 13 Luc 1013) 62 128 dinal component of the plasma dielectric permittivity, and *L* is the 63 *E*-mail address: ydjung@hanyang.ac.kr (Y.-D. Jung). Slab thickness, and $k (= |\mathbf{k}|) = \sqrt{k_x^2 + k_z^2}$. Since the *y*-component 129 *z*-components of the wave vector **k**, respectively, ε_{ℓ} is the longitu-

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66 and the contract of the con

4 ric (upper sign) and anti-symmetric (lower sign) modes. For the ω_{ce}^2 ω_{ce}^2 ω_{ce}^2 ω_{ce} ω_{ce 5 symmetric mode, we have $E_z(x = L) = E_z(x = 0)$, whereas for the We also find another two branches of non-hybrid waves for the anti-symmetric mode $E_z(x = L) = -E_z(x = 0)$.

73
When the parallel magnetic field $\mathbf{B}_0 = B_0 \hat{\mathbf{z}}$ is applied to the tained in the form, 8 74 boundary surfaces, the longitudinal plasma dielectric permittivity 9 in dusty plasma for $kv_{T\alpha}$, ω_{cd} , $\omega_{ci} \ll \omega \ll \omega_{ce}$ is obtained as fol-
1 + $\frac{\omega_{pe}^2}{\omega_{pe}^2}$ + $\frac{\omega_{pd}^2}{\omega_{pd}^2}$ 1 10 \log [22]: $\frac{1}{2}$ lows [\[22\]:](#page--1-0)

$$
\varepsilon_{l,\parallel}(\omega, k_x, k_z) = 1 + \frac{\omega_{pe}^2 k_x^2}{\omega_{ce}^2 k^2} - \frac{\omega_{pe}^2 k_z^2}{\omega^2 k^2} - \frac{\omega_{pi}^2}{\omega^2} - \frac{\omega_{pd}^2}{\omega^2},
$$
\n(2) and

¹⁶ species *α* (= *e*, *i*, *d* for electron, ion and dusty grain, respectively) $\bar{\omega}_{\parallel AS} = \left(\frac{\omega_{pi}^2}{2}\right)^2$, (10) ⁸² ¹⁷ and $\omega_{c\alpha} = q_{\alpha} B_0 / m_{\alpha} c$ is the cyclotron frequency of species α . Plug-
¹⁹ $1 - \frac{2}{k \cdot l}$ / ³³ ¹⁸ ging Eq. (2) into Eq. [\(1\),](#page-0-0) the dispersion equation becomes $\frac{k_z L}{r}$ 84

$$
\frac{1}{22}
$$
\n
$$
\frac{1}{\pi (1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} - \frac{\omega_{pi}^2 + \omega_{pd}^2}{\omega^2})} \int_{-\infty}^{\infty} \frac{dk_x}{k_x^2 + F_{\parallel}^2(\omega)k_z^2} \left(\frac{1 + e^{ik_x}L}{1 \pm e^{ik_x}L}\right)
$$
\n
$$
= 0,
$$
\n
$$
\frac{1}{22}
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$$
\frac{1}{22}
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$$
\frac{1}{22}
$$
\n
$$
\frac{1}{22}
$$
\nSolved for the symmetric parallel propagation to **B**₀ but it
\ndisappears for the anti-symmetric propagation.
\n
$$
\frac{1}{22}
$$

26 where the symbol $F_{\parallel}(\omega)$ in the denominator is defined as $\frac{92}{2}$

$$
F_{\parallel}^{2}(\omega) = \frac{1 - \frac{\omega_{pe}^{2} + \omega_{pi}^{2} + \omega_{pd}^{2}}{\omega^{2}}}{1 + \frac{\omega_{pe}^{2}}{\omega_{ce}^{2}} - \frac{\omega_{pi}^{2} + \omega_{pd}^{2}}{\omega^{2}}}.
$$
\n(4)

33 Since the integral in Eq. (3) vanishes as $k_x \rightarrow \infty$, we calculate $\frac{1}{2}$ and $\frac{1}{2}$ a magnetoplasma slab such that

$$
\begin{aligned}\n\frac{^{39}}{^{40}} \quad & \left[\left(1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} - \frac{\omega_{pi}^2 + \omega_{pd}^2}{\omega^2} \right) \left(1 - \frac{\omega_{pe}^2 + \omega_{pi}^2}{\omega^2} \right) \right]^{\frac{1}{2}} \\
& + \tanh \left[\frac{1}{2} F_{\parallel}(\omega) k_z L \right] = 0 \quad \text{(symmetric mode)} \\
& \text{(5)} \quad \begin{array}{c}\n\text{and} \\
\left[1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} - \frac{\omega_{pi}^2 + \omega_{pd}^2}{\omega^2} \right) \left(1 - \frac{\omega_{pe}^2 + \omega_{pi}^2 + \omega_{pd}^2}{\omega^2} \right) \right]^{\frac{1}{2}} \\
& + \coth \left[\frac{1}{2} F_{\perp}(\omega) k_z L \right] = 0 \quad \text{(anti-symmetric mode)},\n\end{array}\n\end{aligned}
$$

and

and

$$
\begin{aligned}\n\frac{47}{49} \quad & \left[\left(1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} - \frac{\omega_{pi}^2 + \omega_{pd}^2}{\omega^2} \right) \left(1 - \frac{\omega_{pe}^2 + \omega_{pi}^2}{\omega^2} \right) \right]^{\frac{1}{2}} \\
& \quad + \coth\left[\frac{1}{2} F_{\parallel}(\omega) k_z L \right] = 0 \quad \text{(anti-symmetric mode)}.\n\end{aligned}
$$
\nwhere

\n
$$
F_{\perp}(\omega) = \left(\frac{1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} - \frac{\omega_{pi}^2 + \omega_{pd}^2}{\omega^2}}{1 - \frac{\omega_{pe}^2 + \omega_{pi}^2 + \omega_{pd}^2}{\omega^2}} \right)^{\frac{1}{2}}.
$$
\n(14)

\n
$$
F_{\perp}(\omega) = \left(\frac{1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} - \frac{\omega_{pi}^2 + \omega_{pd}^2}{\omega^2}}{1 - \frac{\omega_{pe}^2 + \omega_{pi}^2 + \omega_{pd}^2}{\omega^2}} \right)^{\frac{1}{2}}.
$$
\n(14)

\n
$$
F_{\perp}(\omega) = \left(\frac{1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} - \frac{\omega_{pi}^2 + \omega_{pd}^2}{\omega^2}}{1 - \frac{\omega_{pe}^2 + \omega_{pd}^2}{\omega^2}} \right)^{\frac{1}{2}}.
$$

57 123 lations for the symmetric mode. We denote the upper-hybrid wave 58 as $\bar{\omega}_{\parallel S}^{UH}$ and the lower-hybrid wave as $\bar{\omega}_{\parallel S}^{LH}$ where $\bar{\omega} = \omega/\omega_{pi}$ is the $1 + \frac{\omega_{pe}^2}{1 + \omega_{pe}^2} + \frac{\omega_{pd}^2}{1 + \omega_{pd}^2}$

61 127 62 128 63 129 64 130 65 131 *ω*¯ *UH ^S* = ¹ ⁺ *^ω*² *pd ω*2 *pi* ¹ ⁺ *^ω*² *pe ω*2 *ce* [−] ¹ 2 ¯ *kz L*¯ 1 2 *(*upper-hybrid wave*)* (7)

of wave vector has a translational invariance, it is ignored in our geometry without loss of generality. The double signs in Eq. (1)
$$
\bar{\omega}_{\parallel S}^{LH} = \left(\frac{1 + \frac{\omega_{pd}^2}{\omega_{pi}^2}}{1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} + \frac{1}{2}\bar{k}_z\bar{l}}\right)^{\frac{1}{2}}
$$
 (lower-hybrid wave). (8)

6 anti-symmetric mode $E_z(x=L) = -E_z(x=0)$.

anti-symmetric mode: $\bar{\omega} = \bar{\omega}_{\parallel AS+}$ and $\bar{\omega} = \bar{\omega}_{\parallel AS-}$ which are ob-

73 We also find another two branches of non-hybrid waves for the tained in the form,

9 in duty plasma for
$$
kv_{T\alpha}
$$
, ω_{cd} , $\omega_{ci} \ll \omega \ll \omega_{ce}$ is obtained as fol-
\n10
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\n
$$
\bar{\omega}_{\parallel AS+} = \left(\frac{1 + \frac{\omega_{pe}^2}{\omega_{pi}^2} + \frac{\omega_{pd}^2}{\omega_{pl}^2}}{1 + \frac{2}{k_z L}}\right)^{\frac{1}{2}}
$$
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and

where
$$
\omega_{p\alpha} = (4\pi n_{\alpha}q_{\alpha}/m_{\alpha})^{1/2}
$$
 is the plasma frequency of
species α (= e, i, d for electron, ion and dusty grain, respectively) and $\omega_{\alpha\alpha} = q_{\alpha}B_0/m_{\alpha}c$ is the cyclotron frequency of species α . Plug-
¹⁷ and $\omega_{\alpha\alpha} = q_{\alpha}B_0/m_{\alpha}c$ is the cyclotron frequency of species α . Plug-
¹⁸

19 where $\bar{k}_z \equiv k_z \lambda_{De}$ and $\bar{L} \equiv L/\lambda_{De}$ are the scaled wave number and $\frac{85}{96}$ ²⁰ 8⁶ 86
Scaled slab thickness. It is interesting to note that the hybrid mode $\frac{21}{1}$ $\frac{k_z}{1}$ $\frac{dk_x}{1 + k_z}$ $\frac{dk_x}{1 + k_z}$ is observed for the symmetric parallel propagation to **B**₀ but it $\frac{87}{1}$ $\frac{22}{\pi}$ $\frac{1}{2}$ $\frac{1}{\omega_{pe}^2}$ $\frac{\omega_{pi}^2 + \omega_{pd}^2}{\omega_{pi}^2}$ $\frac{1}{\omega_{p}^2 + F_{\parallel}^2(\omega)k_z^2}$ $\frac{1}{1 \pm e^{ik_x L}}$ disappears for the anti-symmetric propagation.

 ϵ^{24} = 0. ϵ^{90} = 0. 25 $-$ 3, kv_{α} , ω_{cd} , ω_{cd} , $\omega_{cd} \ll \omega \ll \omega_{ce}$ is written as ω

26 ω

$$
z_{1, \perp}(\omega, k_x, k_z) = 1 + \frac{\omega_{pe}^2 k_z^2}{\omega_c^2 k_z^2} - \frac{\omega_{pe}^2 k_x^2}{\omega^2 k_z^2} - \frac{\omega_{pi}^2}{\omega^2} - \frac{\omega_{pi}^2}{\omega^2} - \frac{\omega_{pd}^2}{\omega^2}.
$$
 (11)

30 $\frac{1}{\sqrt{2}}$ $\frac{\omega_{\rm pi}^2 + \omega_{\rm nd}^2}{\omega_{\rm pi}^2 + \omega_{\rm nd}^2}$ Equation (11) can be inserted into the dispersion equation and 96 31 $1 + \omega_{ce}^2 = \omega^2$ ω^2 the integral can be executed again by residue theorem to yield the s 32 98 following dispersion relations,

the integral by applying the Cauchy residue theorem with inte-
gration being performed along a closed contour. By picking up
the pole at
$$
k_x = F_{\parallel}(\omega)k_z
$$
, we find the dispersion relation for the
symmetric and the anti-symmetric modes of surface waves in the
magnetoplasma slab such that

$$
+ \tanh\left[\frac{1}{2}F_{\perp}(\omega)k_zL\right] = 0
$$
 (symmetric mode) (12)

and

$$
\begin{bmatrix}\n\left(1 + \frac{\omega_{ce}^2}{\omega_{ce}^2} - \frac{\omega^2}{\omega^2}\right)\left(1 - \frac{\omega^2}{\omega^2}\right)\n\end{bmatrix}\n+ tanh\n\begin{bmatrix}\n\frac{1}{2}F_{\parallel}(\omega)k_zL\n\end{bmatrix}\n= 0 \quad \text{(symmetric mode)}\n\begin{bmatrix}\n\left(1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} - \frac{\omega_{pi}^2 + \omega_{pd}^2}{\omega^2}\right)\left(1 - \frac{\omega_{pe}^2 + \omega_{pi}^2 + \omega_{pd}^2}{\omega^2}\right)\n\end{bmatrix}^{\frac{1}{2}}\n+ coth\n\begin{bmatrix}\n\frac{1}{2}F_{\perp}(\omega)k_zL\n\end{bmatrix}\n= 0 \quad \text{(anti-symmetric mode)},\n\tag{13}\n\end{bmatrix}^{\frac{107}{110}}
$$

46 112 where

$$
\begin{bmatrix}\n(1 + \frac{\nu^2}{\omega_{ce}^2} - \frac{\nu^2}{\omega^2})\left(1 - \frac{\nu^2}{\omega^2}\right)\n\end{bmatrix}\n+ \coth\left[\frac{1}{2}F_{\parallel}(\omega)k_zL\right] = 0 \quad \text{(anti-symmetric mode)}.\n\tag{6}
$$
\n
$$
\begin{aligned}\nF_{\perp}(\omega) &= \left(\frac{1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} - \frac{\omega_{pi}^2 + \omega_{pd}^2}{\omega^2}\right)^{\frac{1}{2}}\n\end{aligned}.\n\tag{14}
$$

52
53 For long-wavelength oscillations, when $F_{\parallel}(\omega)k_zL \ll 1$, the ar-
53 For long-wavelength oscillations, when $F_{\parallel}(\omega)k_zL \ll 1$, the ar-
53 For long-wavelength oscillations, when $F_{\parallel}(\omega)k_zL \ll 1$, the ar- 53 For long-wavelength oscillations, when $F_{\parallel}(\omega)k_zL \ll 1$, the ar-
functions can be expanded and terms with higher order than the 54 guments in the hyperbolic functions can be expanded and terms and constructions can be expanded and terms with insular order than the 120 55 with higher order than the primary can be truncated to obtain the trimary can be truncated to blain the wave nequency. Then, two 121 56 wave frequency. We see that there exist two kinds of hybrid oscil-
 $\frac{1}{2}$ functions can be expanded and terms with higher order than the primary can be truncated to obtain the wave frequency. Then, two branches of non-hybrid oscillations for the symmetric mode are found as $\bar{\omega} = \bar{\omega}_{\perp S+}$ and $\bar{\omega} = \bar{\omega}_{\perp S-}$ where

58 as
$$
\omega_{\text{IS}}^{\text{OT}}
$$
 and the lower-hybrid wave as $\omega_{\text{IS}}^{\text{LT}}$ where $\omega = \omega/\omega_{\text{pi}}$ is the
\n59 scaled wave frequency and $\bar{\omega}_{\text{IS}}^{\text{UT}}$ and $\bar{\omega}_{\text{IS}}^{\text{LH}}$ are obtained by
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and

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$$
^{13}
$$
 $\left(1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} - \frac{1}{2}\bar{k}_z\bar{L}\right)$
\n65 $\bar{\omega}_{\perp S-} = \left(\frac{1 + \frac{\omega_{pe}^2}{\omega_{pi}^2} + \frac{\omega_{pd}^2}{\omega_{pi}^2}}{1 - \frac{1}{2}\bar{k}_z\bar{L}}\right)^{\frac{1}{2}}$
\n66 and (16) 131

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