COUPLING PHYSICS OF UNCONVENTIONAL ECH SCENARIOS FOR LOW FIELD DEVICES

**R.I. Pinsker, C.B. Forest[†], P. Chattopadhyay[†],
M. Thomas[†], M.D. Carter[*]**

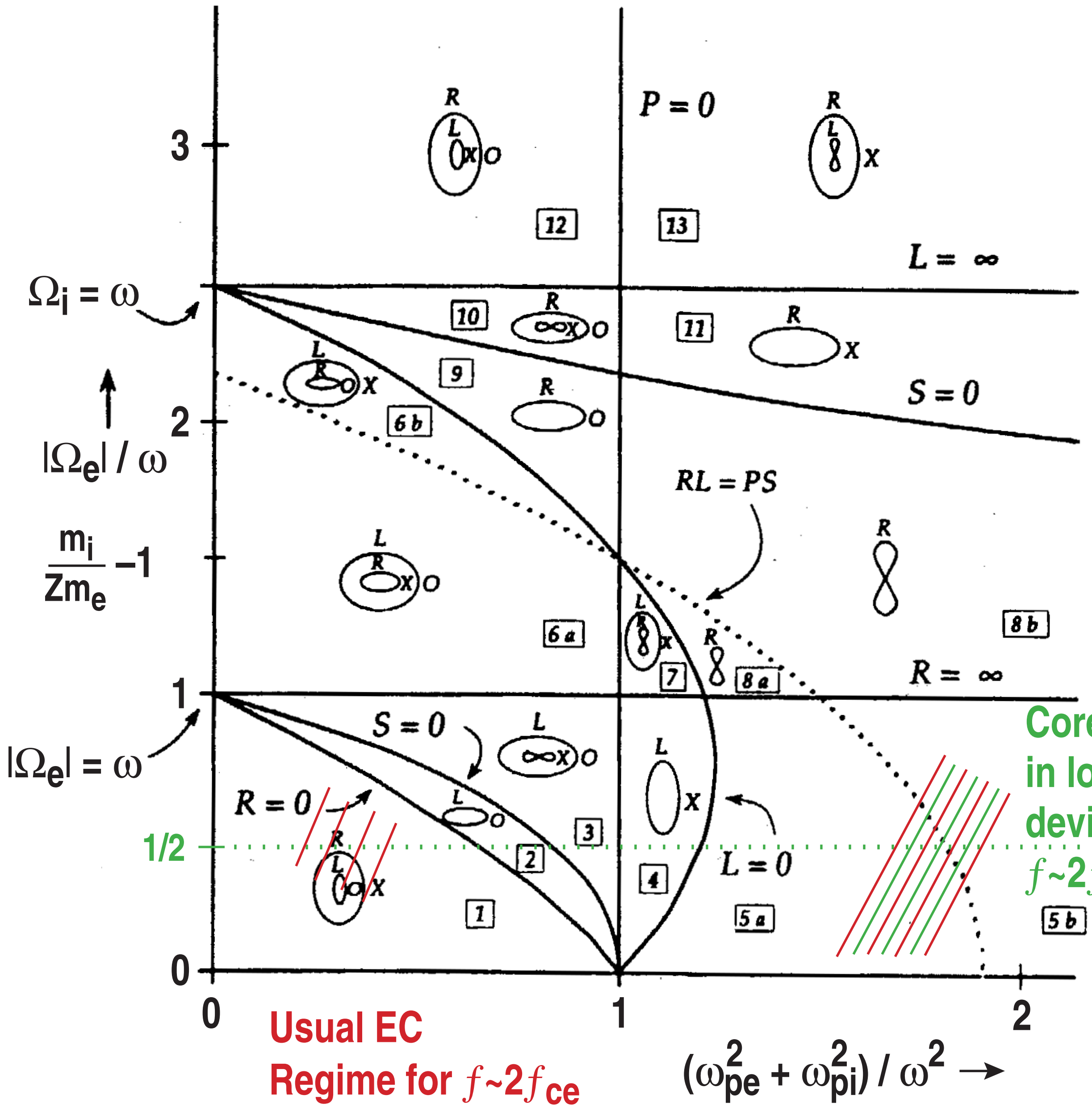
**General Atomics
[†] U. Wisconsin-Madison
[*] Oak Ridge National Laboratory**

285-00/jy

INTRODUCTION

- Electron cyclotron heating and current drive has proven very useful in toroidal plasma devices, due to its strong, localized absorption and its utter lack of coupling difficulties

- However, wave physics dictates that in plasmas in which $\omega_{pe}^2 / \omega_{ce}^2 >> 1$ (low field / high density), conventional ECH is not possible as a method of heating the core plasma



Core plasma in low field devices for f~2f_{ce}

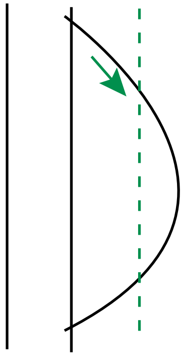
Usual EC Regime for f~2f_{ce}

NSTX

GENERAL ATOMICS

CAN WE USEFULLY APPROACH
STOP–BAND 5 FROM REGION 8 ?

- In an attempt to use cold plasma modes to do ECH in low field devices, one might use high-field side launch of whistler (= FW) or LH wave near $f < f_{ce}$



Problems: 1) usual accessibility limits, leading to:

2) difficulty of coupling very slow waves

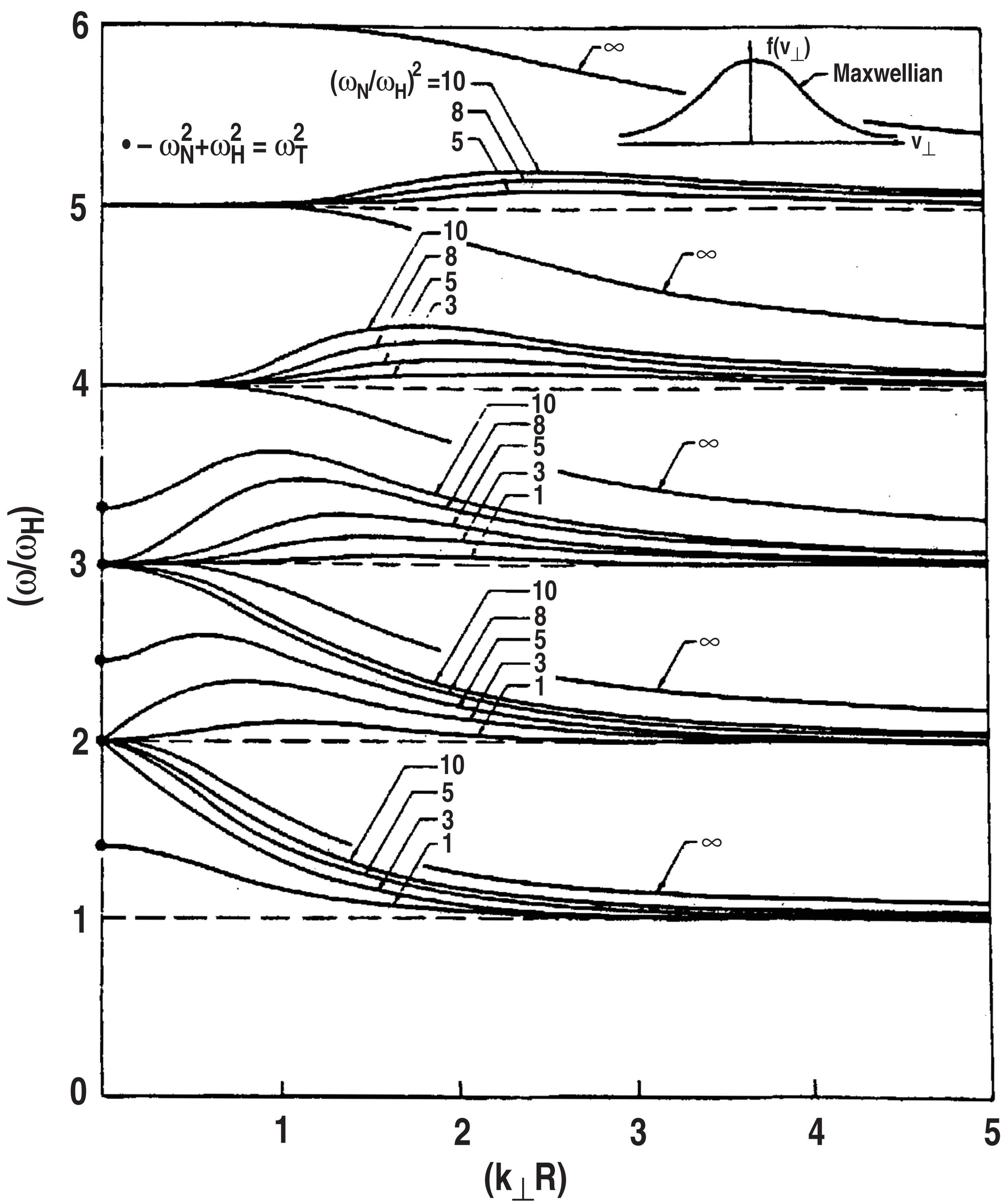
3) But probably insurmountable difficulty is that absorption zone will be reached before wave has significantly penetrated plasma -
wave wants to propagate along field lines, not across

Answer: in a toroidal device, not practical except possibly for extreme edge heating

POSSIBLE SOLUTION: ELECTRON BERNSTEIN WAVE

- Since no cold plasma wave propagates in most of the plasma, we are motivated to examine waves that can: the finite temperature modes known as electron Bernstein waves, which were extensively studied in small laboratory plasmas in the 60's and early 70's

Typical EBW Dispersion Curves



NSTX

GENERAL ATOMICS

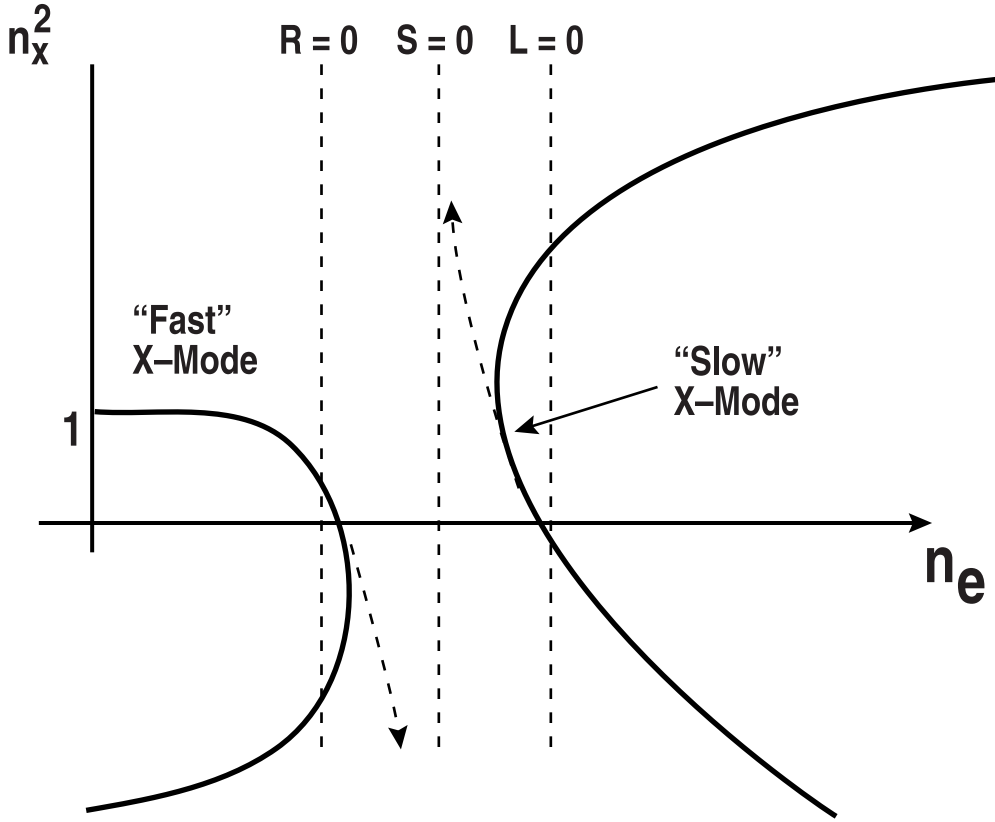
IS “MODE TRANSFORMATION” A POSSIBILITY FOR EBW LAUNCH?

For ion Bernstein waves, a propagating mode carries the energy to the mode conversion zone, where finite T_i can make the connection fairly smooth: “mode transformation”

But in EBW regime, mode conversion occurs at densities below $f = f_{pe} \Rightarrow$ no electrostatic cold mode available – both O and X modes are evanescent for $n_z^2 > 1$

Answer: unfortunately, NO

X–mode and EBW propagation in coupling region



For
f = 2.8 GHz
B_T = 0.07 T

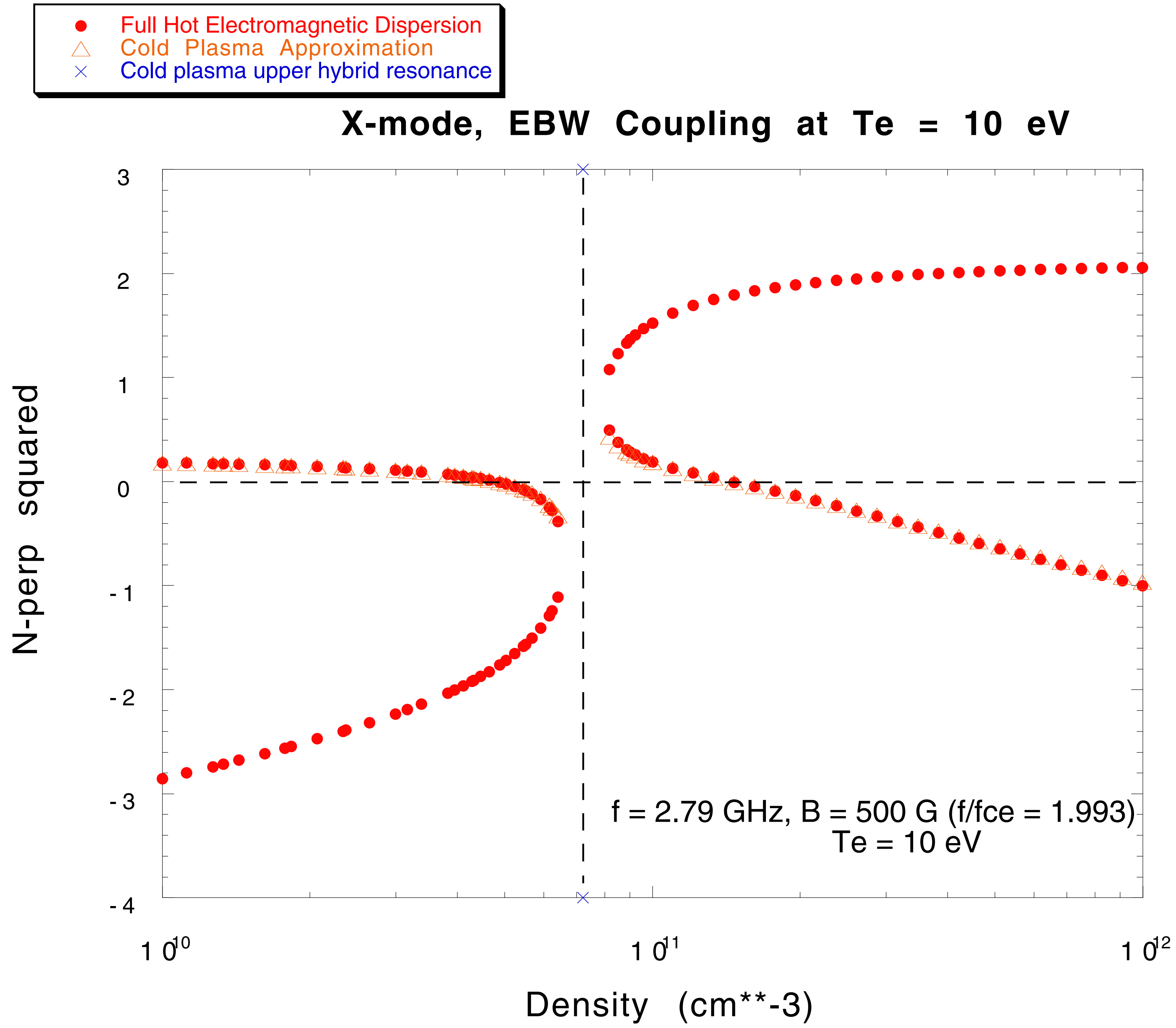
$$n_e\Big|_L^R = \begin{cases} 2.9\times10^{10}\ \mathrm{cm}^{-3} \\ 1.6\times10^{11}\ \mathrm{cm}^{-3} \end{cases}$$

$$\omega_{UH}^2 = \omega_{pe}^2 + \omega_{ce}^2$$

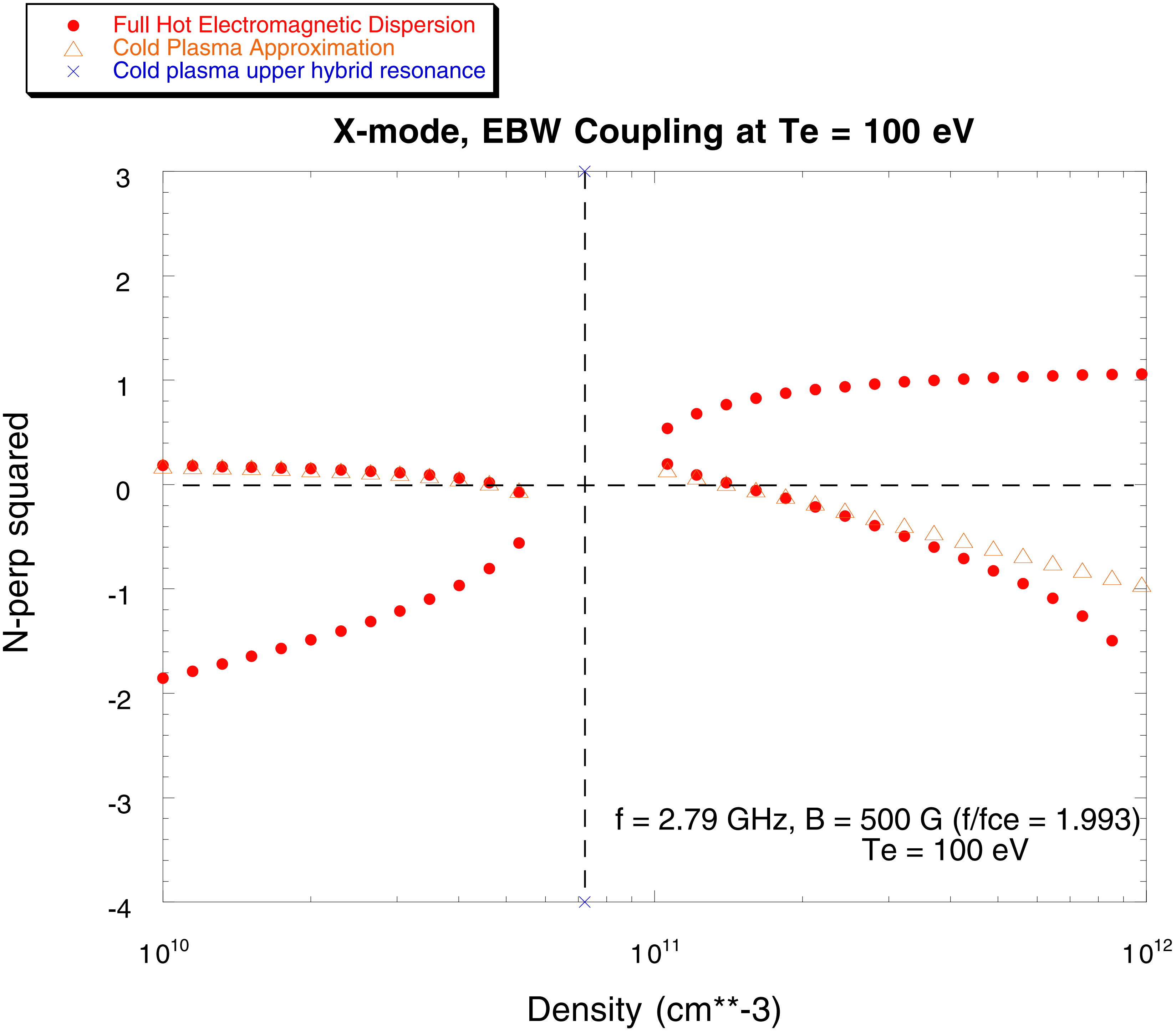
$$\frac{\omega}{n_e}\Big|_{UH} = \sqrt{1 + \left(\frac{\omega_{pe}}{\omega_{ce}}\right)^2}$$

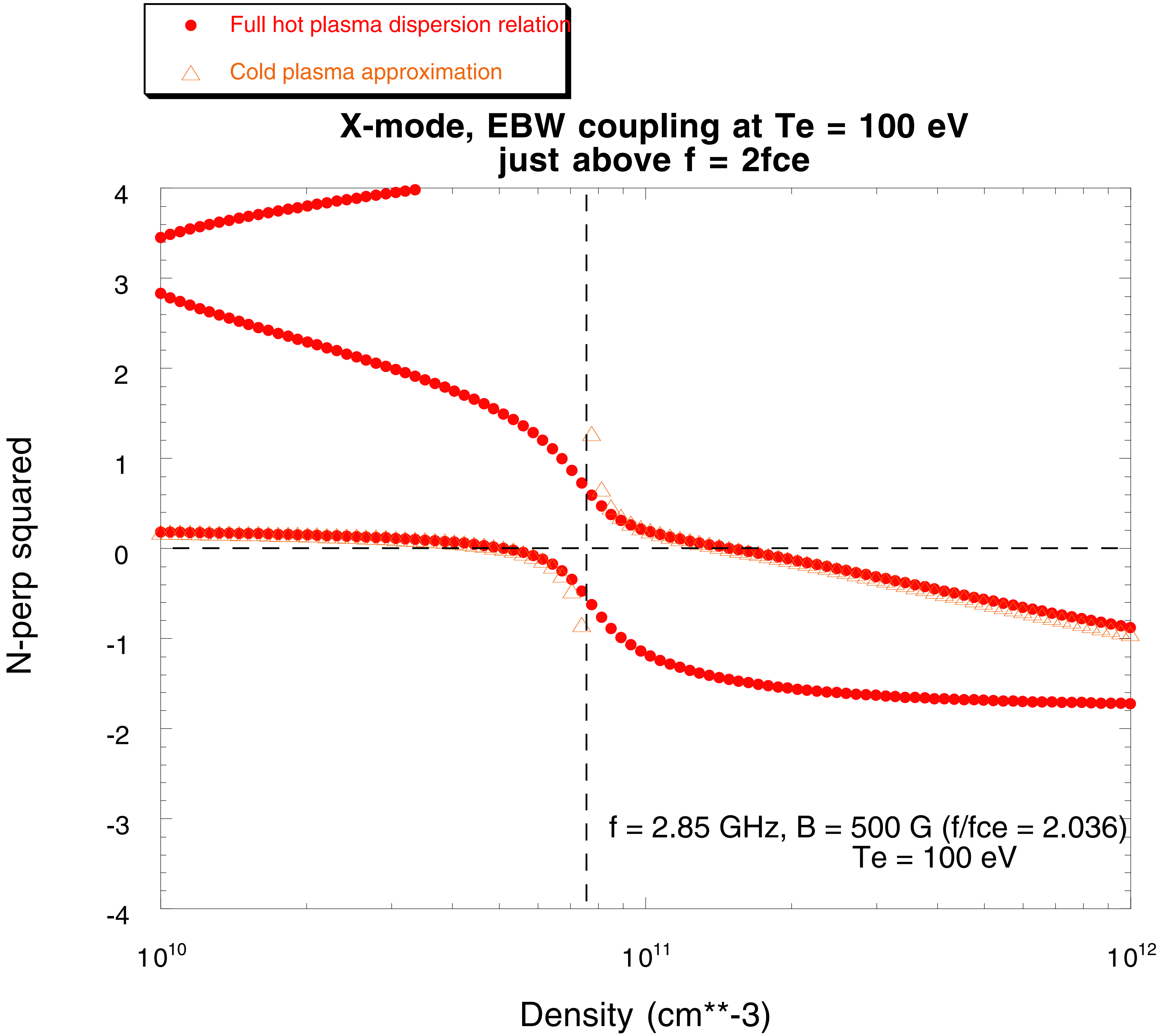
$$n_e\Big|_{\mathrm{cutoff}}\Big|_L^R = 1.24\times10^{10}\, f_{GHz}\,(f_{GHz} \mp 28\,\frac{\mathrm{GHz}}{\mathrm{T}} \times B_T)$$

X-mode, EBW Coupling at Te = 10 eV



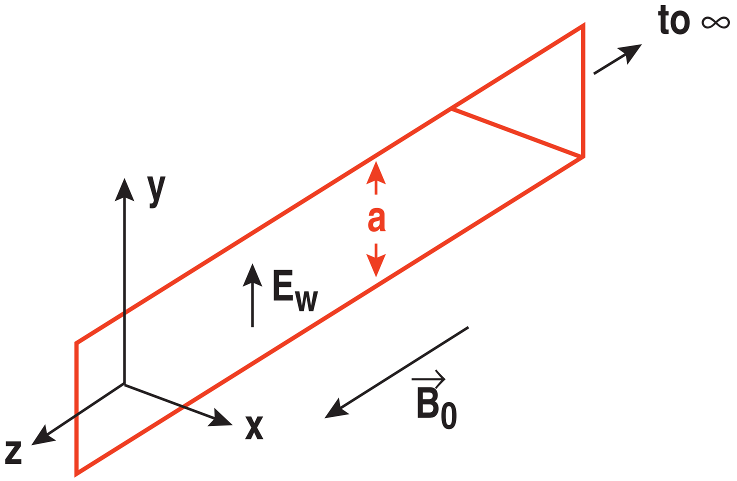
f = 2.79 GHz, B = 500 G (f/fce = 1.993)
Te = 10 eV


● Full Hot Electromagnetic Dispersion
△ Cold Plasma Approximation
× Cold plasma upper hybrid resonance
X-mode, EBW Coupling at Te = 100 eV
N-perp squared
3
2
1
0
-1
-2
-3
-4
10^{10}
10^{11}
10^{12}
Density (cm**-3)
f = 2.79 GHz, B = 500 G (f/fce = 1.993)
Te = 100 eV


Full hot plasma dispersion relation
Cold plasma approximation
X-mode, EBW coupling at Te = 100 eV
just above f = 2fce
N-perp squared
4
3
2
1
0
-1
-2
-3
-4
f = 2.85 GHz, B = 500 G (f/fce = 2.036)
Te = 100 eV
10^{10}
10^{11}
10^{12}
Density (cm**-3)

Model Problem

- Antenna: single infinitely wide waveguide, long dimension aligned with uniform B–field ($E_W = \hat{y}E_W$)
- Uniform, finite T_e plasma filling halfspace X > 0, possible vacuum gap



- For n_e below R = 0, X–mode excitation
- For n_e above L = 0, only EBW

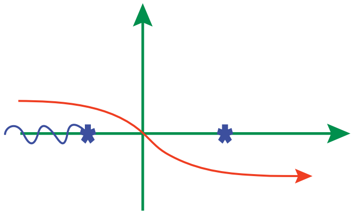
SOLUTION OBTAINED BY BRAMBILLA'S METHOD

- Matching Ey at x = 0, B_z only in waveguide opening, obtain equation for waveguide reflection coefficient ρ

$$\frac{1-\rho}{1+\rho} \equiv \Lambda = \frac{(k0\ a/2)}{\pi\sqrt{\varepsilon_w}} \int dn_y \underbrace{Y\ (n_y)}_{\text{plasma admittance}} \underbrace{\frac{\sin^2\left(\frac{k_oa}{2}n_y\right)}{\left(\frac{k_oa}{2}n_y\right)^2}}_{\text{antenna spectrum}}$$

$$Y \equiv \left.\frac{B_z}{Ey}\right|_{x=0^+}$$

- Integral must be performed over the path determined by causality if there are any singularities of Y (n_y) for real n_y



Brambilla, M., Nucl. Fusion 16 (1976) 47.

ADMITTANCE FOR COLD UNIFORM PLASMA

For $T_e \rightarrow 0$, then the X–mode dispersion is just $n_\perp^2 = \frac{RL}{S}$ (Stix's notation)

and $$Y = \frac{B_z}{E_y} = \frac{\sqrt{\frac{RL}{S} - n_y^2} - i(D/S)\, n_y}{1 - \frac{n_y^2}{S}}$$

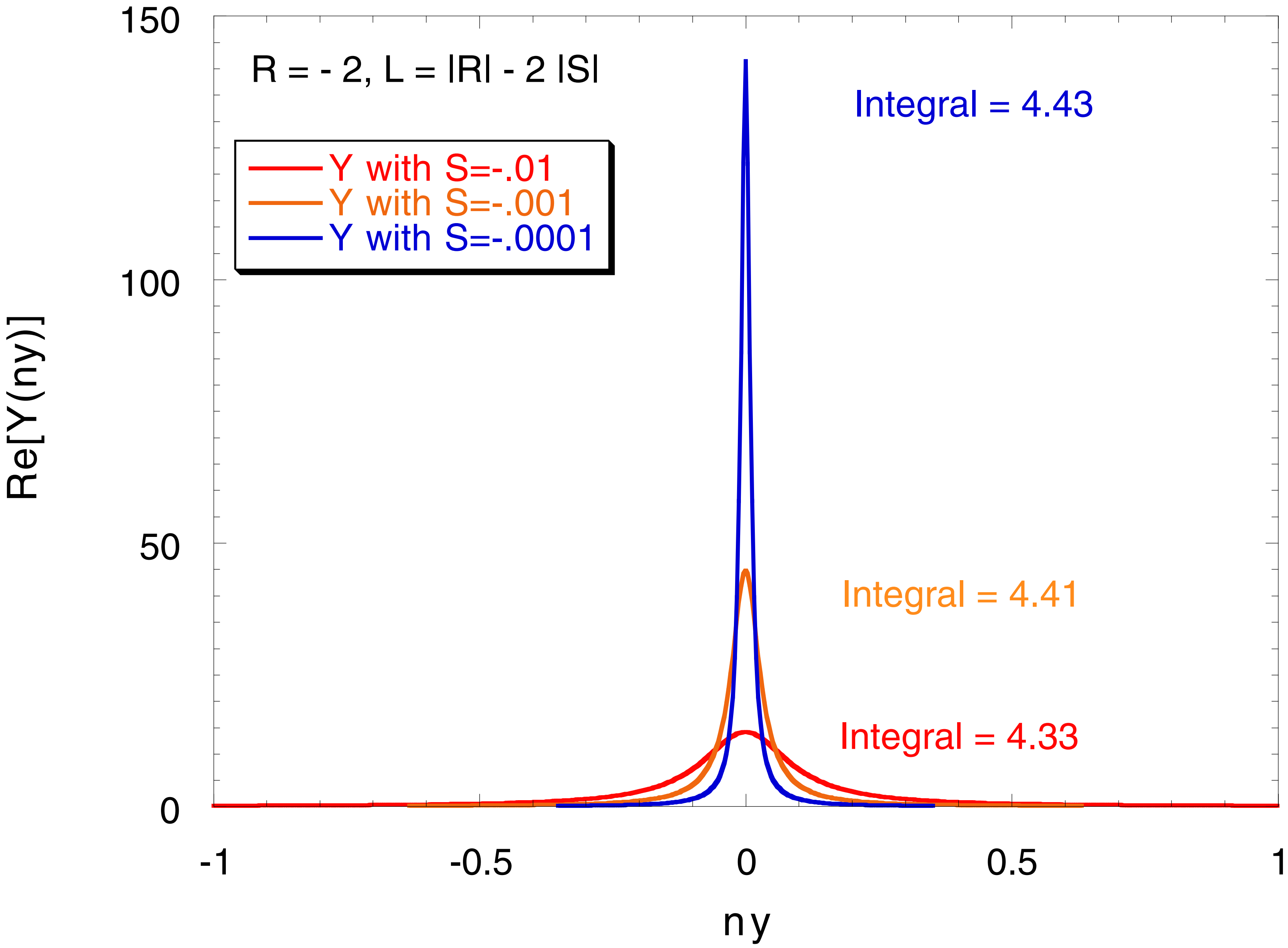
For S > 0, singularity at $ny = -\sqrt{S}$

Note

$$|\rho|^2 = \frac{(1 - \mathrm{Re}\Lambda)^2 + (\mathrm{Im}\Lambda)^2}{(1 + \mathrm{Re}\Lambda)^2 + (\mathrm{Im}\Lambda)^2}$$

(Surface wave - see Pinsker, R., Nucl. Fusion 32, 1789 (1992))

Re[Y(ny)] for nearly electrostatic slow X-mode (S = 0 would be exactly electrostatic)



ADMITTANCE FOR HOT PLASMA

For exactly perpendicular propagation ($n_z = 0$), this problem is tractable

Since dielectric tensor elements are calculated in rotated frame in which $n_y = 0$, we must compute polarization in that rotated frame, then transform the field components back to the lab frame

Result:

$$Y = \frac{\varepsilon'_{xx}\, n_\perp^2}{\varepsilon'_{xx}\, n_x - \varepsilon'_{xy}\, n_y}$$

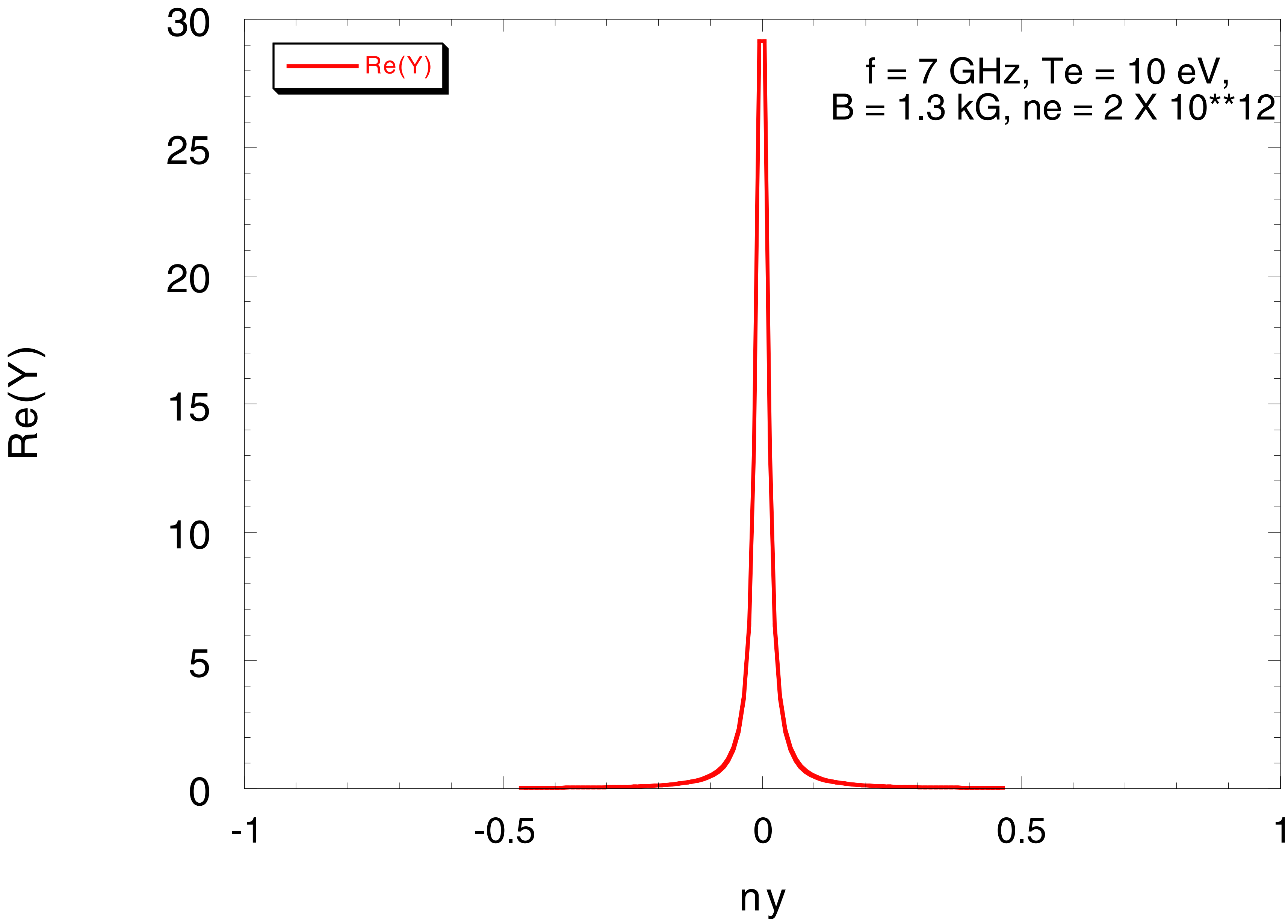
in which $n_\perp^2$ is the solution of

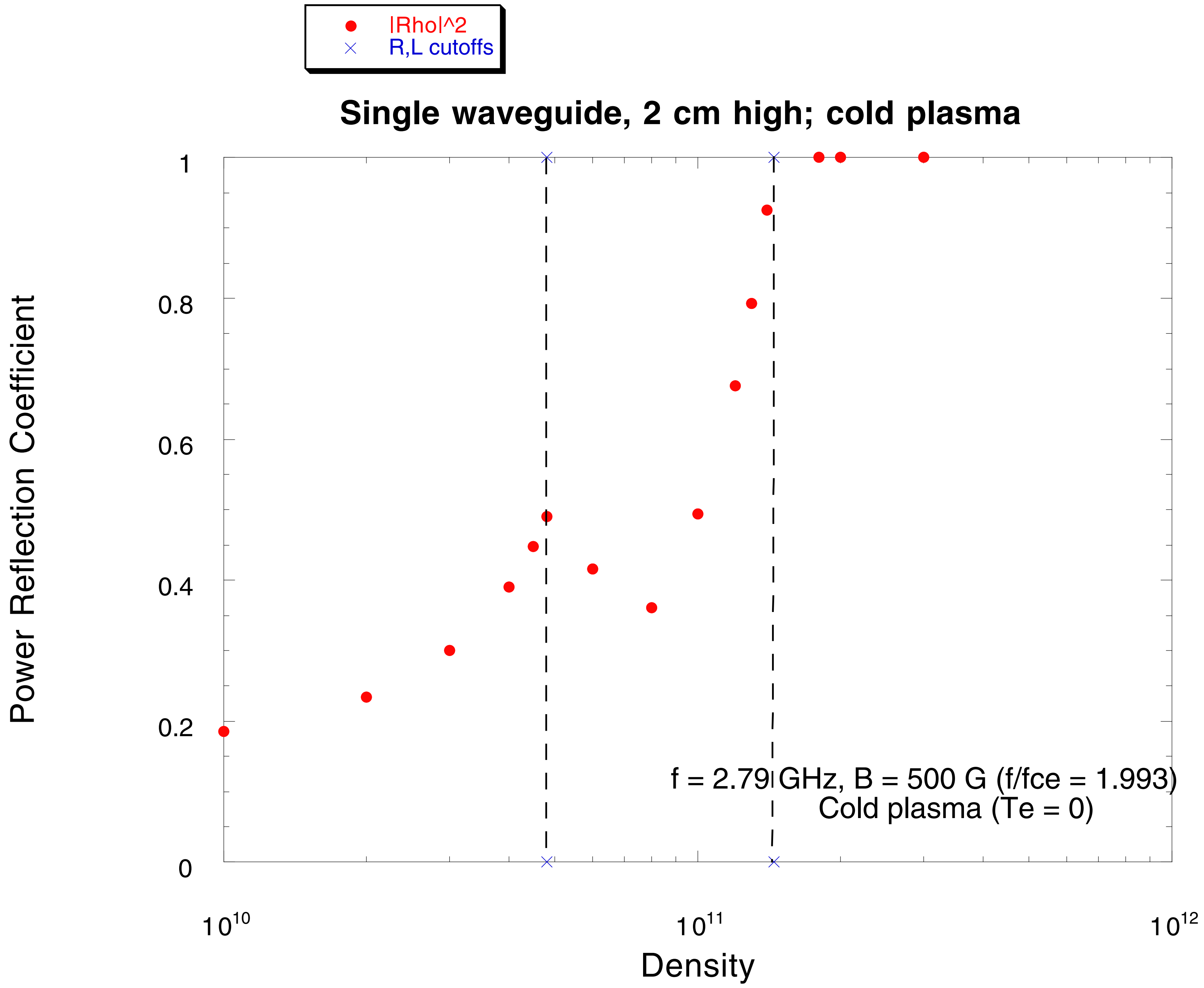
$$\varepsilon'_{xx}\,(\varepsilon'_{yy} - n_\perp^2) = (\varepsilon'_{xy})^2 = 0$$

$n_x = \sqrt{n_\perp^2 - n_y^2}$ Note $\varepsilon'_{xx} \neq \varepsilon'_{yy}$

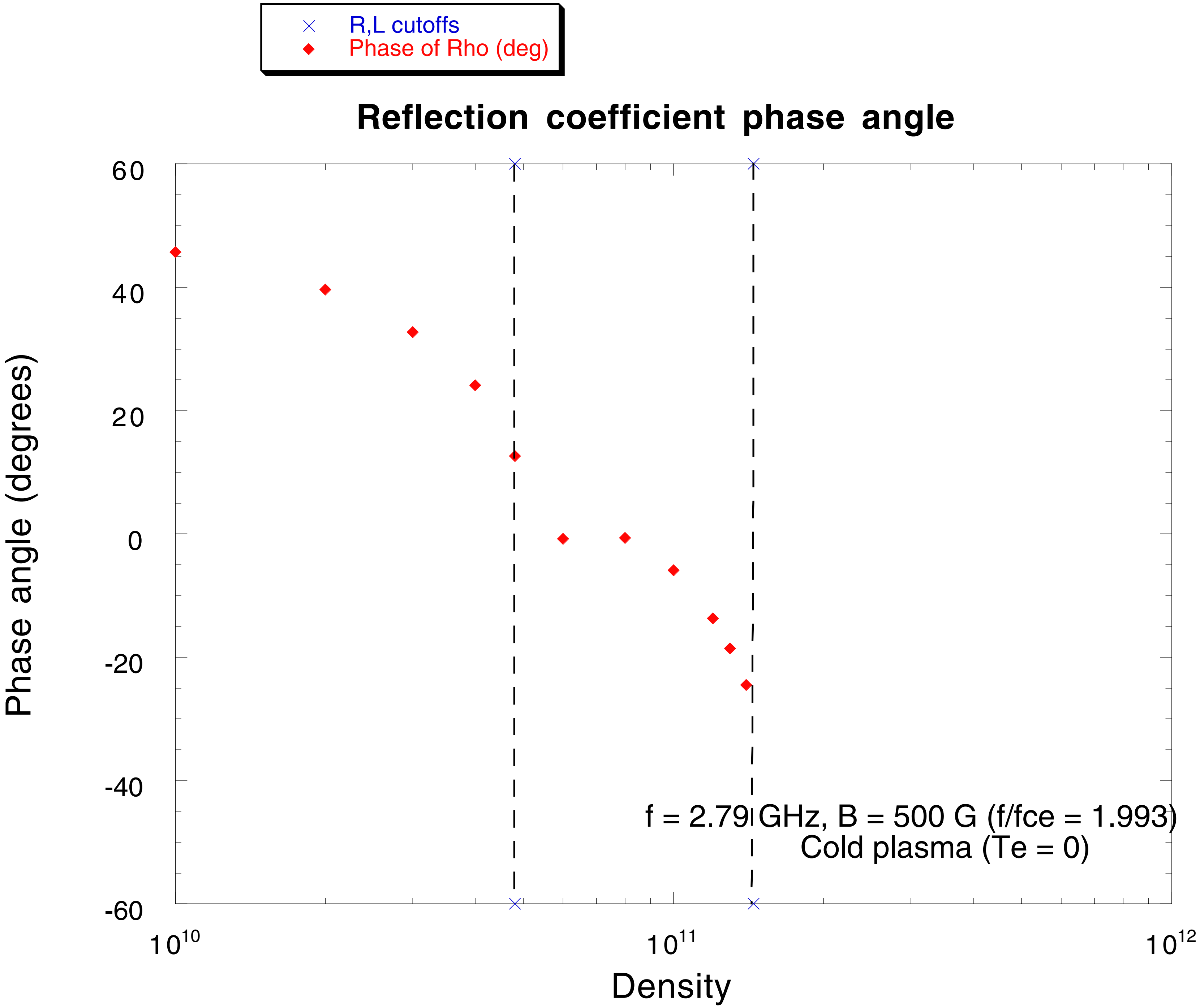
Primes are the frame in which $n_y=0$

Re[Y(ny)] for very electrostatic EBW; CDX-U-like parameters

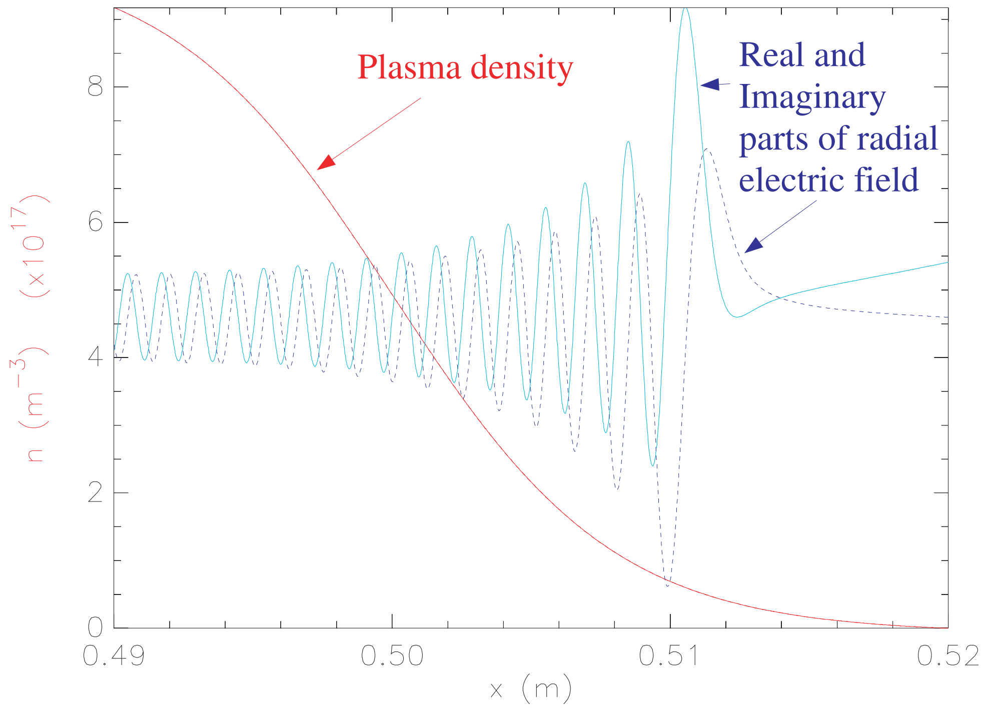


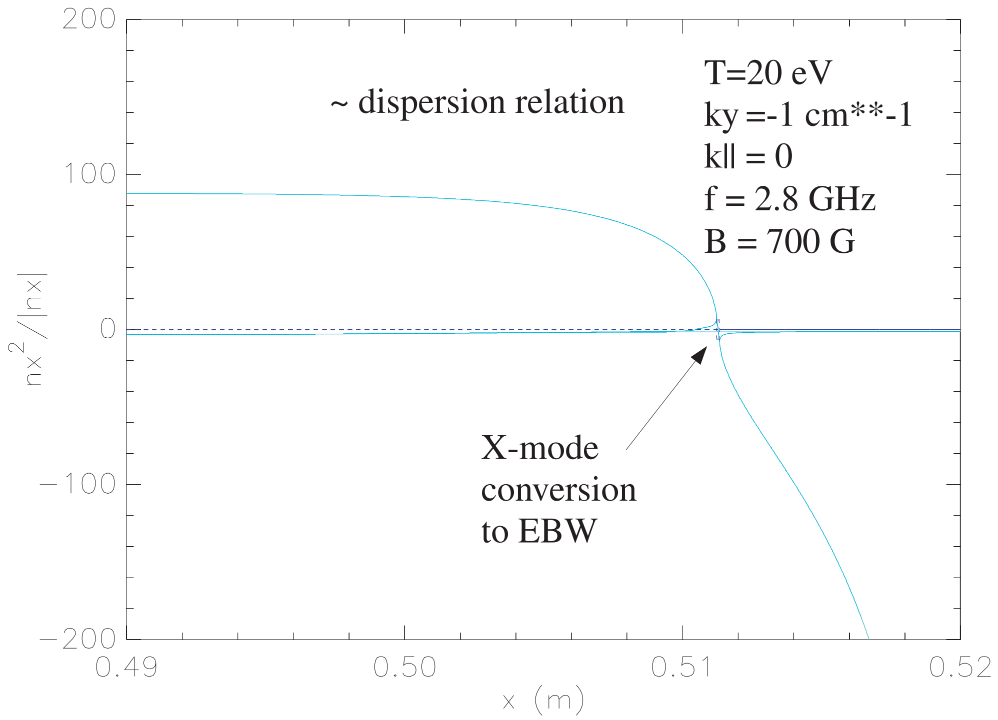


● |Rho|^2
× R,L cutoffs
Single waveguide, 2 cm high; cold plasma
Power Reflection Coefficient
1
0.8
0.6
0.4
0.2
0
10^{10}
10^{11}
10^{12}
Density
f = 2.791 GHz, B = 500 G (f/fce = 1.993)
Cold plasma (Te = 0)

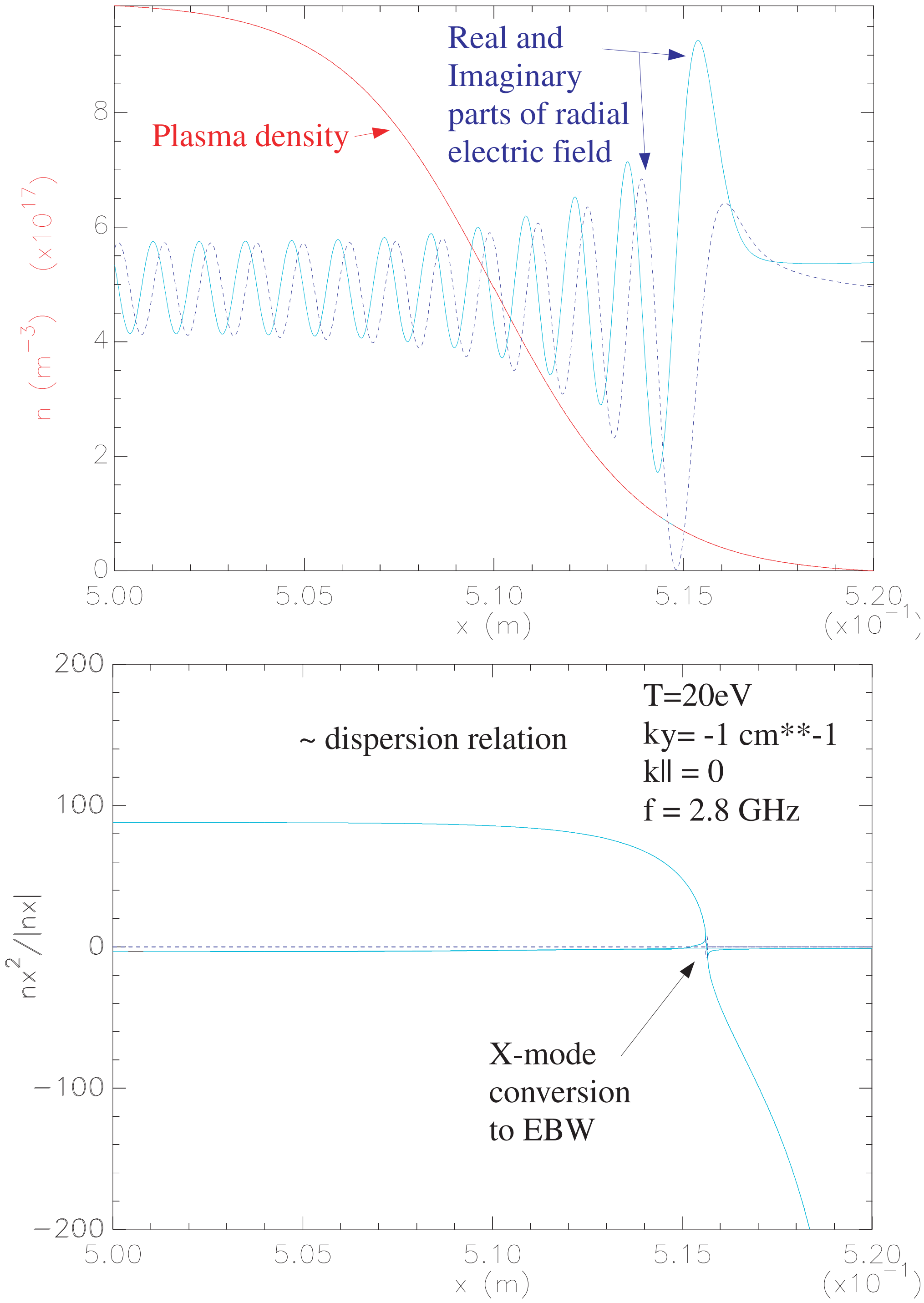

R,L cutoffs
Phase of Rho (deg)
Reflection coefficient phase angle
Phase angle (degrees)
60
40
20
0
-20
-40
-60
10^{10}
10^{11}
10^{12}
Density
f = 2.79 GHz, B = 500 G (f/fce = 1.993)
Cold plasma (Te = 0)

Full wave calculation of EBW mode conversion launch with GLOSI code; gentler density gradient case

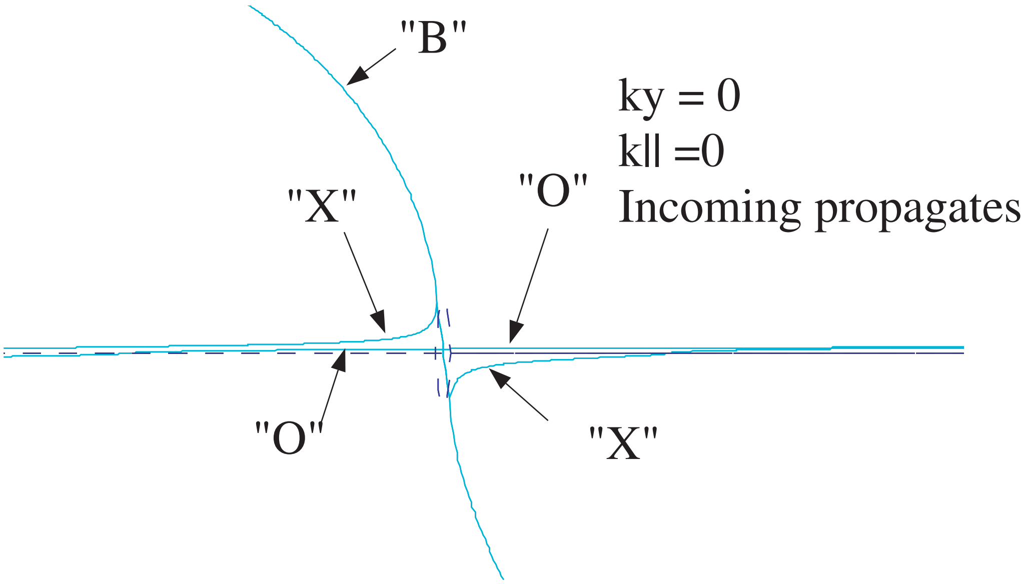


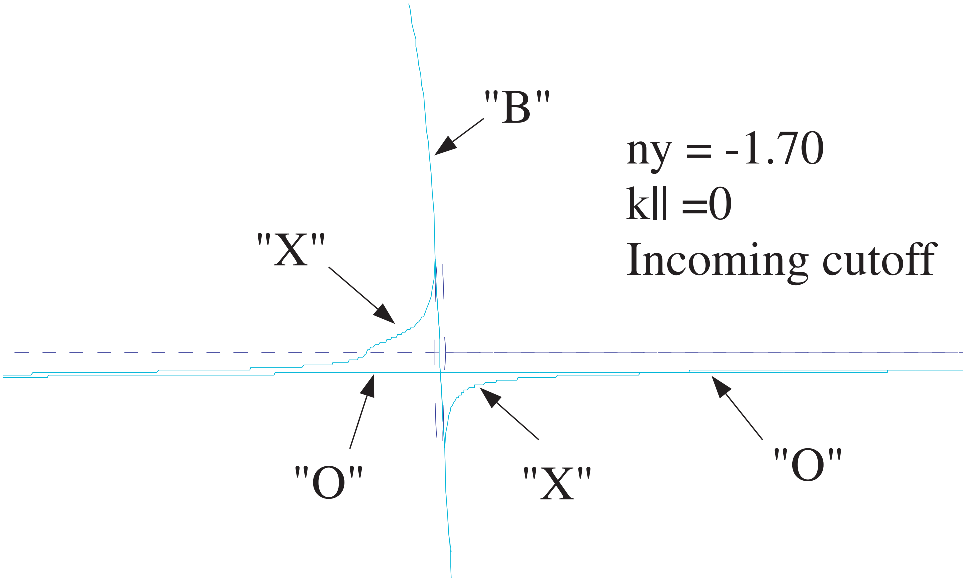


Full wave calculation of EBW mode conversion launch with GLOSI code; steeper density gradient case



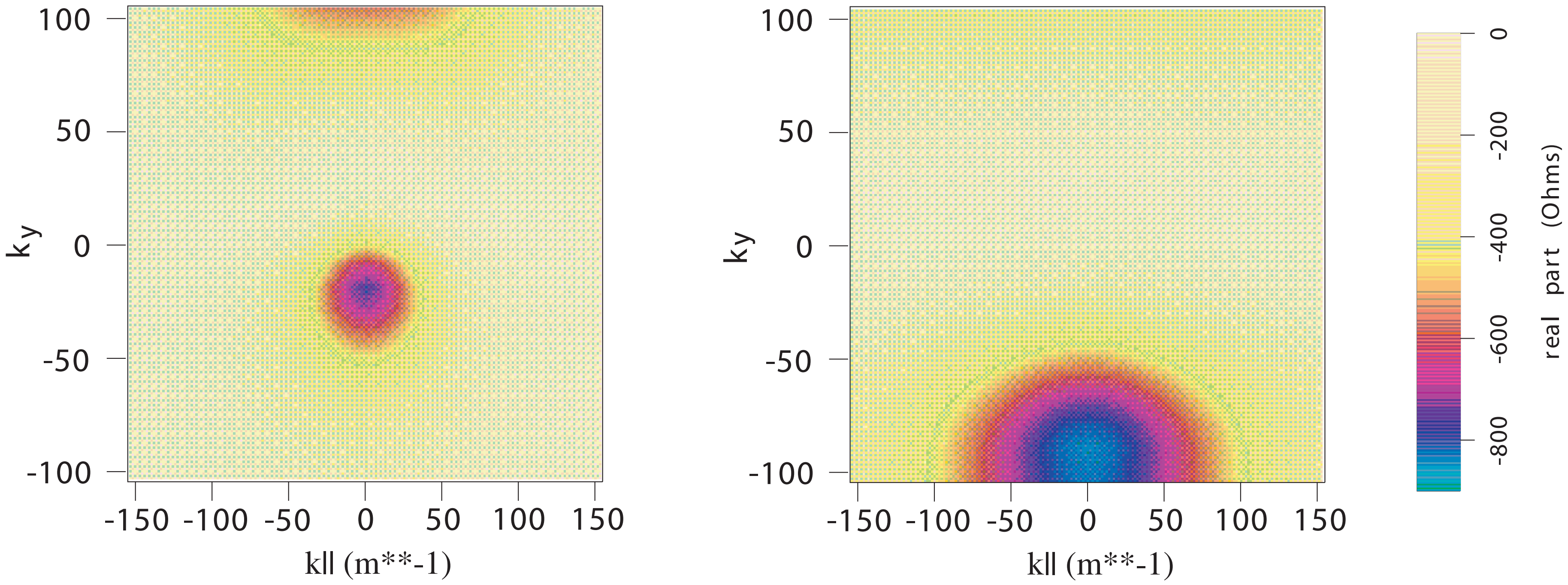
Enlargement of dispersion around upper hybrid





Real part of X polarization impedance can be very high

Steeper profiles provide higher loading, but best angle is further from radial, and asymmetry is stronger
(note: mode conversion not at same radial location)

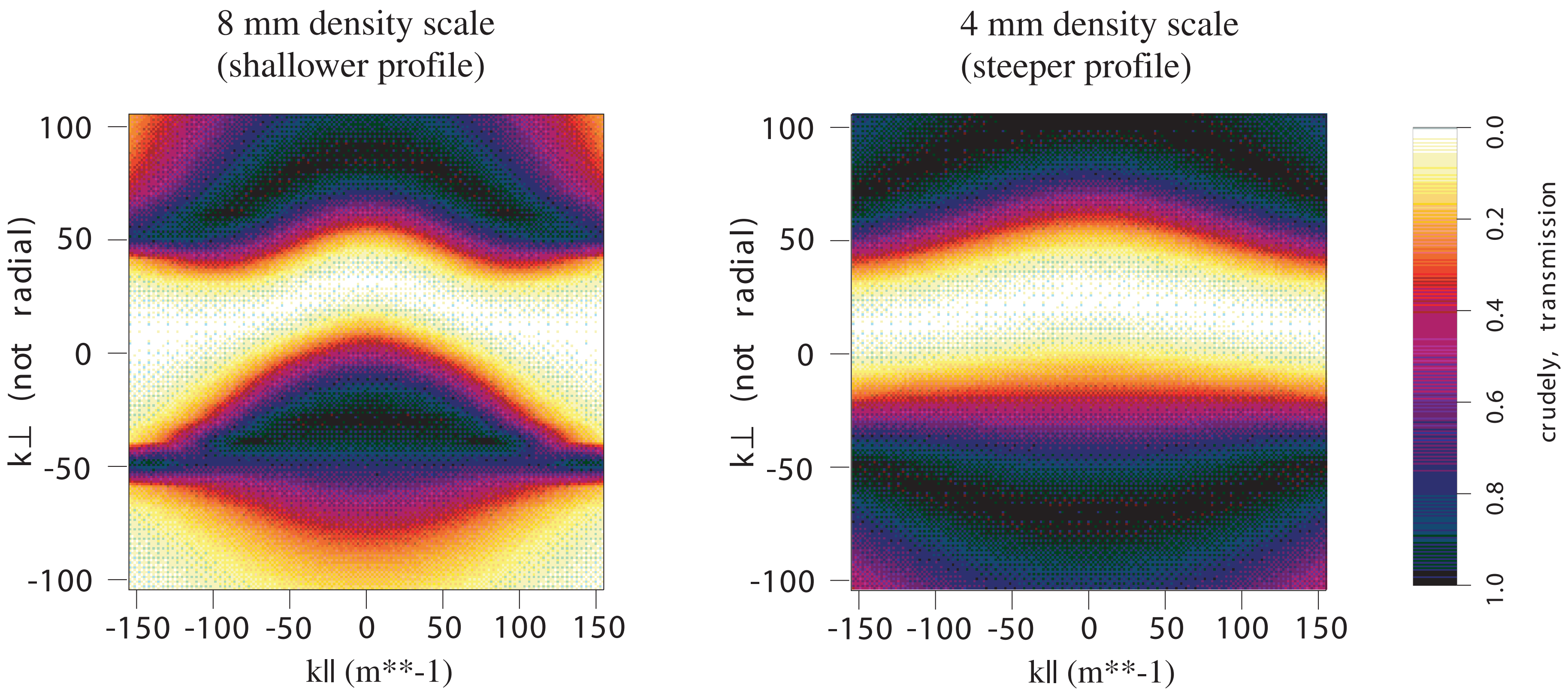


8 mm density scale
(shallower profile)

4 mm density scale
(steeper profile)

Real part of X polarization impedance normalized to total impedance is indicative of transmission through the mode conversion layer

Steeper profiles allow more modes to convert, but may cause more reflection for propagation straight in



Tentative conclusions

- Remarkably, it appears that rather low reflection coefficients and quite reasonable coupling can be obtained with a simple waveguide launcher for NSTX/CDX-U-like parameters for direct EBW launch
- Too large of a low density region (where X-modes propagate) can result in substantial power loss to coaxial types of surface waves
- Comparison between simple semi-analytic estimates of the surface impedance with full-wave (GLOSI) code calculations are just beginning
- Low power loading measurements for such a simple structure could begin quite soon on a number of devices