

Lecture note

Plasma Sheath Lab[†]

Theory of Waves in Plasmas

(PSL-LN-01)

September 13, 2004

Y. S. Bae^a and W. Namkung

Department of Physics, POSTECH

[†]homepage:<http://psl.postech.ac.kr>

^aDepartment of Physics, Pohang University of Science and Technology
San 31, Hyoja-dong, Nam-gu, Pohang 790-784, Korea.
e-mail: ysbae7@postech.ac.kr

Contents

1	Dispersion Relation in a Cold Uniform Plasmas	1
1.1	Resonances ($N \rightarrow \infty$)	5
1.2	Cut-offs ($N = 0$)	6
1.3	Polarization	6
1.4	CMA diagram	6
2	EC-wave propagation using Mathematica	8
2.1	O-X propagation for 2nd harmonic resonance for KSTAR tokamak with low density	8
2.2	O-X propagation for 2nd harmonic resonance for KSTAR tokamak with high density	15
2.3	O-X-B heating	22
3	Dispersion Relations in a Hot Plasma	32
3.1	Electromagnetic Dispersion Relation	32
3.2	Electrostatic Dispersion Relation	50
3.2.1	Electrostatic Modes in Hot Plasma	55
4	Dispersion plots of electron modes using Mathematica	64
4.1	Electron modes	64
4.2	Electron Bernstein (EB) modes	69
5	Landau Damping	74
6	ECR Heating [or Damping] Rates	83
6.1	Fund. Harm. Damping Rate - classical approach($\det \overleftrightarrow{M}$) . . .	83
6.1.1	The Dielectric Tensor for $\omega \gg \omega_{pi}$, Ω_i and $\omega \sim |\Omega_e|$ . .	83
6.1.2	Damping Rates near the ECR Region	86
6.2	Damping Rates Using Quasi-linear Theory	97
6.2.1	Higher Harmonics ($n \geq 2$)	103
6.2.2	Fundamental Harmonic ($n = 1$)	108
6.2.3	O-mode & X-mode Heating	115
7	Calculation of ECR optical depth using Mathematica	121
8	LH-wave	131
8.1	Dispersion relation	131
8.2	Wave propagation and accessibility	132
8.3	Phase Velocity and Group Velocity	133
8.4	Parametric study of the 5.0-GHz LH-wave propagation in the KSTAR tokamak	133
8.4.1	Spectral gap and N_{\parallel} shifting	135
8.5	Dispersion relation with thermal correction	145
8.6	Wave absorption	146
9	Ray Tracing in Inhomogeneous Media	147
9.1	Electric and Magnetic fields of E-M waves in a Tokamak with a cold Plasma	148

9.2	Phase velocity and group velocity of EM waves in a tokamak with a cold plasma	153
9.3	Raytracing of EC-wave in KSTAR tokamak	156
A	Calculation of S_x	177
B	The reason of validity of cold plasma dielectric tensor in the calculation of harmonic damping rates($n \geq 2$)	179
C	Quasi-linear Theory	180

List of Figures

1	CMA diagram for a two-component plasma. The ion-to-electron mass ratio is chosen to be 2.5. Bounding surfaces appear as lines in this two-dimensional parameter space. Cross sections of wave-normal surfaces are sketched and labeled for each region. For these sketches the direction of the magnetic field is vertical. The small mass ratio can be misleading here: the $L = 0$ line intersects $P = 0$ at $\Omega_i/\omega = 1 - (Zm_e/m_i)$. From T. Stix's book (AIP, 1992).	7
2	Contour I	75
3	Contour II	75
4	Contour III	76
5	Real and imaginary parts of the frequency as a function of wave number for a stationary one-component plasma in thermal equilibrium. The frequency is given in units of ω_p , while the wave number is expressed in units of the Debye wave number (k_D). The dotted curves represent approximate formulas derived in this section.	79
6	The magnetic pitch angle of KSTAR plasma in mid-plane. $I_p = 2$ MA and $B_0 = 3.5$ T	139
7	The critical N_{\parallel} value vs radial position in mid-plane for various central density. Broad density profile ($\alpha = 1$) is used in this plot.	139
8	The perpendicular refractive index vs radial position in mid-plane for various N_{ϕ}^{gr} . $n_e(0) = 1.0 \times 10^{20} \text{ m}^{-3}$ and $\alpha = 1$. . .	140
9	The perpendicular refractive index vs radial position in mid-plane for various central density. $N_{\phi}^{\text{gr}} = 2.14$ and $\alpha = 1$. . .	140
10	The variation of N_{ϕ} vs radial position.	141
11	N_{\perp}^2 vs radial position in mid-plane with constant $N_{\phi} = N_{\phi}^{\text{gr}} = 2.14$ (solid line) and with increasing N_{ϕ} due to wedge effect.	141
12	The up-shift and down-shift in N_{\parallel} and the fast wave cut-off (FC) for two central densities and fixed $T_e(0) = 20$ keV. The "WD" is defined as the region bounded by up and down shifts and FC. Here, $N_{\phi}^{\text{gr}} = 2.14$	142
13	The wave domain and damping zone in KSTAR plasma for $n_e(0) = 1 \times 10^{20} \text{ m}^{-3}$ with broad profile. The dashed lines are the significant Landau damping for various central temperatures. Here, $N_{\phi}^{\text{gr}} = 2.14$	142
14	The up-shift and down-shift in N_{\parallel} vs radial position in mid-plane for the plasma current. Here, $N_{\phi}^{\text{gr}} = 2.14$	143
15	The up-shift and down-shift in N_{\parallel} vs radial position in mid-plane for broad and peaked profiles. Here, $N_{\phi}^{\text{gr}} = 2.14$	143
16	The up-shift and down-shift in N_{\parallel} vs radial position in mid-plane for N_{ϕ}^{gr}	144
17	The upper limits of up-shift and the lower limits of down-shift vs N_{ϕ}^{gr} , which are results from Fig. 16.	144
18	. . . . .	157
19	. . . . .	158
20	. . . . .	159

21	.....	160
22	.....	161
23	.....	162
24	.....	163
25	.....	164
26	.....	165
27	.....	166
28	.....	167
29	.....	168
30	.....	169
31	.....	170
32	.....	171
33	.....	172
34	.....	173
35	.....	174
36	.....	175
37	.....	176
38	Velocity distribution for “bump-on-tail” instability. Real part of unstable frequencies are such that $v = \omega_0(k)/k$ lies in region where vdf_0/dv is positive (opposite sense to Landau damping). Quasi-linear diffusion due to these modes tends to flatten out the bump.	181