FP1.036 Coupling to the Electron Bernstein Wave With Waveguide Antennas: Theory and Experimental Results from MST

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The Electron Bernstein Wave (EBW) is of interest for both diagnostic applications and for heating and current drive in low field devices such as present spherical torus experiments and the reversed-field pinch (RFP). In these devices, neither X- or O-modes can propagate in the interior of the plasma. We compare the predictions of a generalized waveguide coupling code[1] to the experimental results from the MST RFP in which a pair of S-band waveguides were oriented to excite the X-mode (which couples to the EBW near the upper hybrid resonance) in the edge of the plasma. Good qualitative agreement between the predicted phase dependence of the reflection coefficient and the measured results is obtained. In particular, the predicted strong dependence of the coupling on the sign of the toroidal phasing was observed. Details of the experimental results are presented in the adjacent poster by Chattopadhyay, et al. (FP1.035)

[1] R.I. Pinsker, M.D. Carter, and C.B. Forest, in *Radio Frequency Power in Plasmas (Proc. 14th Top. Conf., Oxnard, CA, 2001*), (AIP, Melville, NY, 2001), p. 350.

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Introduction

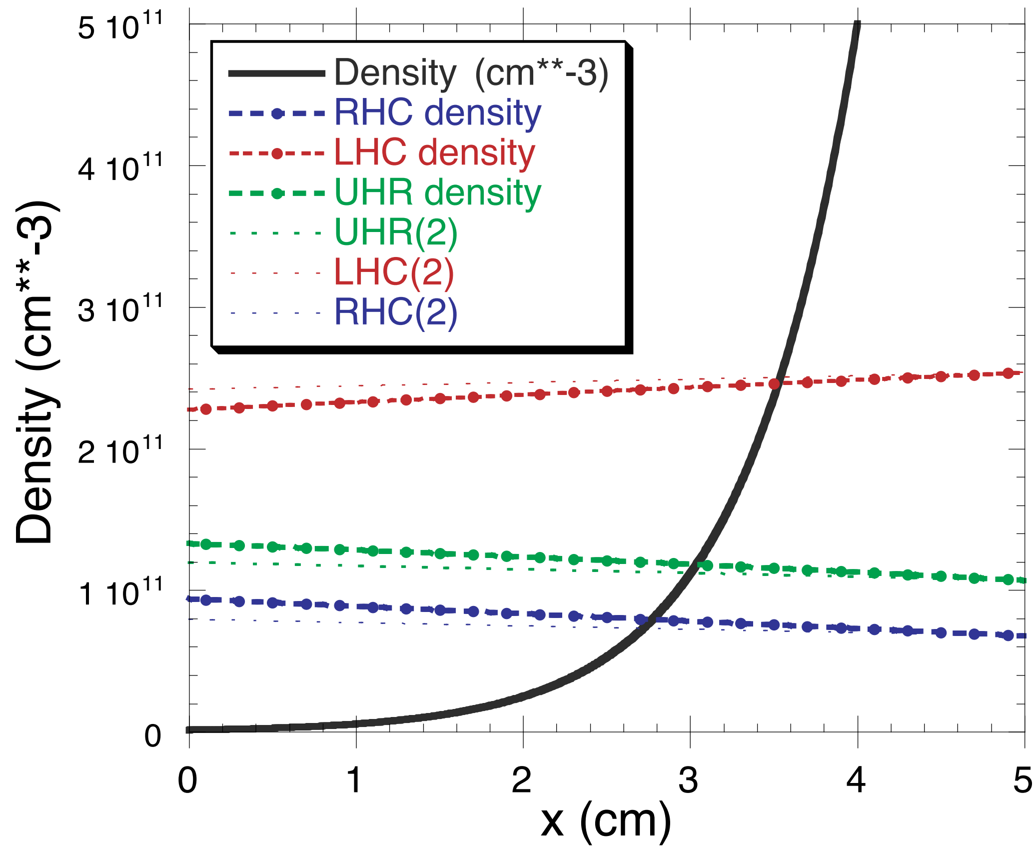
Electron cyclotron heating and current drive has proven very useful in toroidal plasma devices, due to its strong, localized absorption and its utter lack of coupling difficulties

However, wave physics dictates that in plasmas in which ${}^{2}_{pe} / {}^{2}_{e} \gg 1$ (low field / high density), conventional ECH is not possible as a method □ of heating the core plasma. For example, O- and X-modes can penetrate only to a density of a few $10^{11} cm^{-3}$ in RFP discharges in the Madison Symmetric Torus.

The Electron Bernstein Wave (EBW) has been investigated as a means of heating such plasmas by Ram, et al. Several methods of coupling to the wave by mode conversion from 'conventional' EC waves (O- and X-modes) have been studied

In the present work, we solve an antenna coupling problem relevant to this problem, in which the coupling structure is a phased waveguide array, similar to a LH grill

Density profile for 'standard' MST case, based on Langmuir probe measurements



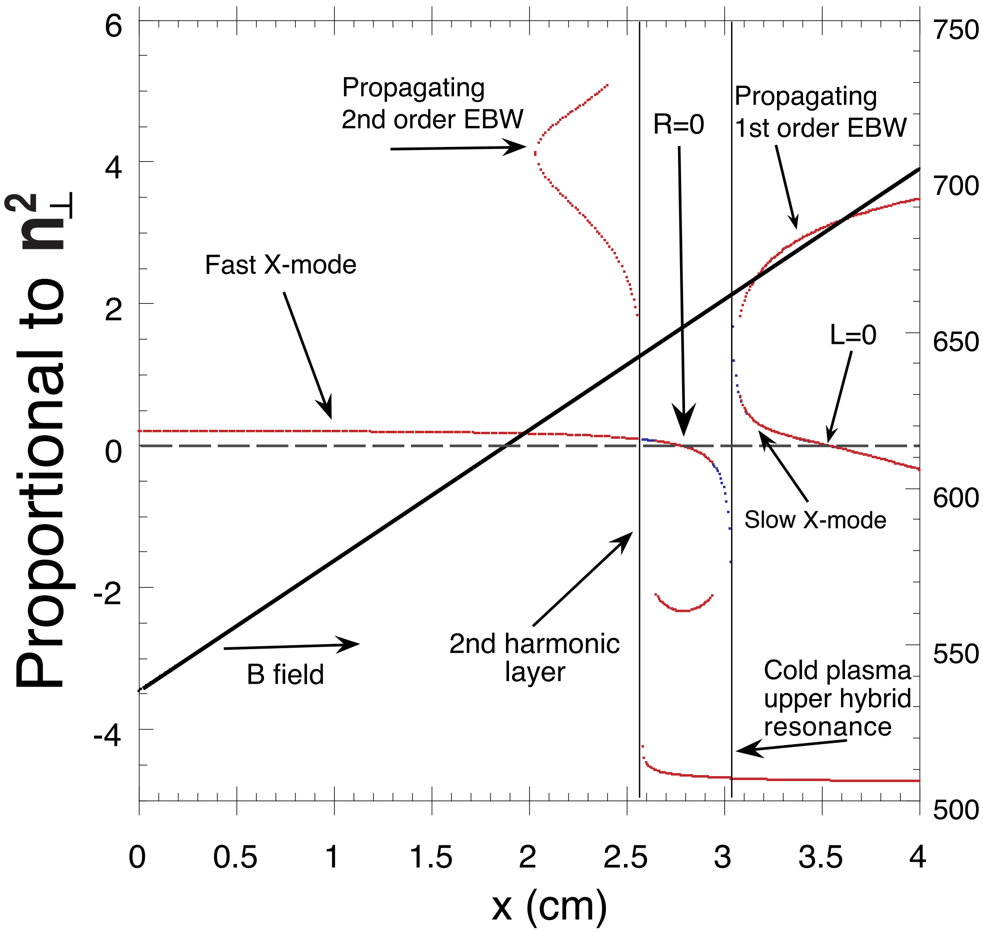
Fit of density profile data from MST to an exponential, showing cutoffs, UHR for f=3.6 GHz for two different linear B-field profiles:

1) B_p (G) = 535 + 41.8 G/cm * x (cm) [has 2nd harmonic near UHR]

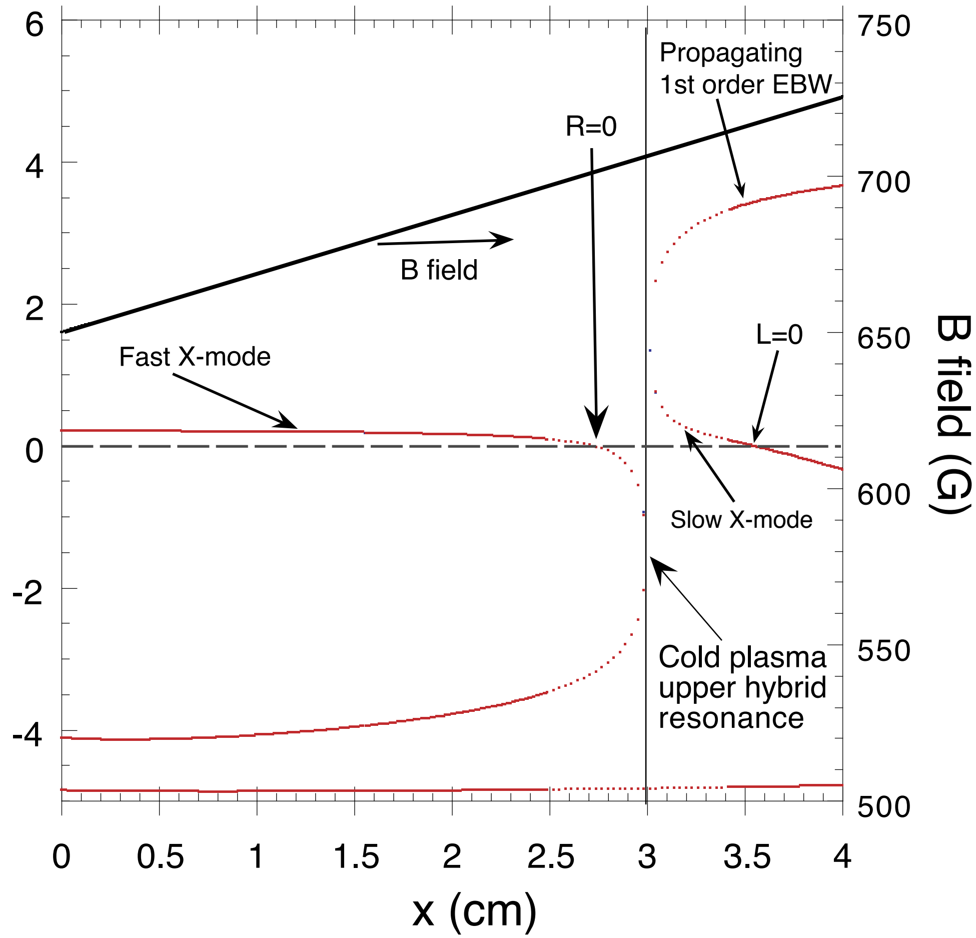
2) B_p (G) = 650 + 18.8 G/cm * x (cm) [no 2nd harmonic]

'Straight-in' dispersion of X-mode and EBW in MST edge region

X–mode, EBW dispersion in case with $\omega = 2\Omega_e$ resonance on low density side of upper hybrid resonance



X–mode, EBW dispersion without second harmonic resonance



Note that the vertical scale is approximately $\log_{10}(|n_\perp^2|)$ for $|n_\perp^2| >> 1$, and is linearly proportional to $n_\perp^2$ for $|n_\perp^2| << 1$

Application of 'rules of thumb' of Ram, Bers, et al.

For 'straight-in' propagation, i.e., $k_y = k_z = 0$, we may apply the theory of Ram and Bers to evaluate the practicality of the X-B and O-X-B schemes

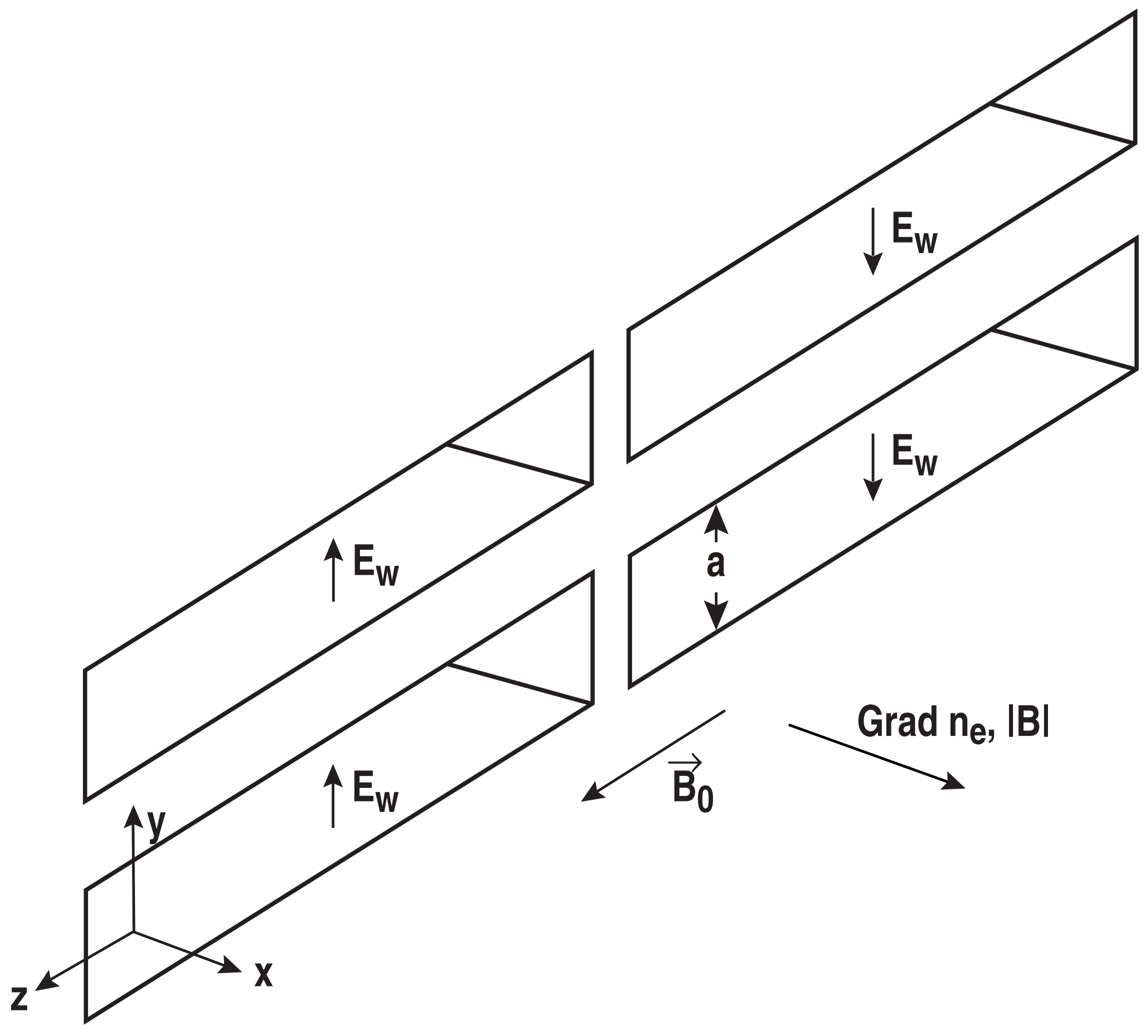
Evaluating the Budden tunneling parameter, $= {}_e L_n / c \times F(L_n / L_B, {}_{pe} / {}_e)$, in which F is an algebraic function, for the MST-like density and B-field profile, we get that the B-field gradient is unimportant compared to the density gradient, and that 0.11, about half of the optimal value for X-B conversion

The fact that $<< 1$ shows that the gradient is much too steep for the WKB approximation ('adiabatic') to be useful, and that the equivalent of the 'sudden' approximation, i.e., matching of boundary conditions across a step change in parameters, is more appropriate here

$<< 1$ also implies that the O-X-B scheme will not be effective here, since there is too much 'leakage' from the slow X-mode inside the upper hybrid resonance out via the fast X-mode

However, these simple considerations do not apply for k_y, $k_z \neq 0$, so for a phased array antenna at phasings other than 0, we must use a more complete model

Slab geometry of coupling problem



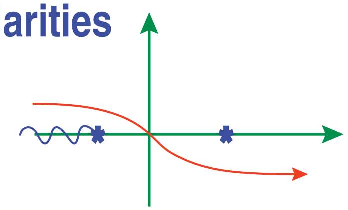
Solution obtained by Brambilla's method

- Matching Ey at x = 0, B_z only in waveguide opening, for simplest case we can write down an equation for the waveguide reflection coefficient ρ:

$$\frac{1-\rho}{1+\rho} \equiv \Lambda = \frac{(k_0 a/2)}{\pi\sqrt{\varepsilon_w}} \int dn_y\, \underbrace{Y(n_y)}_{\text{plasma admittance}} \underbrace{\frac{\sin^2\left(\frac{k_o a}{2} n_y\right)}{\left(\frac{k_o a}{2} n_y\right)^2}}_{\text{antenna spectrum}}$$

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

- Integral must be performed over the path determined by causality if there are any singularities of Y (n_y) for real n_y, such singularities representing surface modes, for example



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

- Plasma physics is entirely embedded in the admittance calculation; spectrum merely provides the weighting appropriate to a given antenna, phasing, etc.

- Surface admittance can be obtained analytically for a uniform plasma, with or without a vacuum gap between the conducting plane at x = 0 and the half space filled with uniform plasma

More notes on the solution of the Brambilla problem

- For more realistic density profiles, admittance must be obtained by numerical integration of the wave equation from a point within the plasma where an outgoing wave boundary condition (radiation condition) is applied back to the wall at $x = 0$

- Surface admittance of uniform plasma, with or without vacuum gap, exhibits poles corresponding to surface modes - these non-pentrating modes nevertheless couple to the upper hybrid resonance (thence to the EBW in a warm plasma) via their radially evanescent fields, as only a few millimeters separate the region of surface wave propagation (near $R=0$) and the UHR (at $S=0$)

- As finite density gradient is introduced, these 'not quite' surface modes are also damped by phase mixing, analogous to Alfven wave heating problem, but for parameters like MST, it appears that damping due to proximity of UHR dominates

- Efficient coupling to the UHR (= to the EBW) appears to be possible with the surface wave-like mode as intermediary: the antenna near fields excite the surface mode propagating in the y-direction and the surface wave's fields excite the UHR, thus coupling the energy to the EBW which then (slowly) propagates inwards and damps

Computation of the surface admittance in three ways

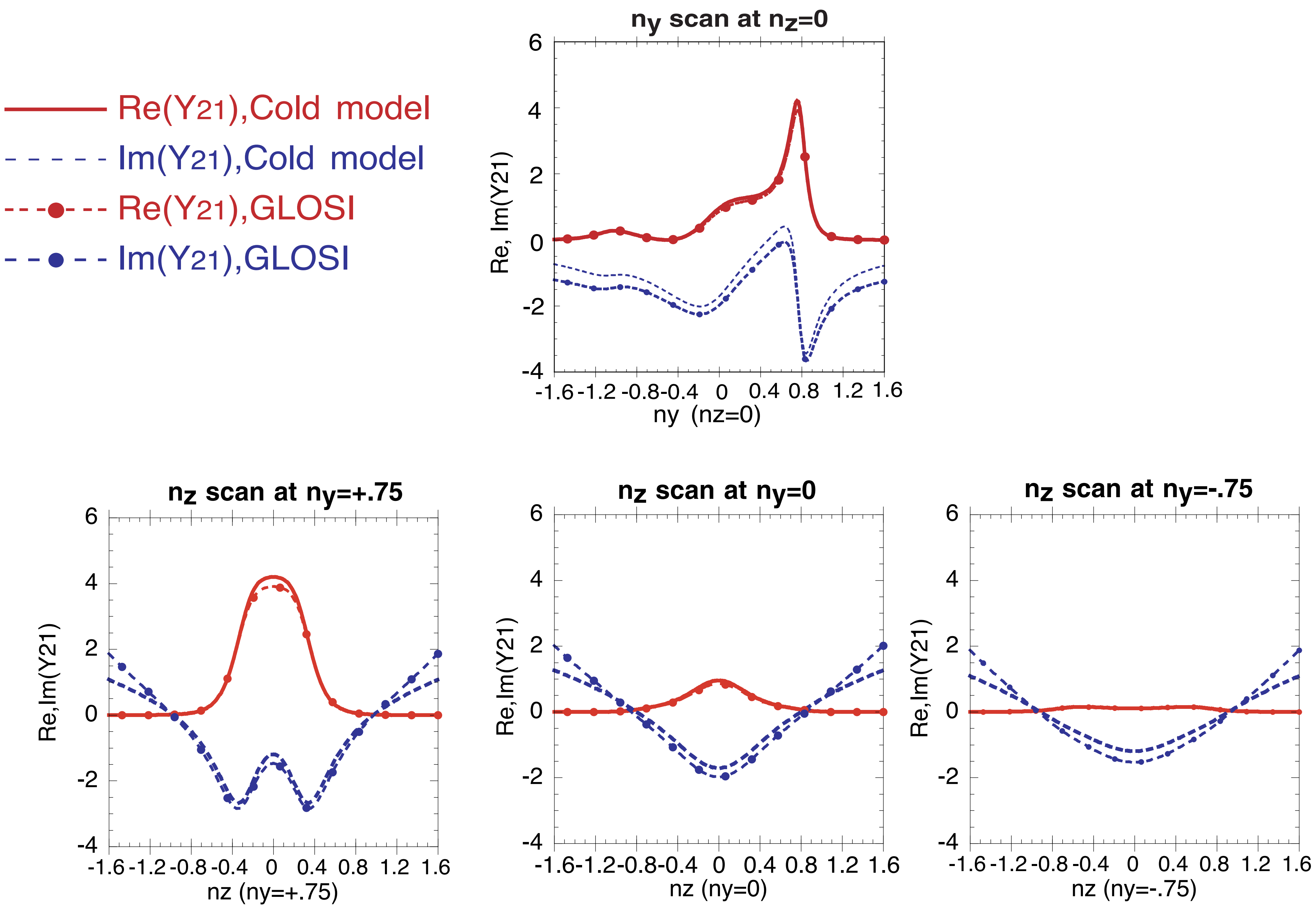
- We have combined a calculation of grill-type coupler fields with computations of surface admittance, the latter performed in three different way with two different models of the plasma dielectric response:

  a) GLOSI [ORNL] - hot plasma model incorporating the lowest order EBW ($\Omega_e<\omega<2\Omega_e$)
  b) Weakly collisional cold plasma model, computed with explicit numerical scheme (GA)
  c) Weakly collisional cold plasma model, computed with implicit numerical scheme (U. Wisc.)

- Agreement between the two numerical methods [(b) and (c) in the above] is within the allowed numerical error. The explicit scheme is much faster, but not as general as the implicit scheme, which was formulated by Svidzinski. For most cases in the regime of interest here, either method works equally well.

- Agreement between surface admittance computed with weakly collisional cold plasma model and GLOSI model is excellent, particularly for the real part of Y_{21}. Hence, there is no Te dependence of the surface admittance up to very high values of Te (at which the electron gyroradius becomes comparable to the gradient scale lengths and the hot plasma model in GLOSI becomes inapplicable).

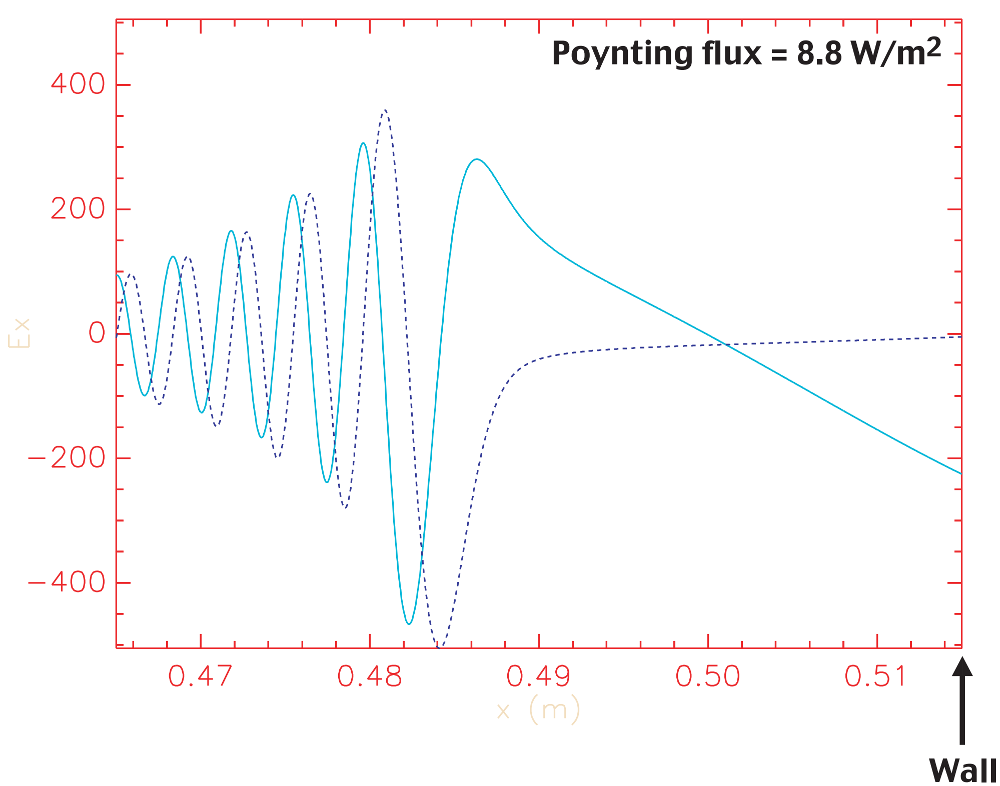
Comparisons of surface admittances Y21 computed with cold plasma model and GLOSI



GLOSI clearly demonstrates that the peak in coupling corresponds to a peak in mode-conversion efficiency to the EBW

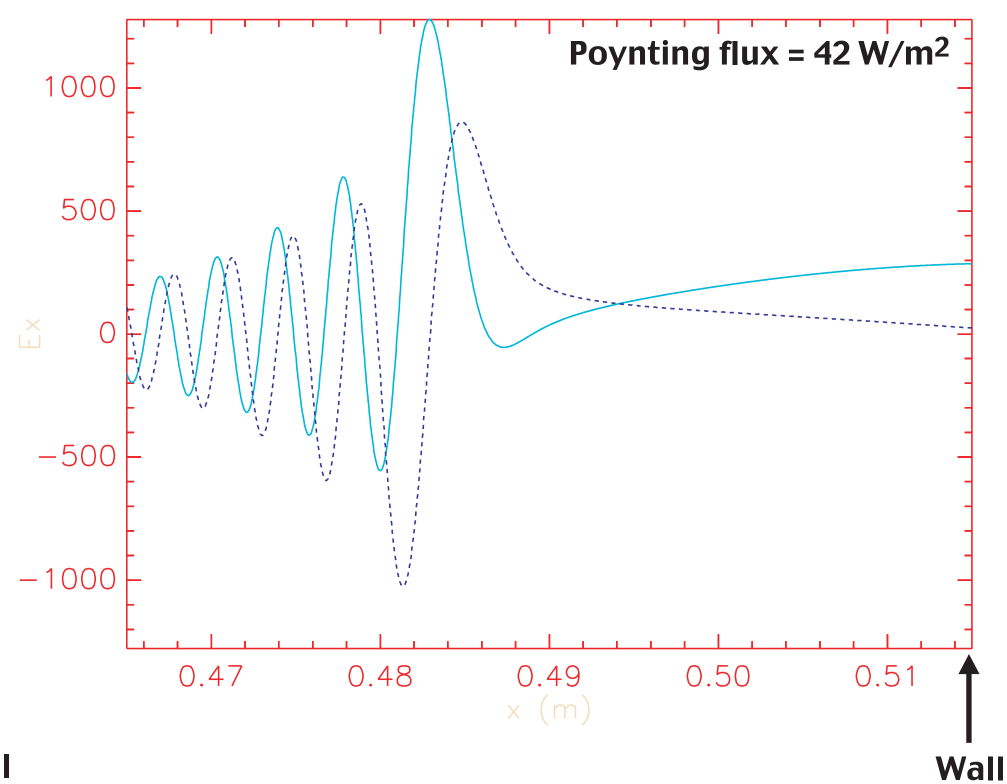
n_y=-0.75, n_z=0

Re, Im E_x



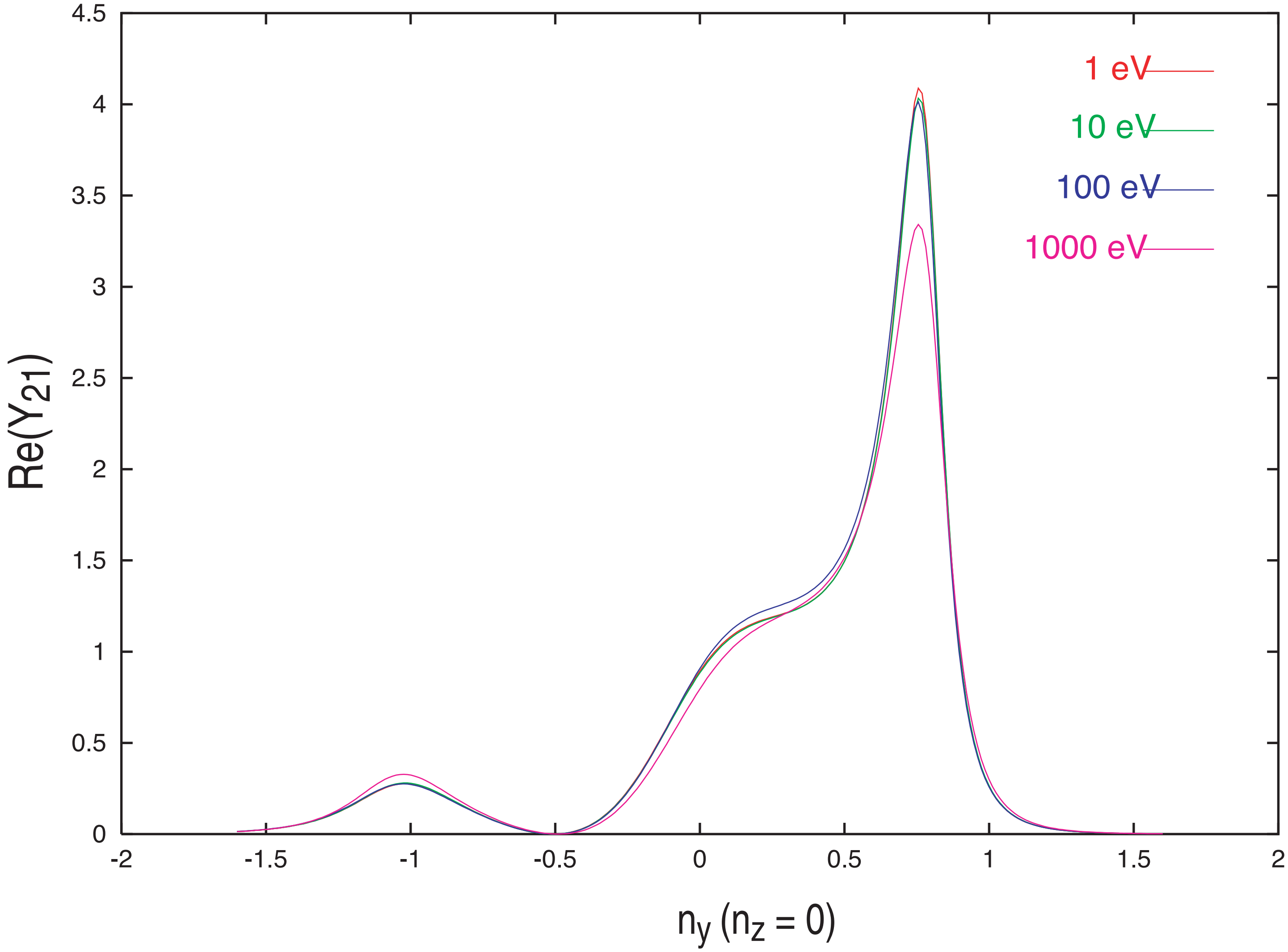
n_y=+0.75, n_z=0

Re, Im E_x



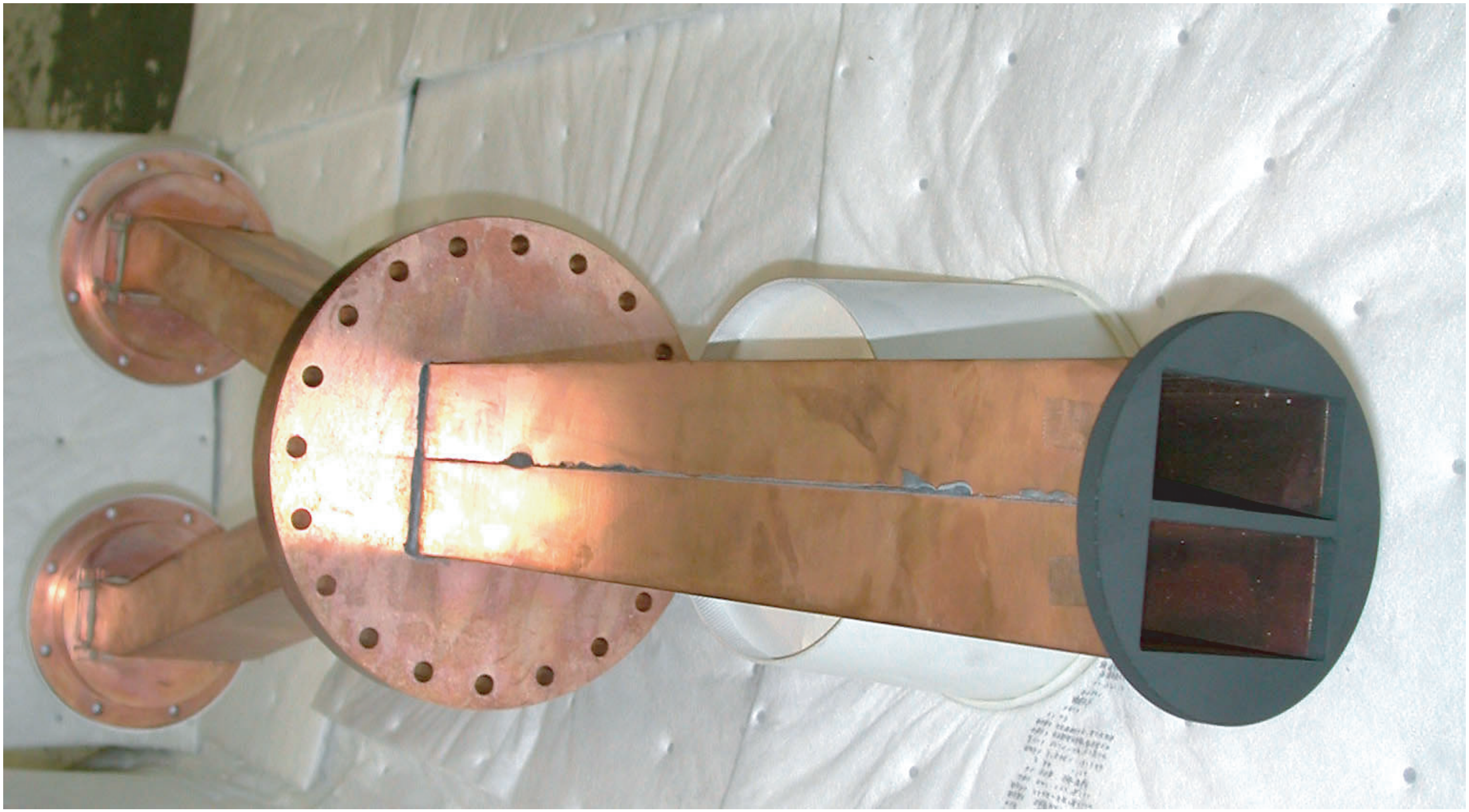
← **Energy propagation direction in GLOSI (increasing density)**

GLOSI shows that the surface admittance is almost independent of T_e, as expected



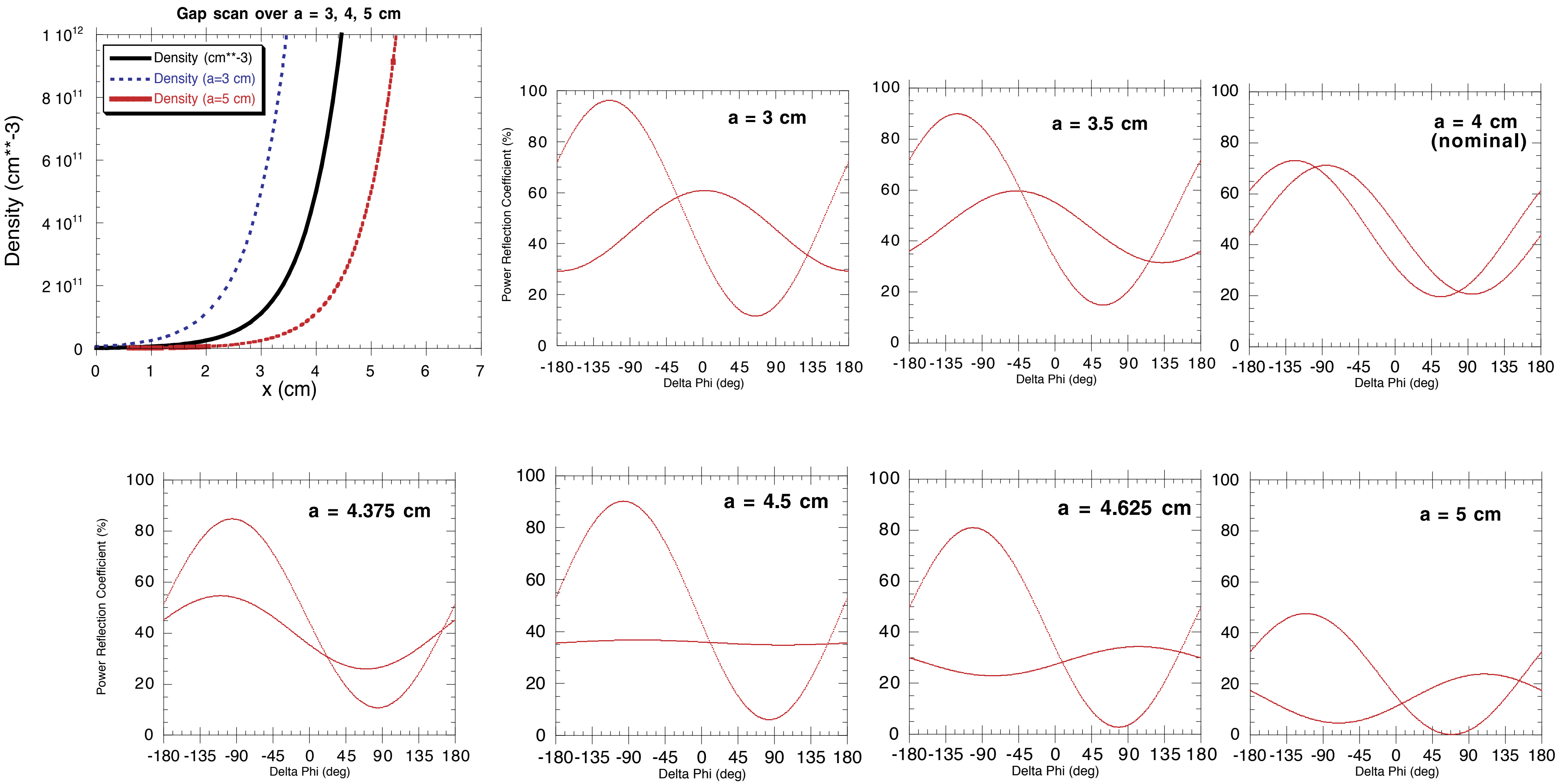
Note that at T_e = 1 keV, the electron gyroradius is about 1.1 mm, compared with the density gradient scale length of 6.6 mm

Twin waveguide coupler is being used in EBW coupling experiments on Madison Symmetric Torus



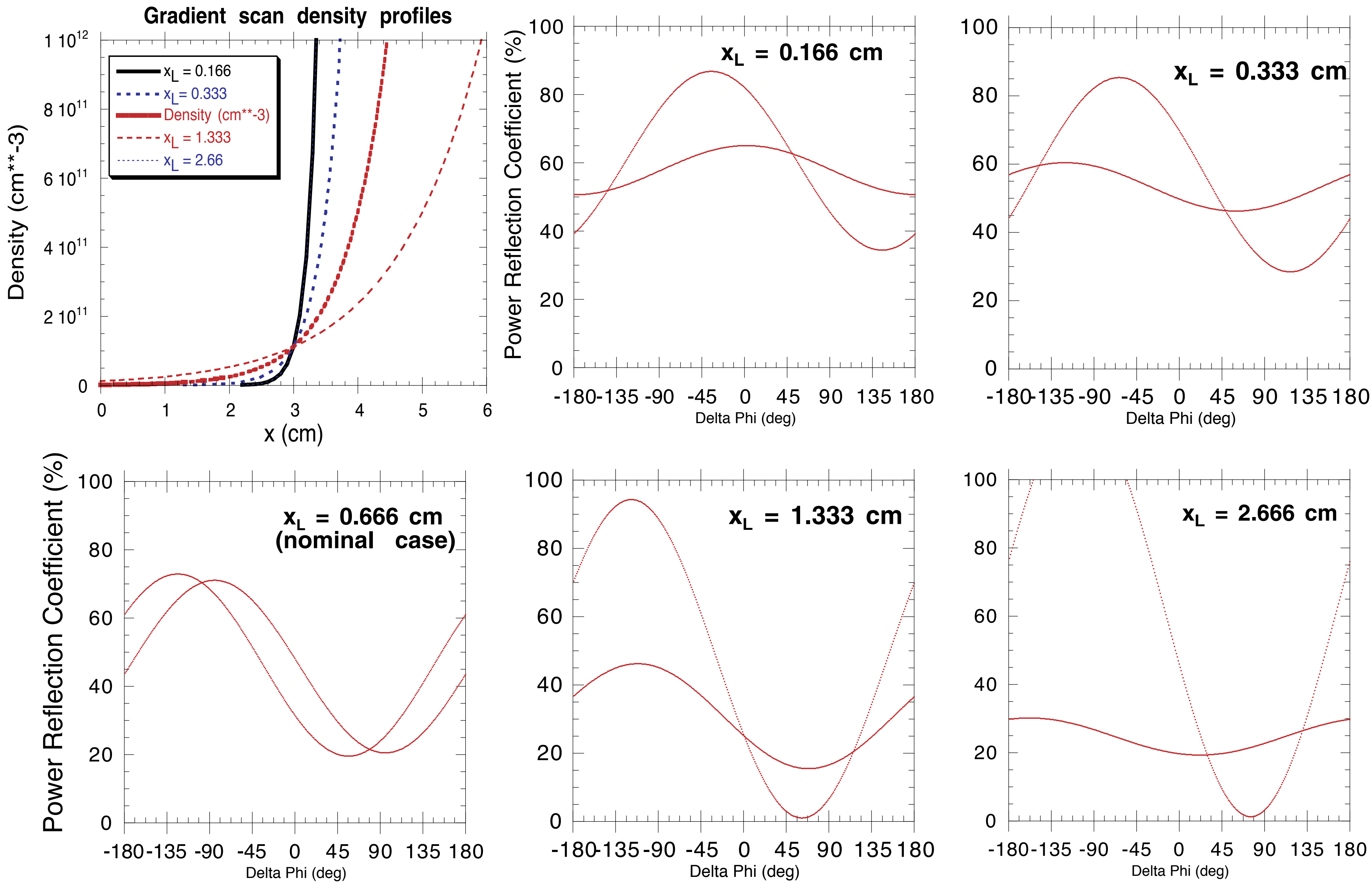
Waveguide openings are 7.21 cm X 3.454 cm (S band); guides can be oriented to excite either O- or X-mode

Scan of 'gap', for X-mode coupling, y-phasing, two-guide array



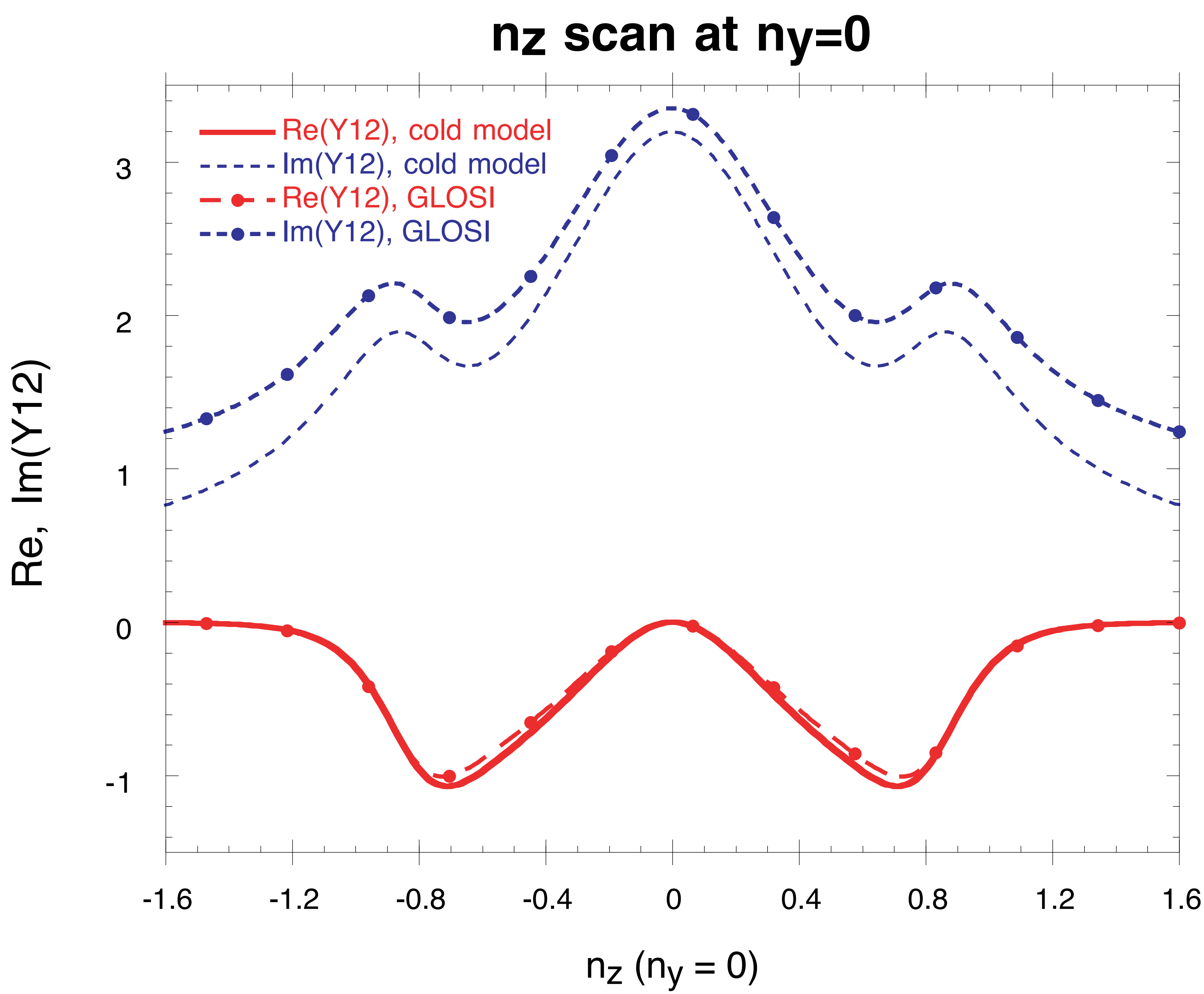
Density profile = $n_0 * \exp([x-a]/x_L)$

Scan of gradient scale length, X-mode coupling, y-phasing, two-guide array

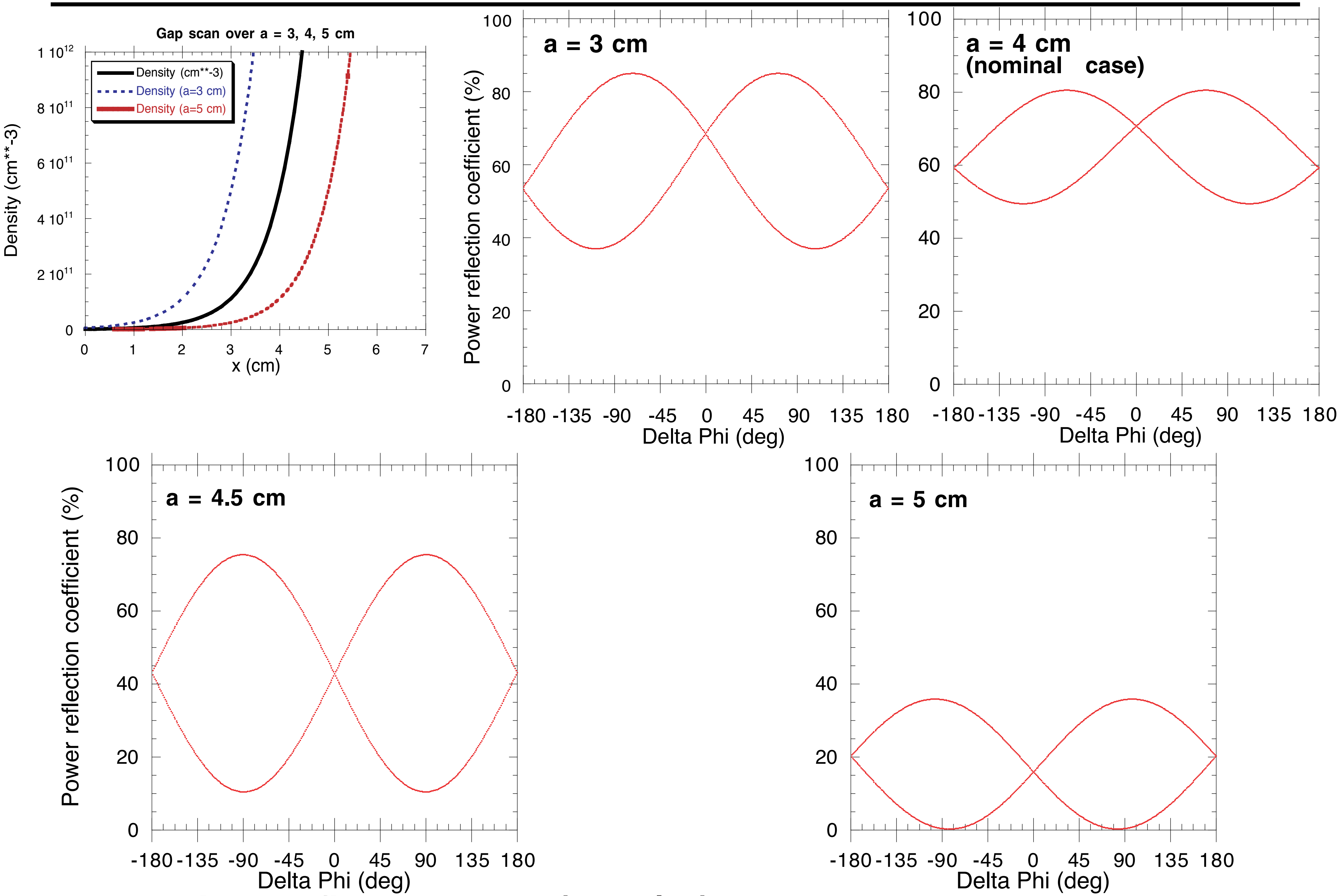


Density profile = $n_0 * \exp([x-a]/x_L)$

Comparison of surface admittances Y12 computed with cold plasma model and GLOSI

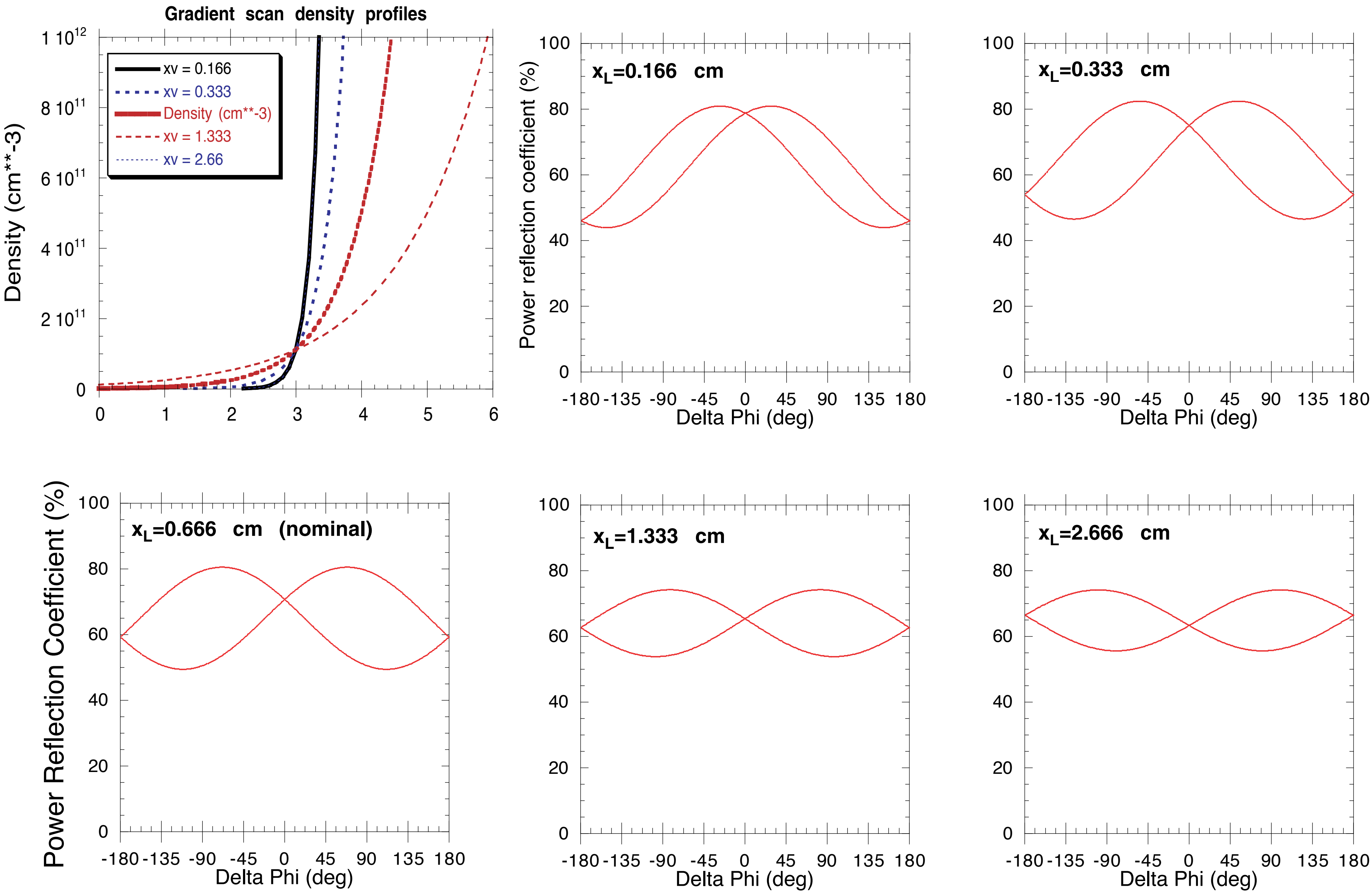


Scan of 'gap', for O-mode coupling, z-phasing, two-guide array



Density profile = $n_0 * \exp([x-a]/x_L)$

Scan of gradient scale length, O-mode coupling, z-phasing, two-guide array



Density profile = $n_0 * \exp([x-a]/x_L)$

Conclusions

- The modified waveguide coupling code can compute EBW coupling

- For X-mode coupling, a strong 'y'-phasing (toroidal for the RFP) asymmetry is predicted for the MST case, resulting from the properties of the surface-like mode, to which most of the power can be coupled. Good coupling via the X-B scheme is predicted for MST, at the optimum toroidal phasing

- By contrast, coupling via the O-X-B scheme is predicted to be rather poor, in agreement with the results of Ram, et al., and completely symmetric with respect to the sign of the (poloidal) phasing

- No dependence of the waveguide reflection coefficients on the edge electron temperature should be observable, even though that parameter determines the wavelength of the EBW

- This predictions are, so far, entirely in agreement with the measurements, as is shown in detail in Chattopadhyay, et al. in the adjacent poster

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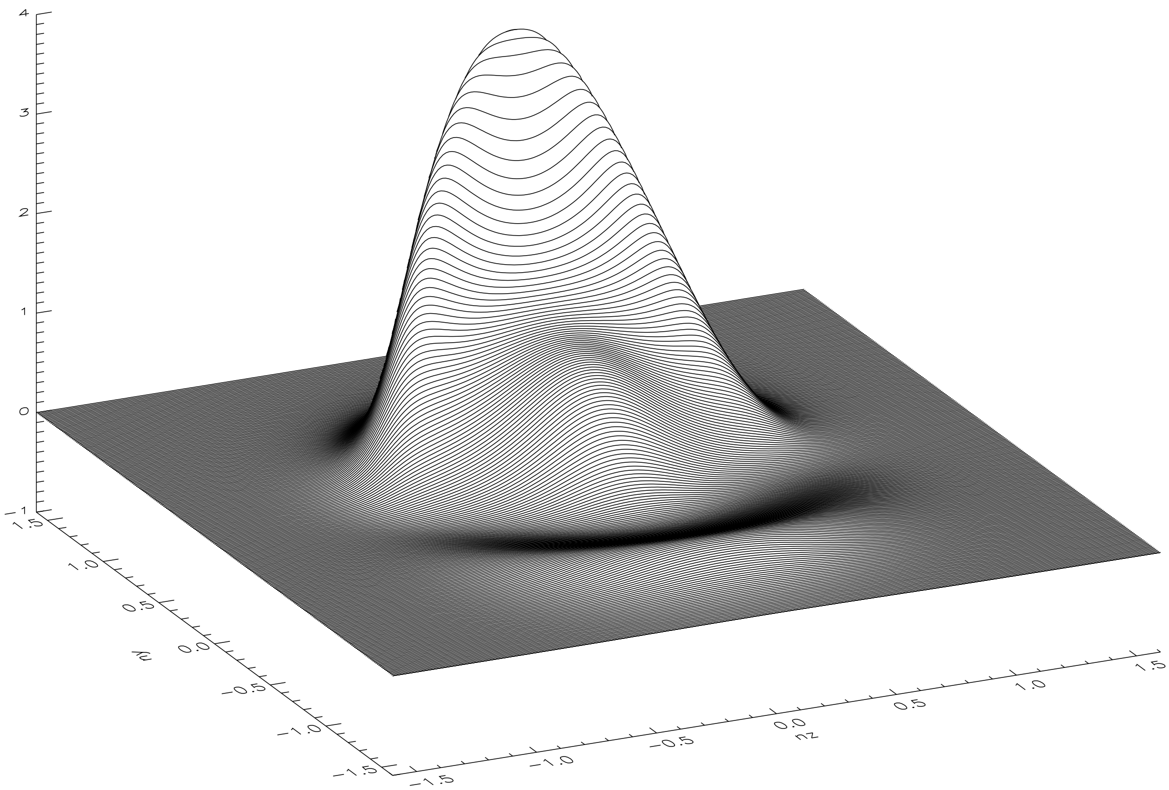
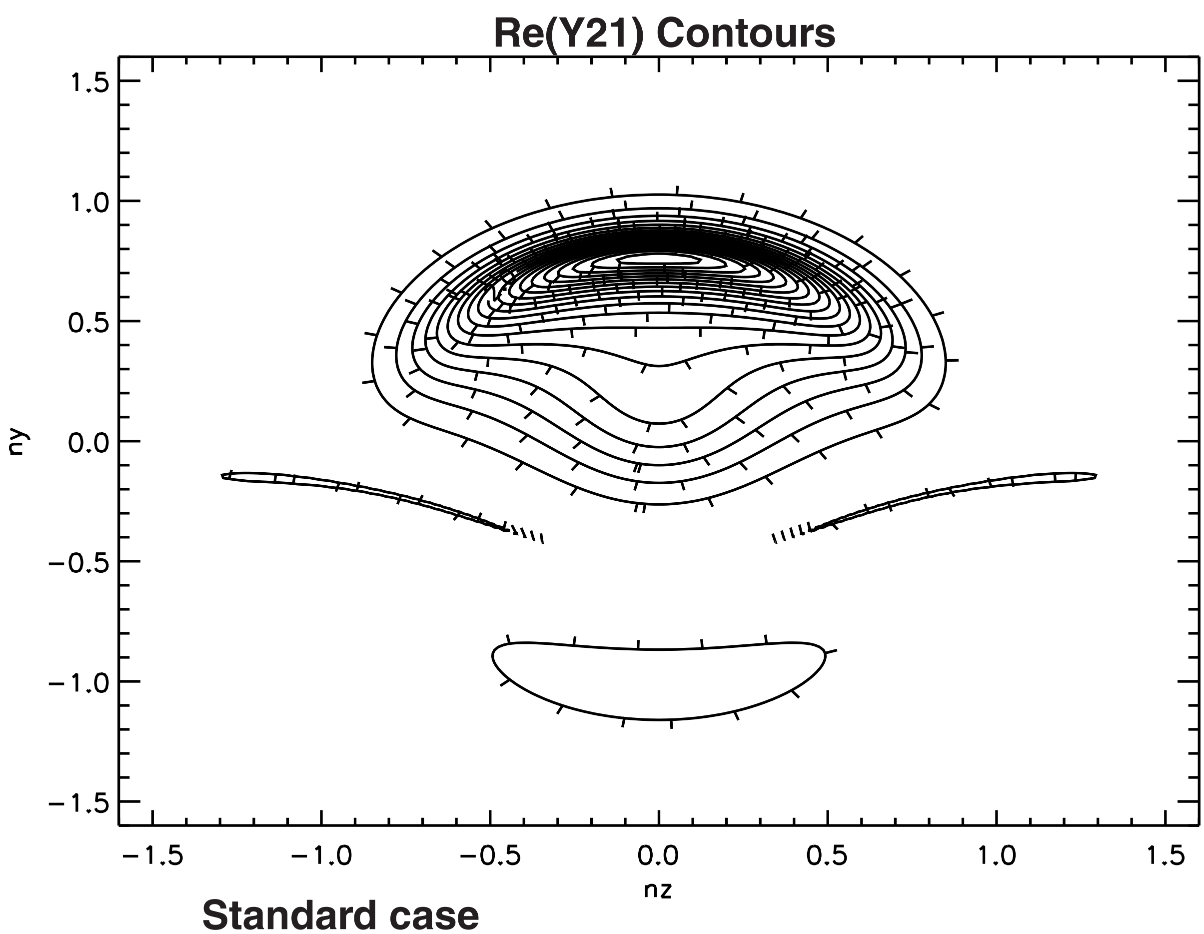
Appendix

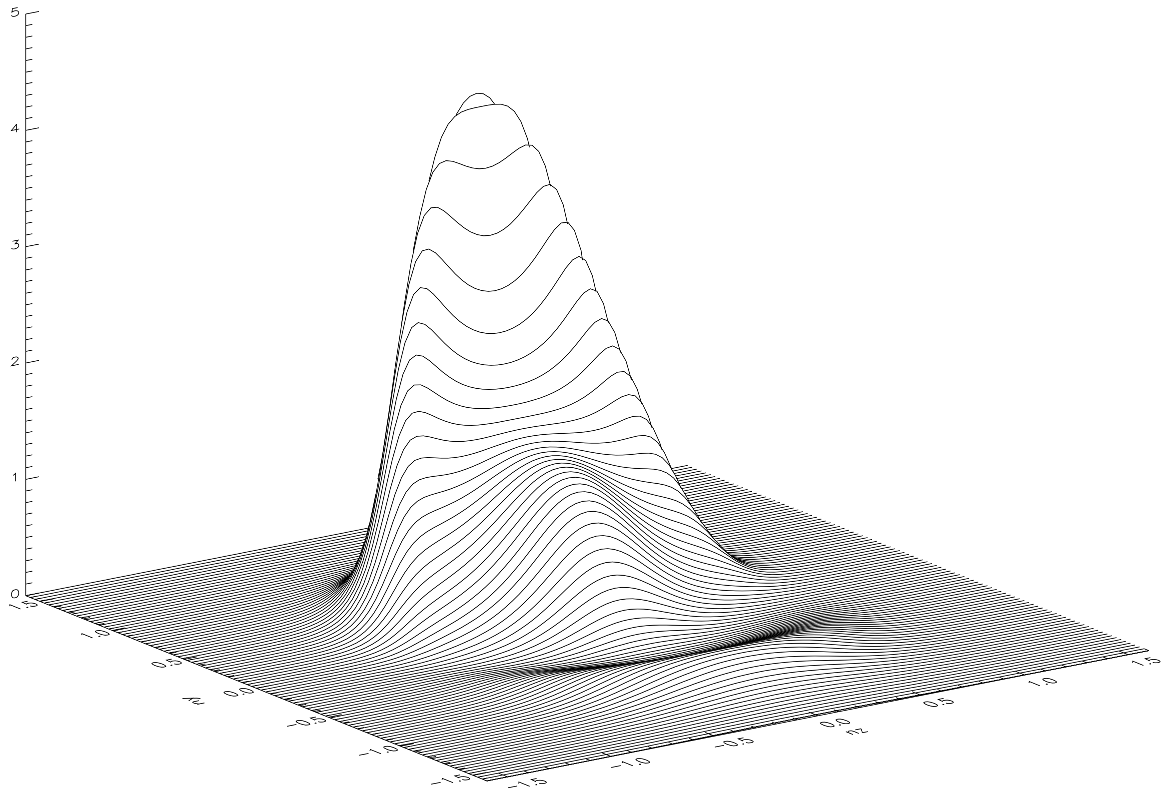
Calculations of admittance matrix elements for standard case computed with GLOSI and with the cold plasma model, and for a half–space filled with uniform lossy cold plasma



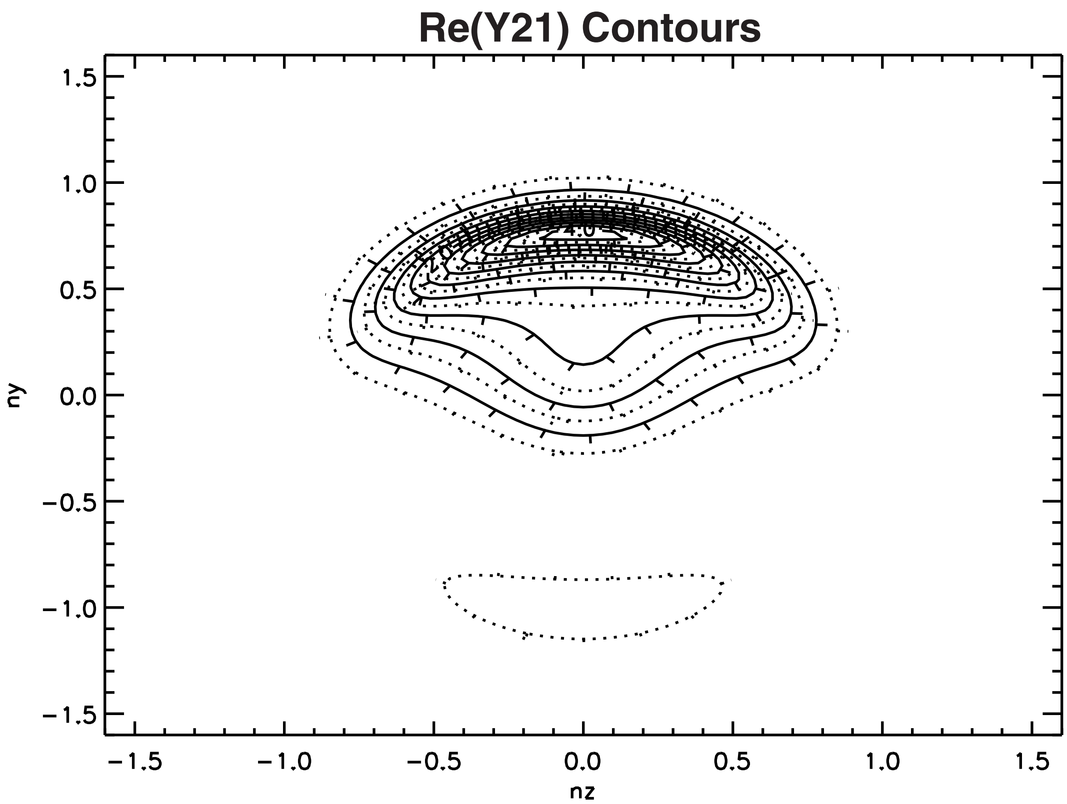
Re(Y21) surface from GLOSI calculation



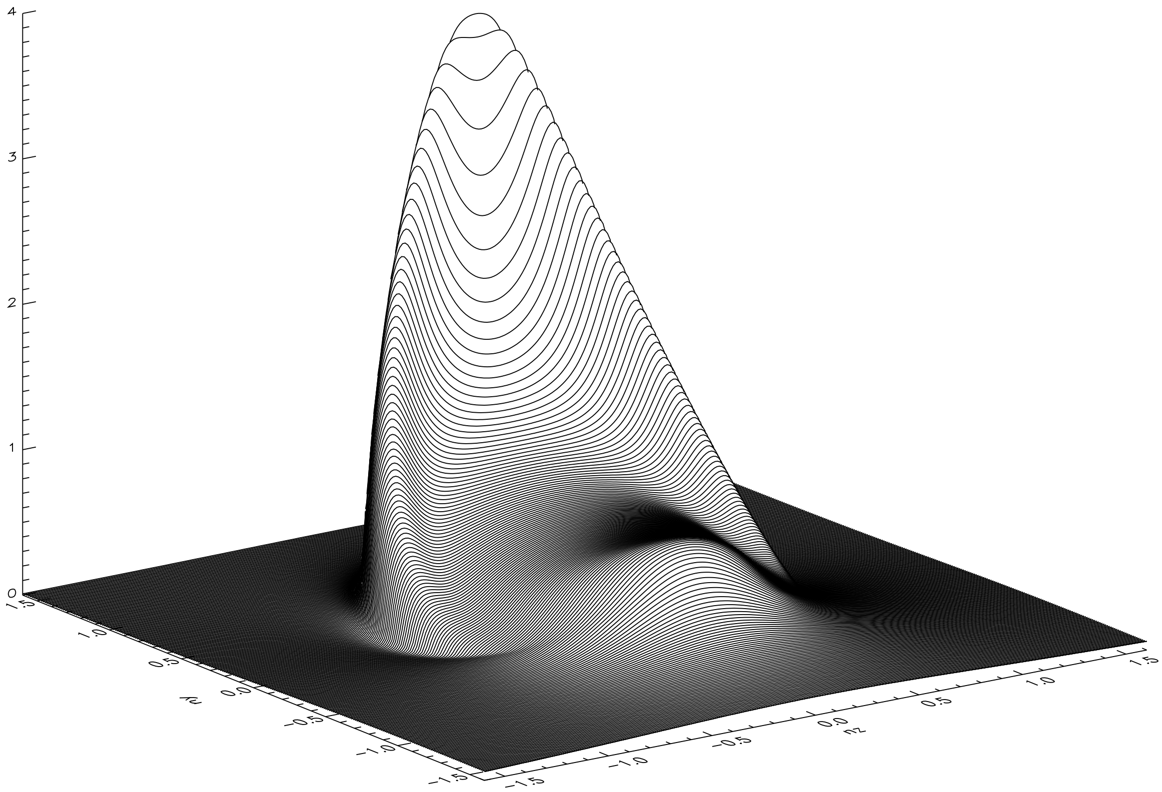
Standard case



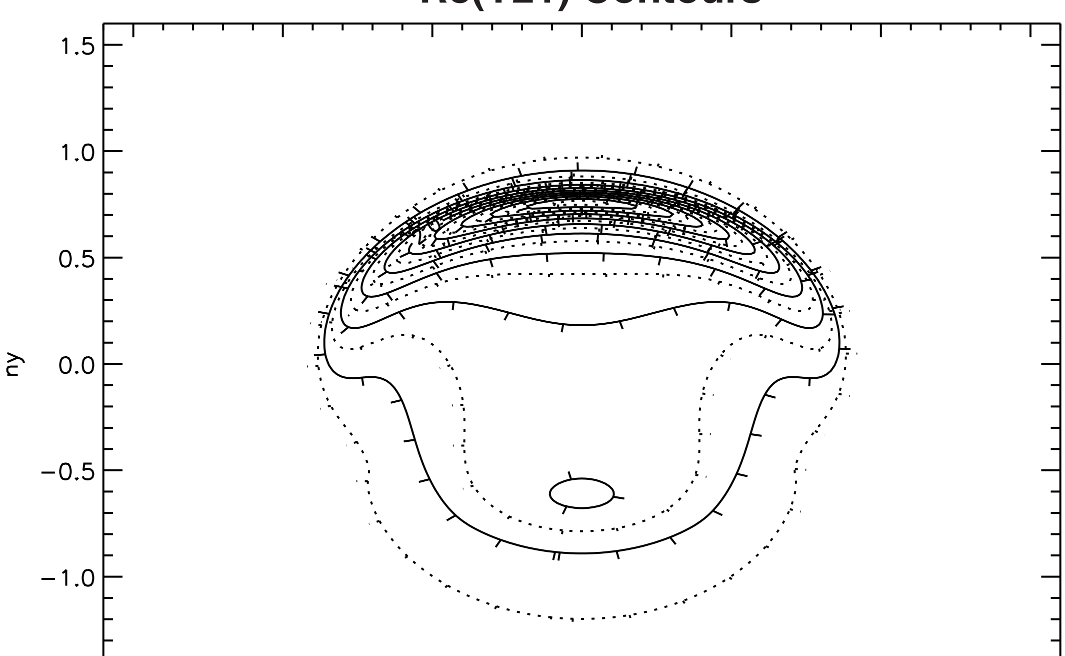
Re(Y21) surface for standard case



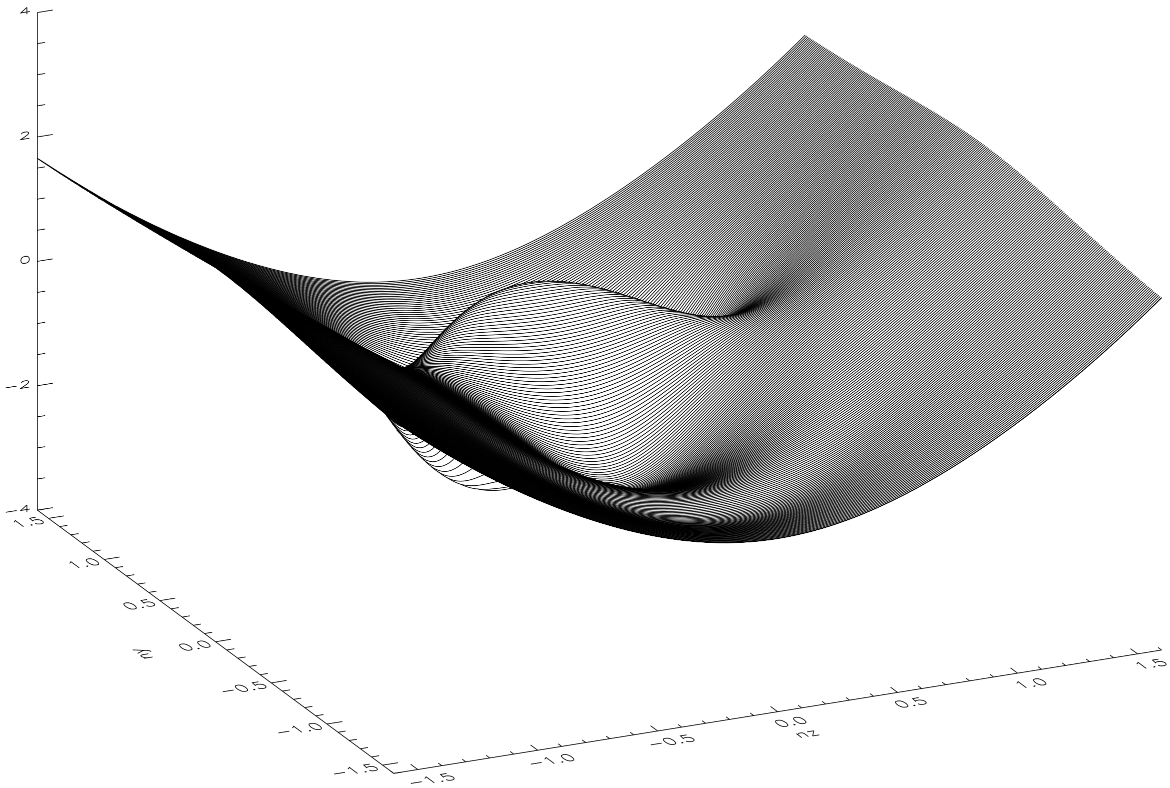
Standard case



Re(Y21) for half space of uniform, collisional plasma

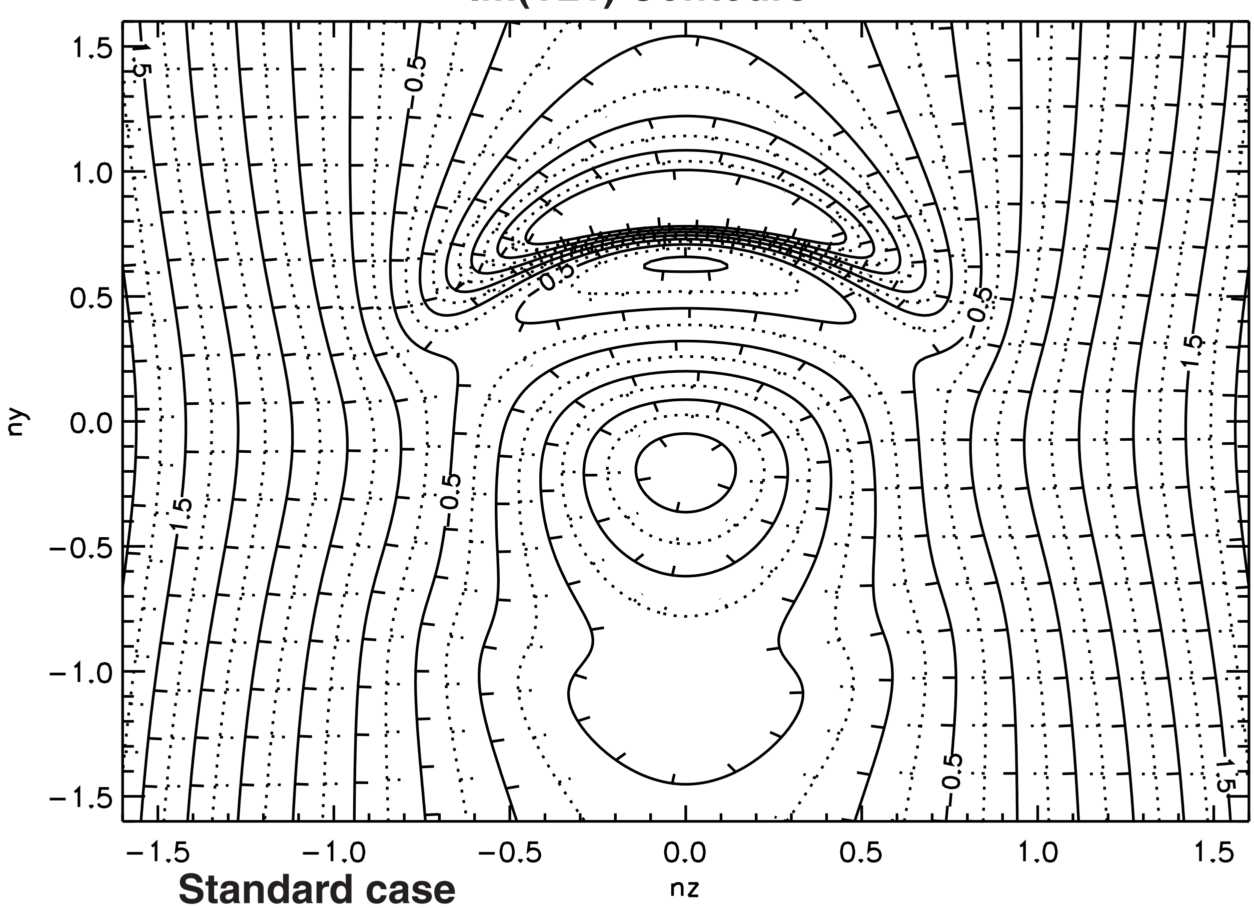


Uniform case

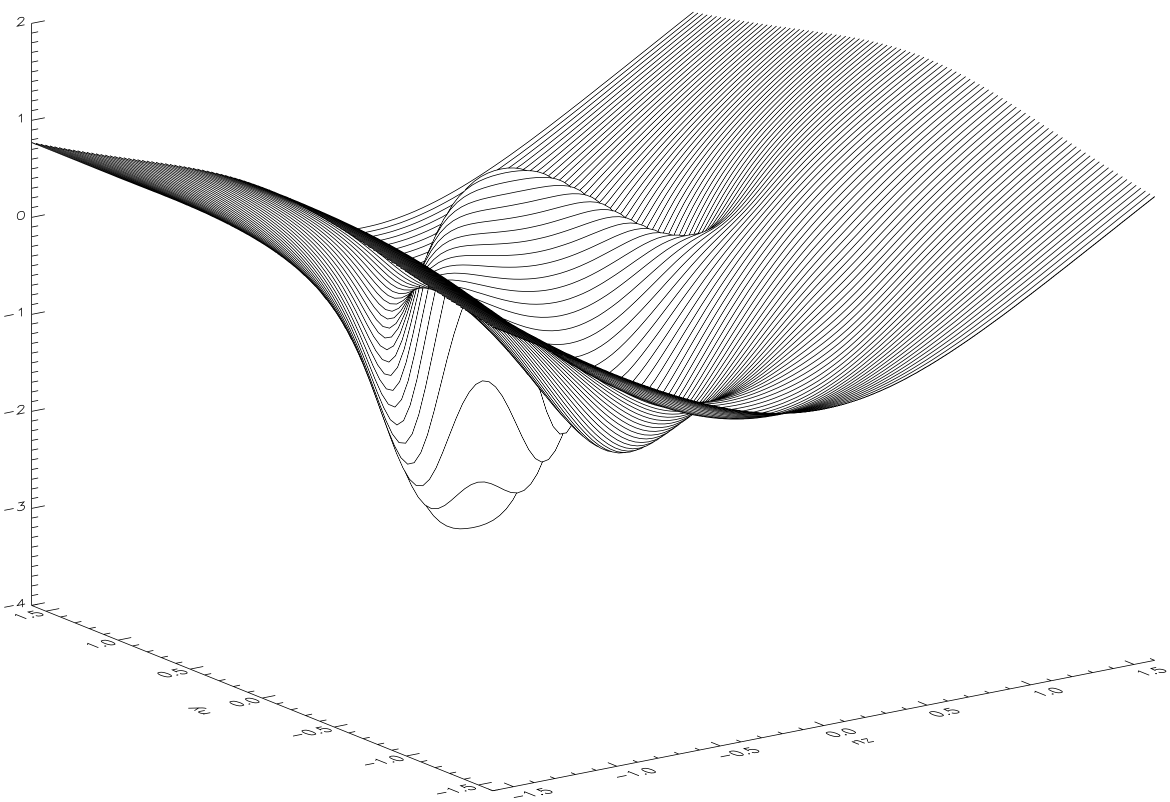


Im(Y21) surface from GLOSI calculation

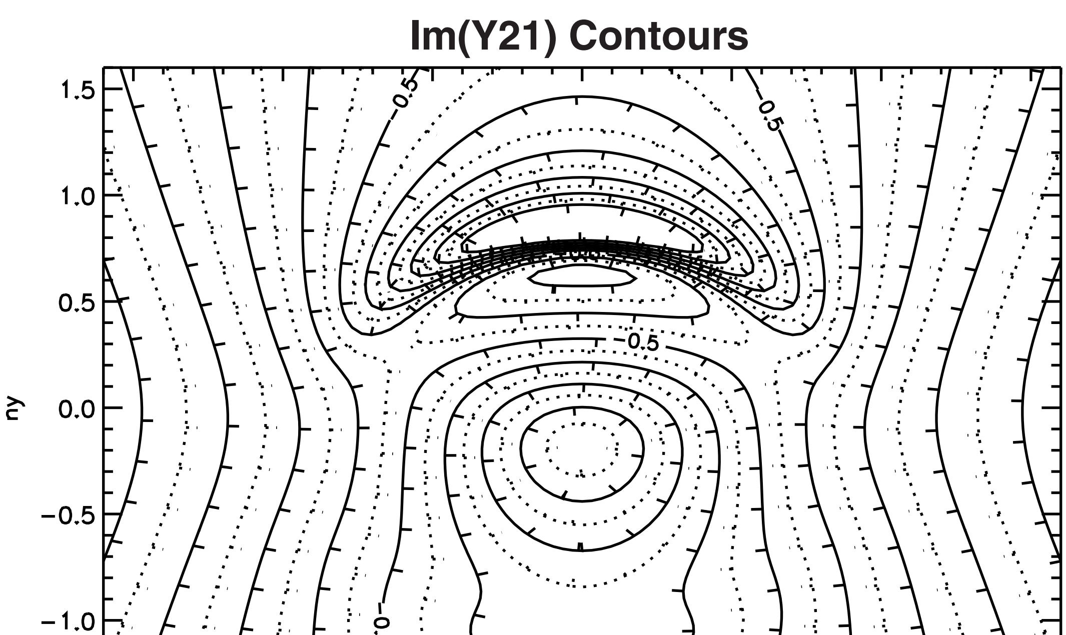
Im(Y21) Contours



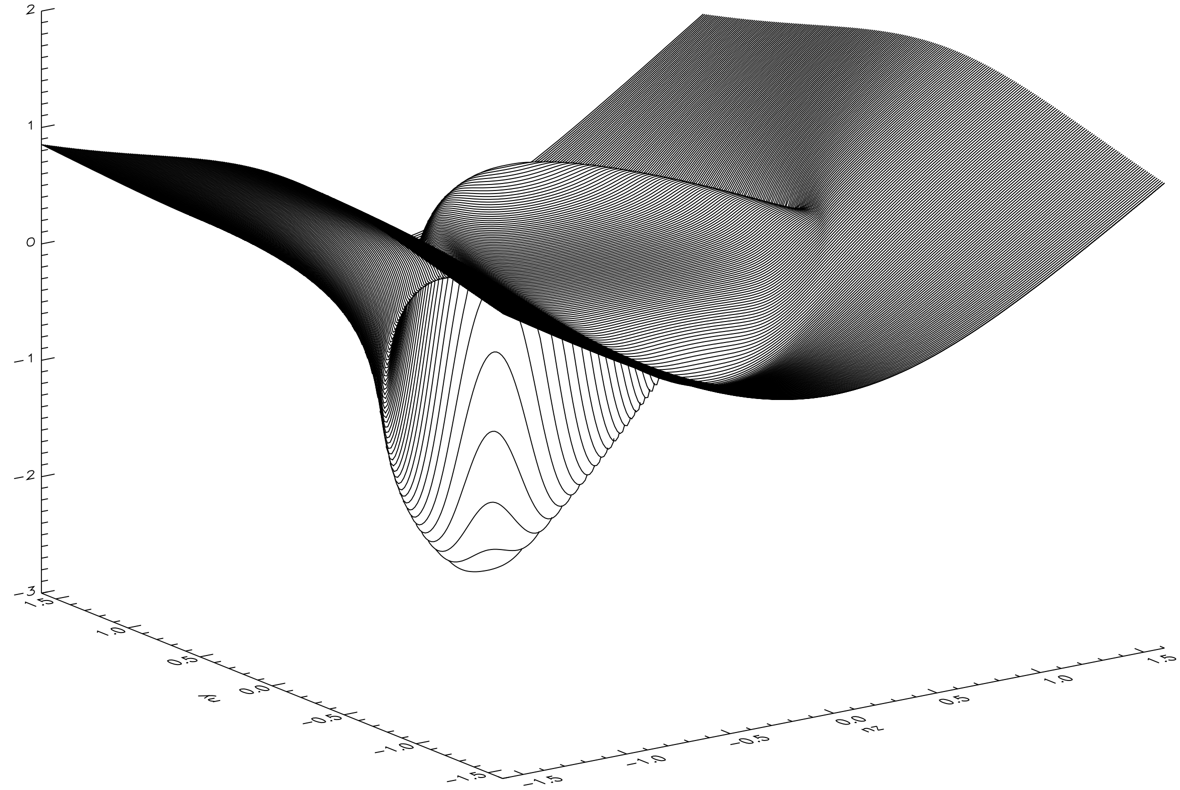
Standard case



Im(Y21) surface for standard case

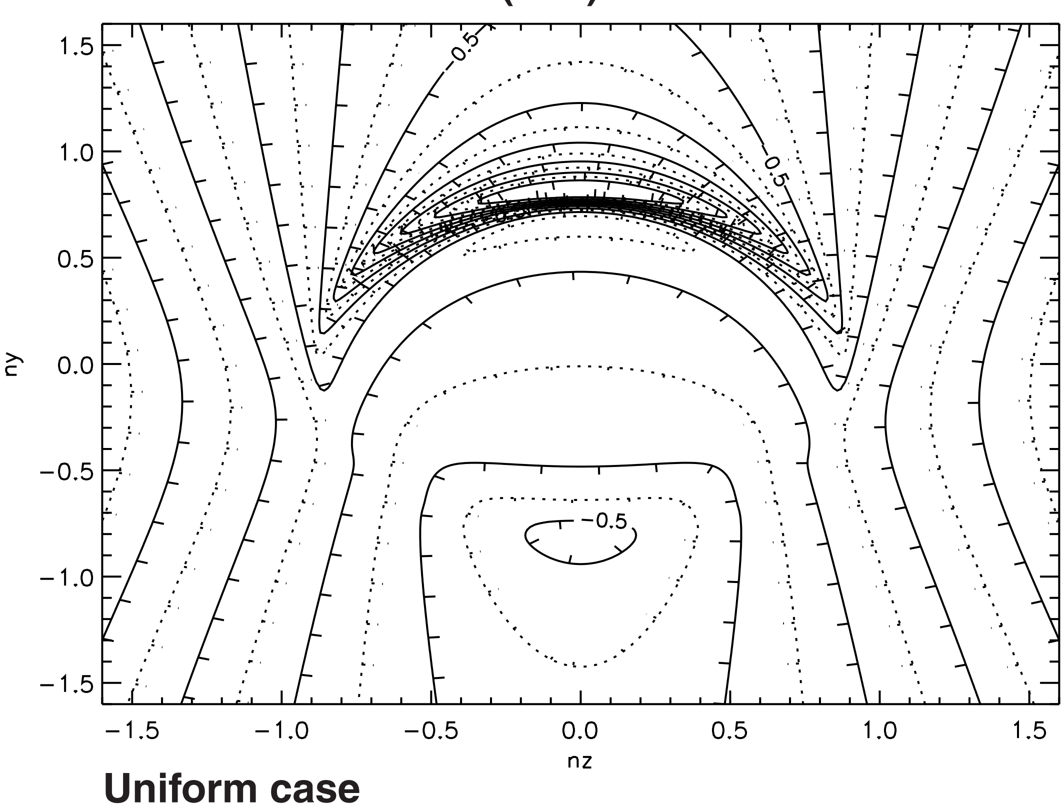


Standard case

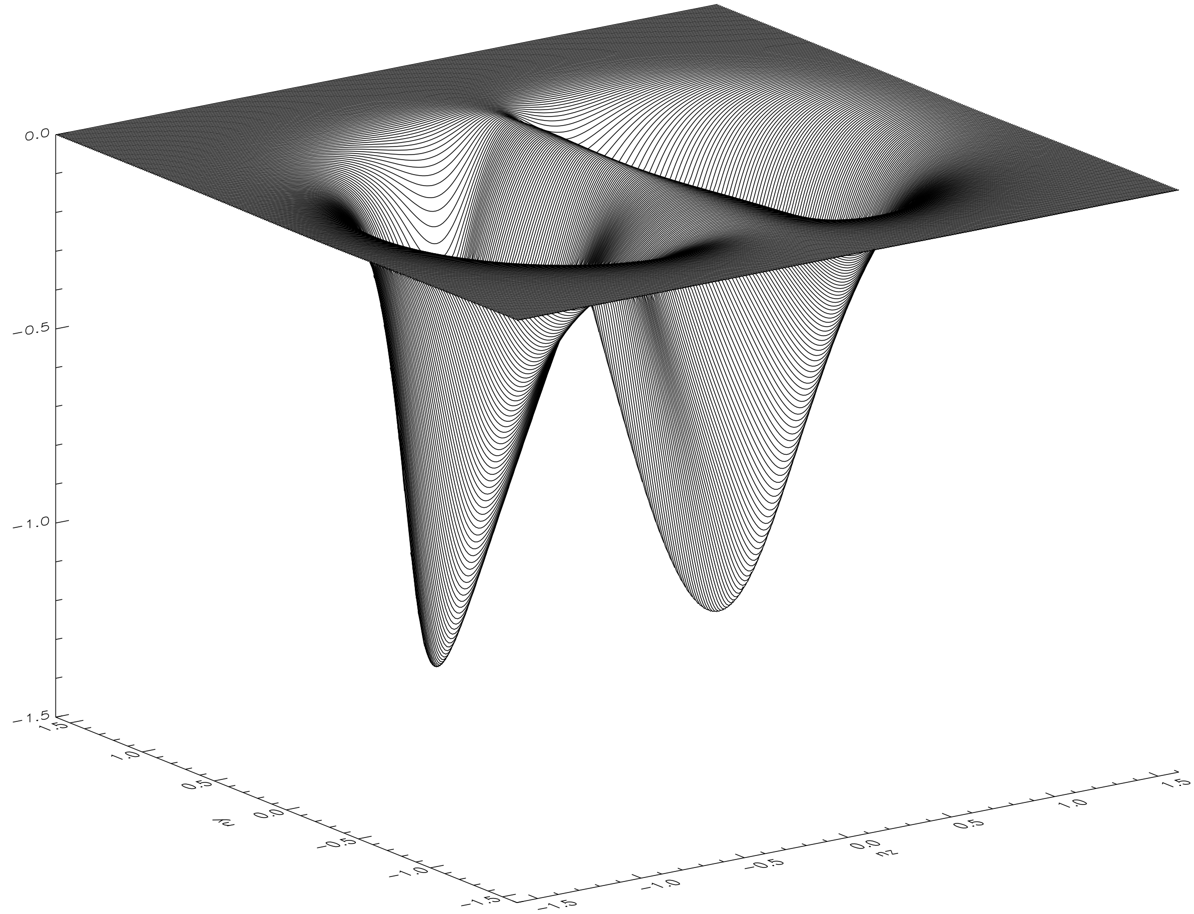


Im(Y21) for half space of uniform, collisional plasma

Im(Y21) Contours

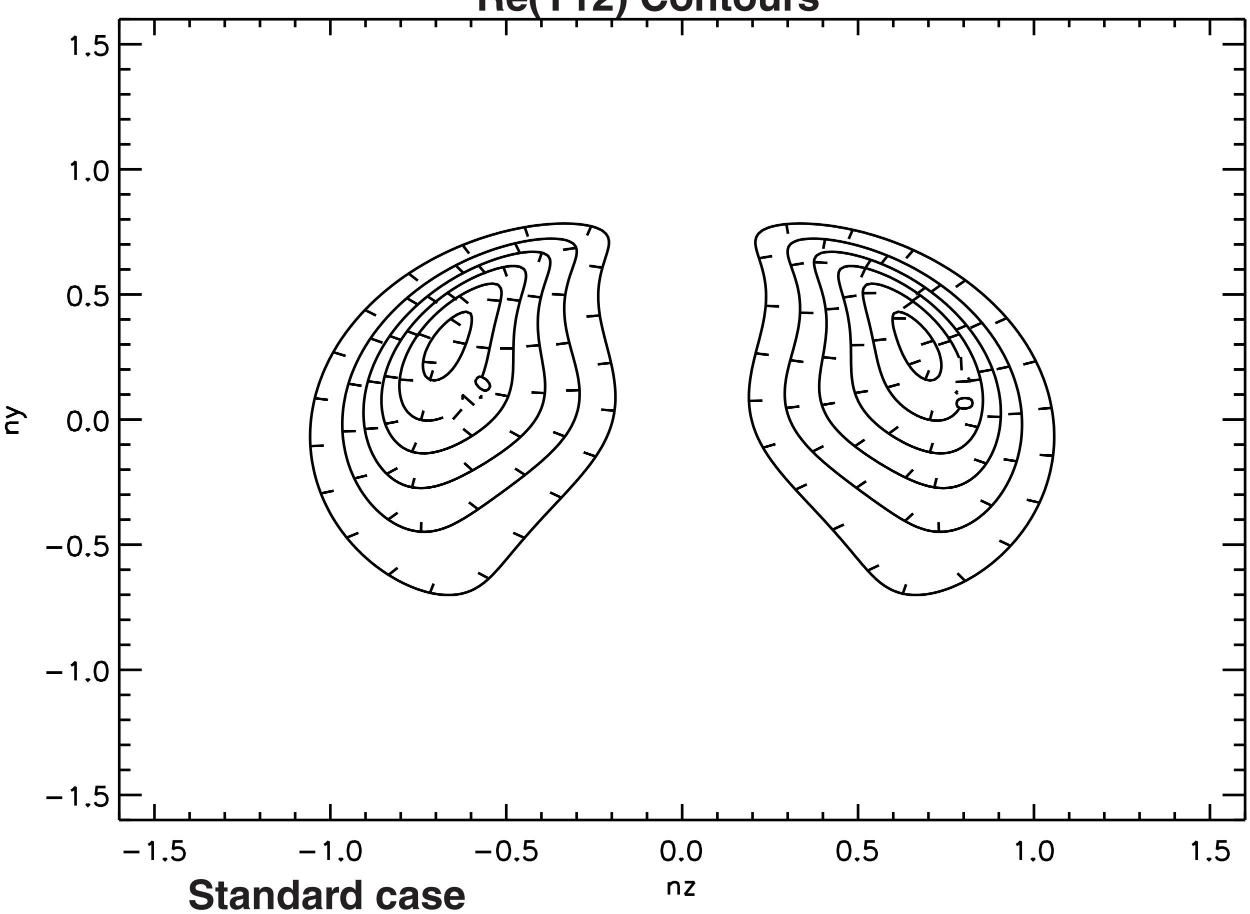


Uniform case

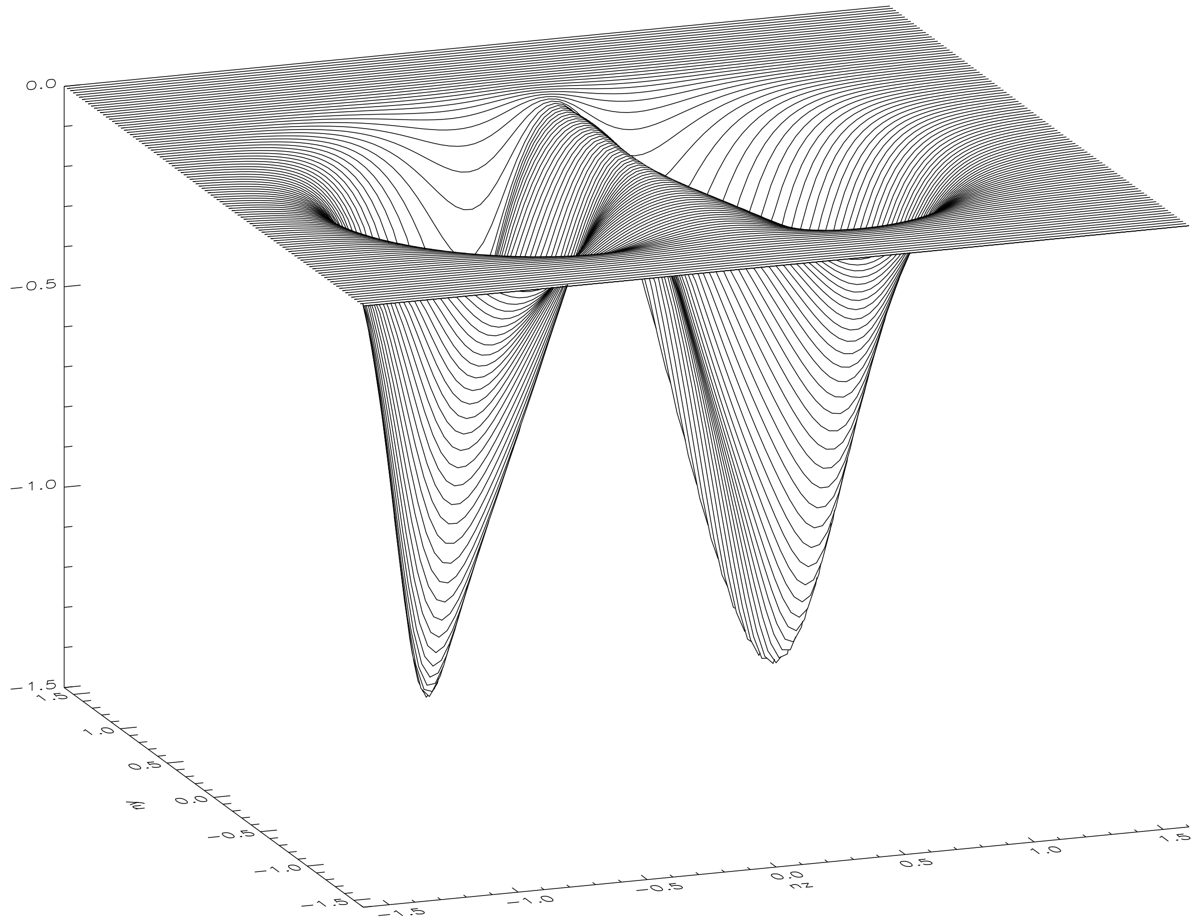


Re(Y12) surface from GLOSI calculation

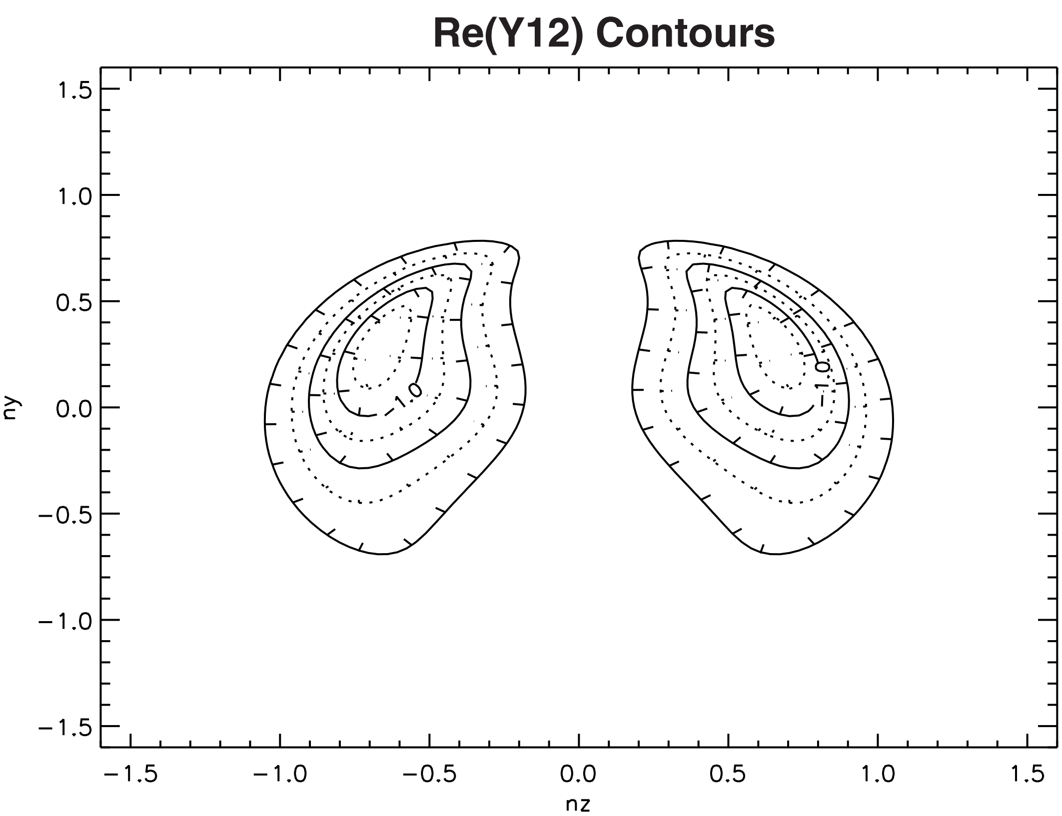
Re(Y12) Contours



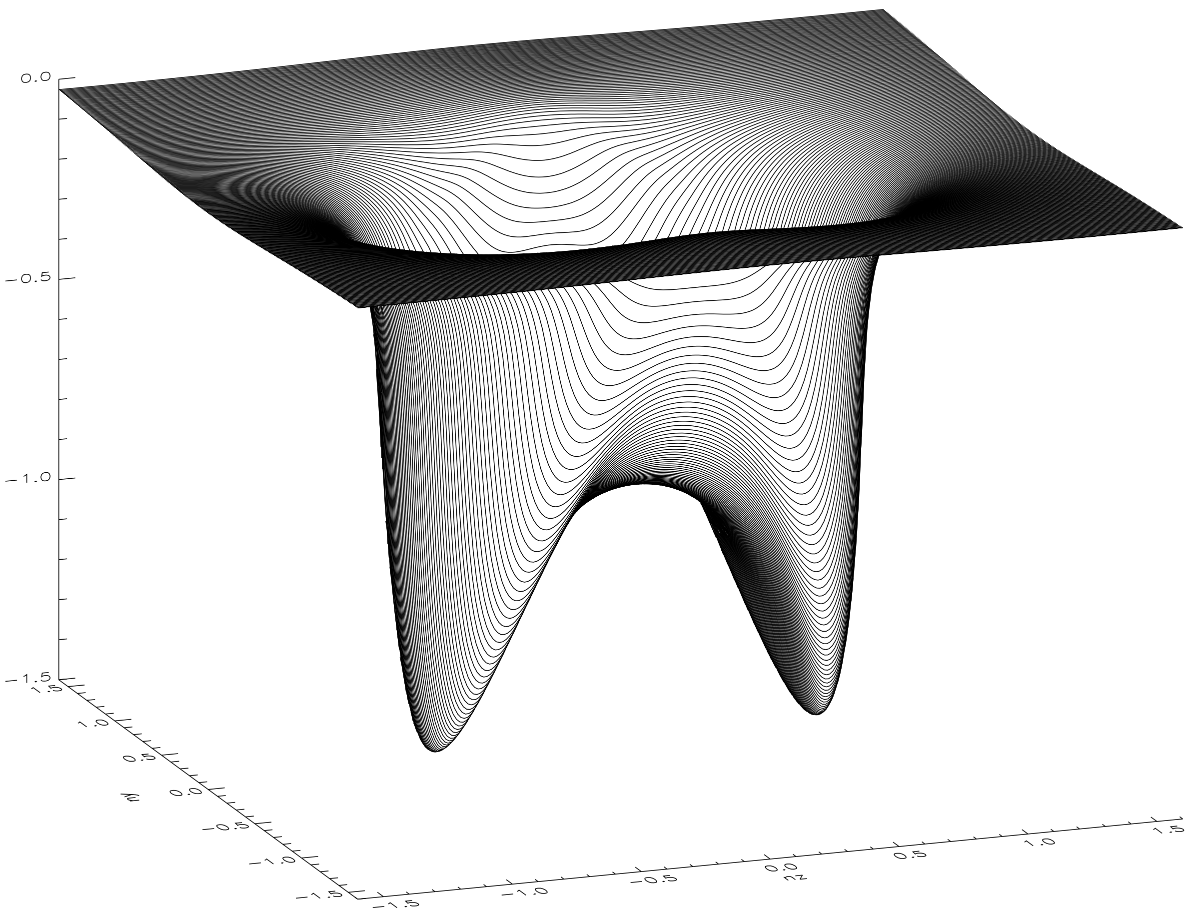
Standard case



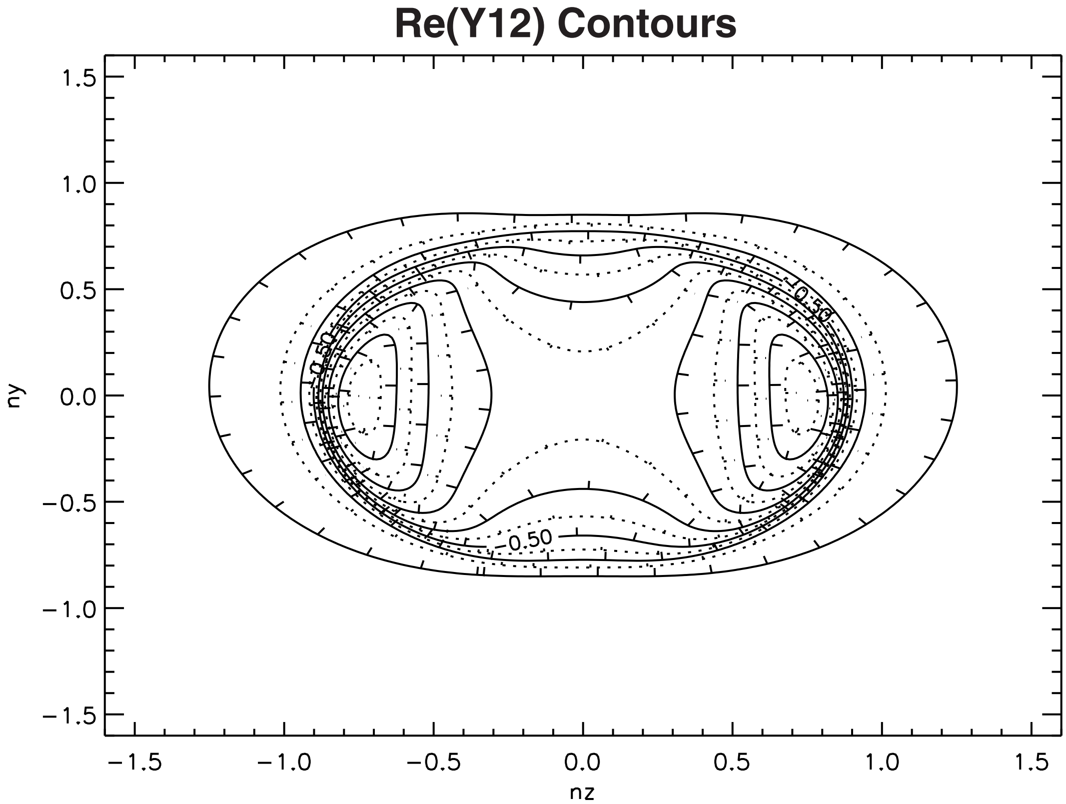
Re(Y12) surface for standard case



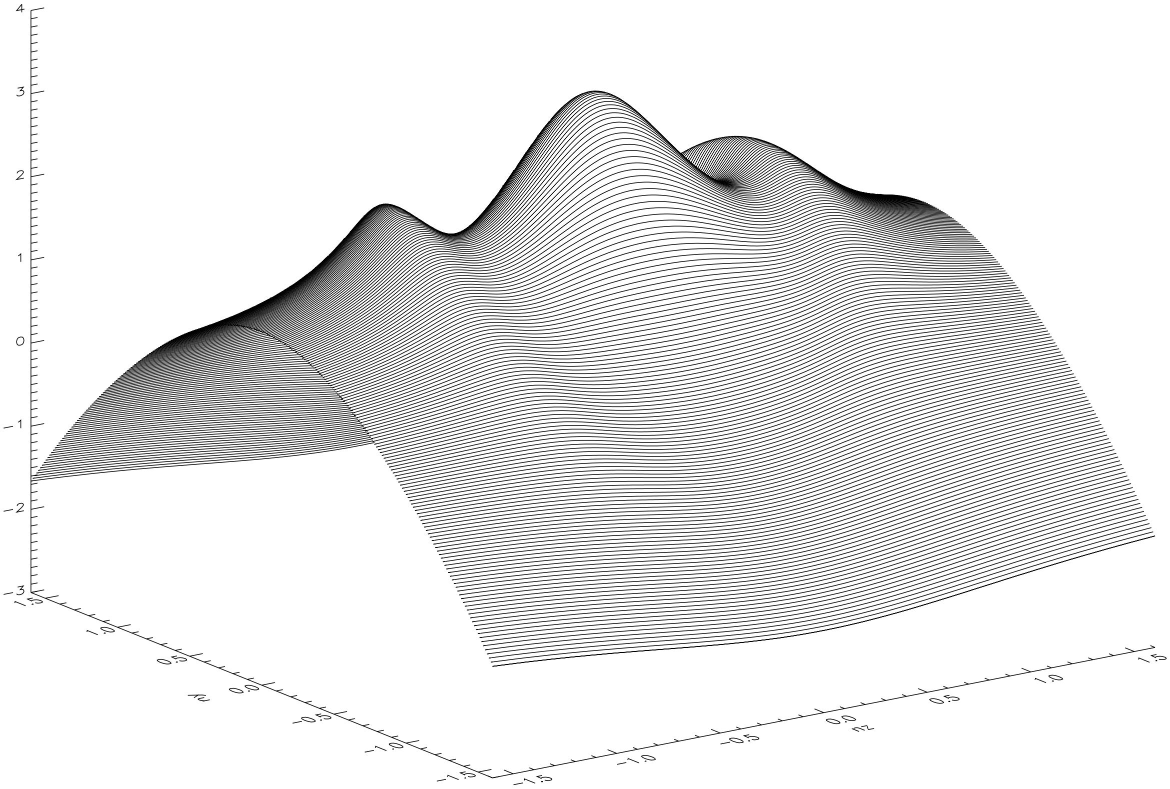
Standard case



Re(Y12) for half space of uniform, collisional plasma

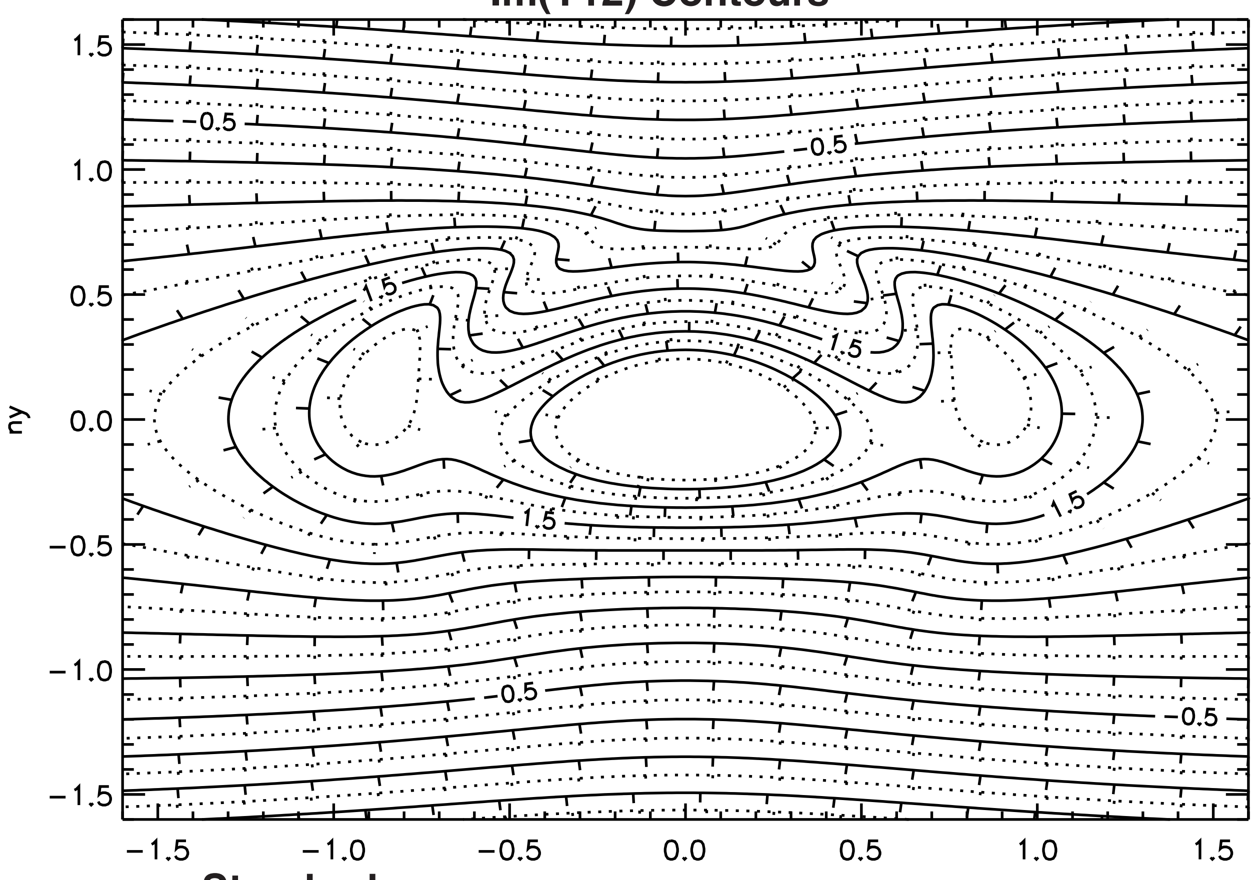


Uniform case

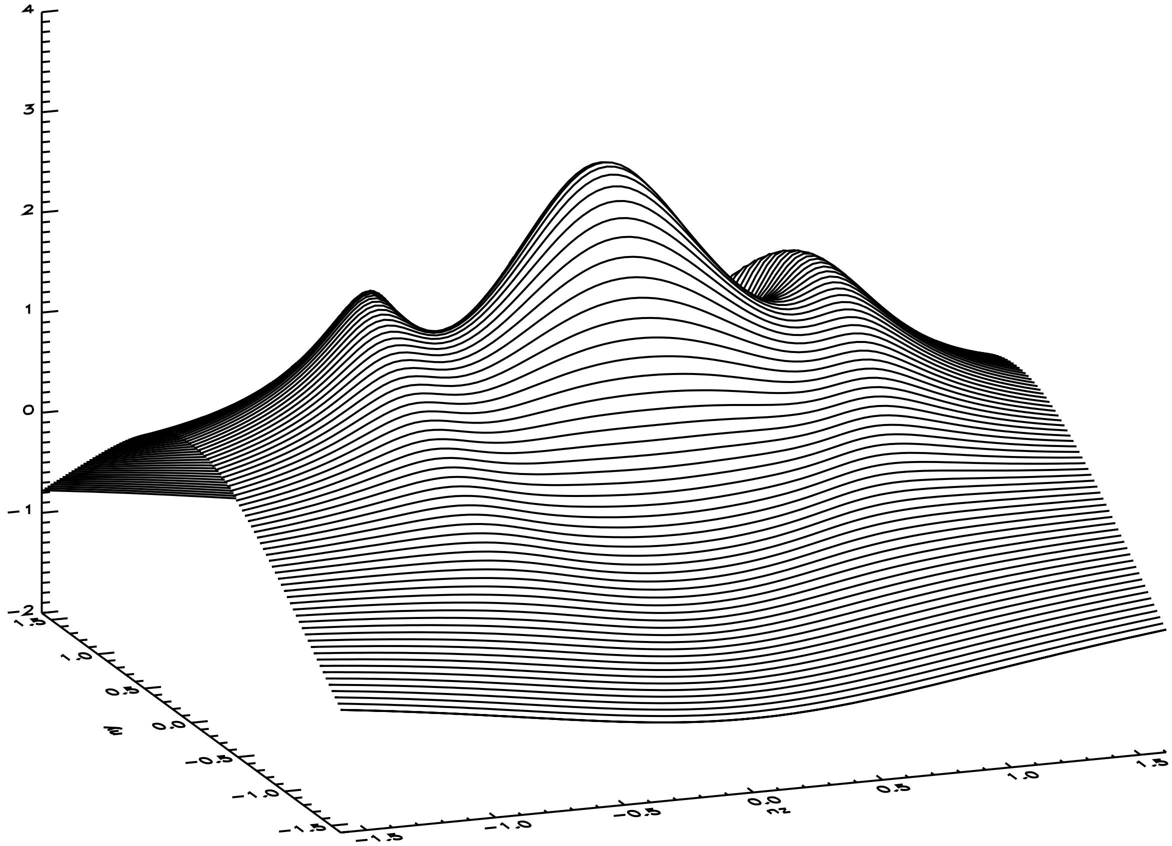


Im(Y12) surface from GLOSI calculation

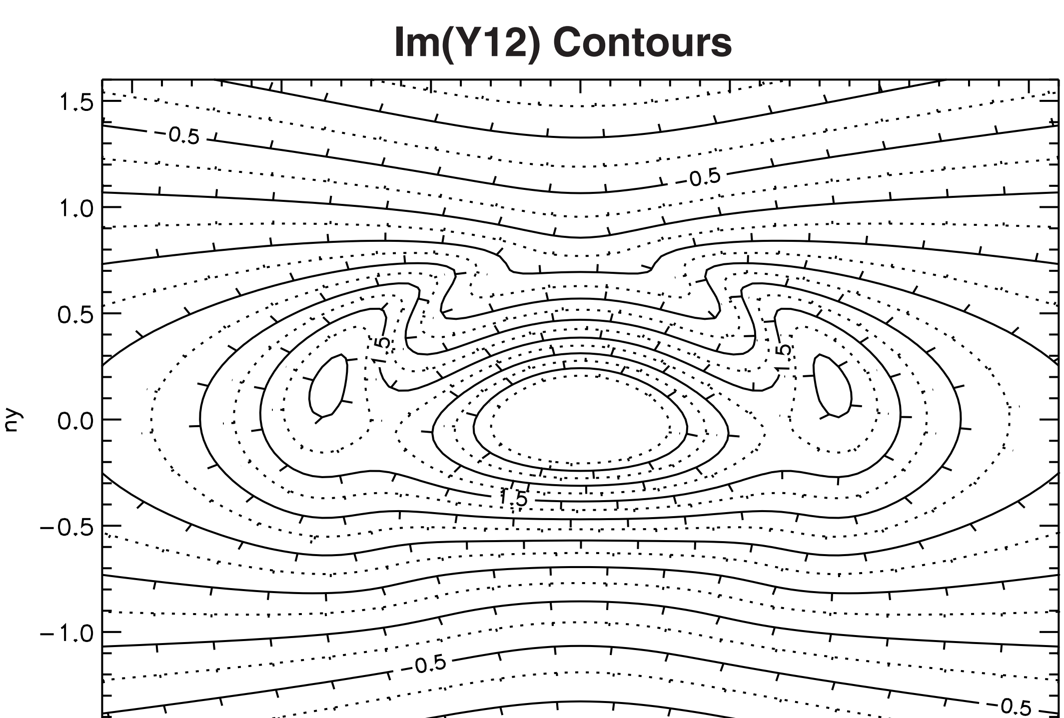
Im(Y12) Contours



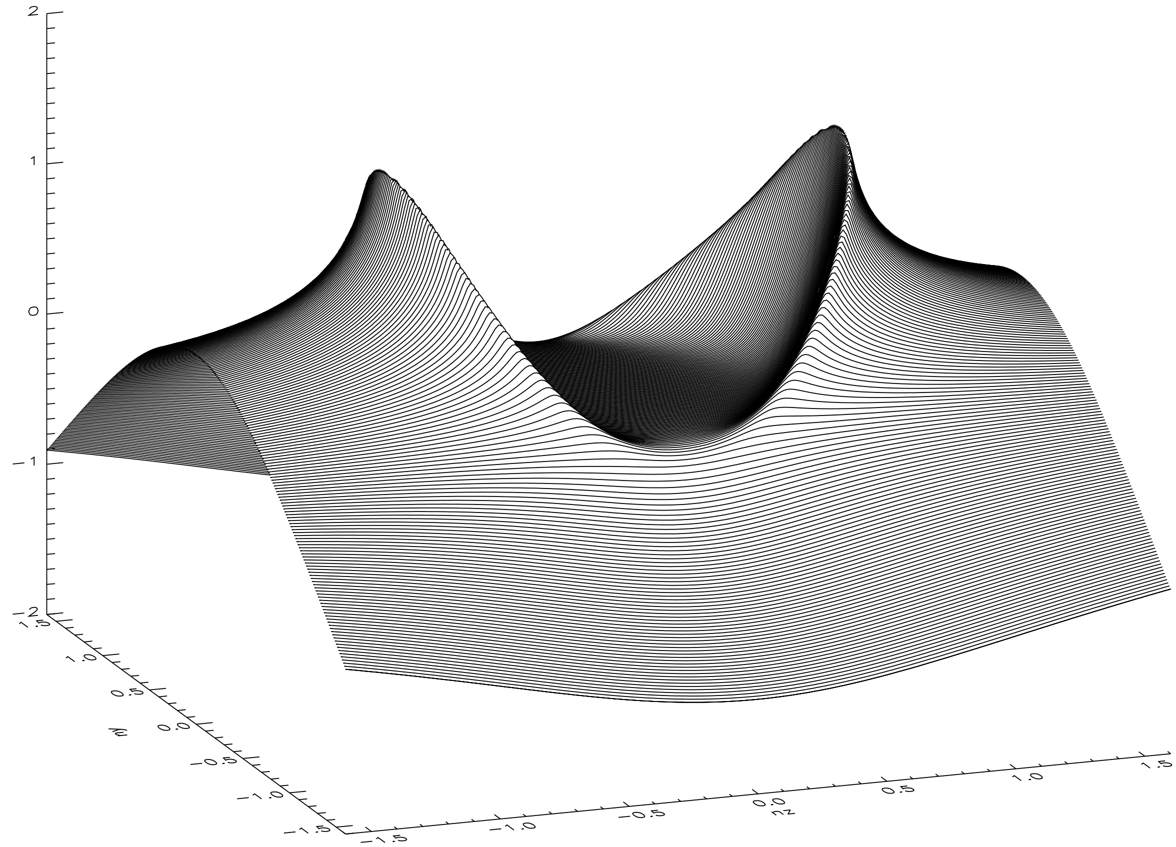
Standard case



Im(Y12) surface for standard case

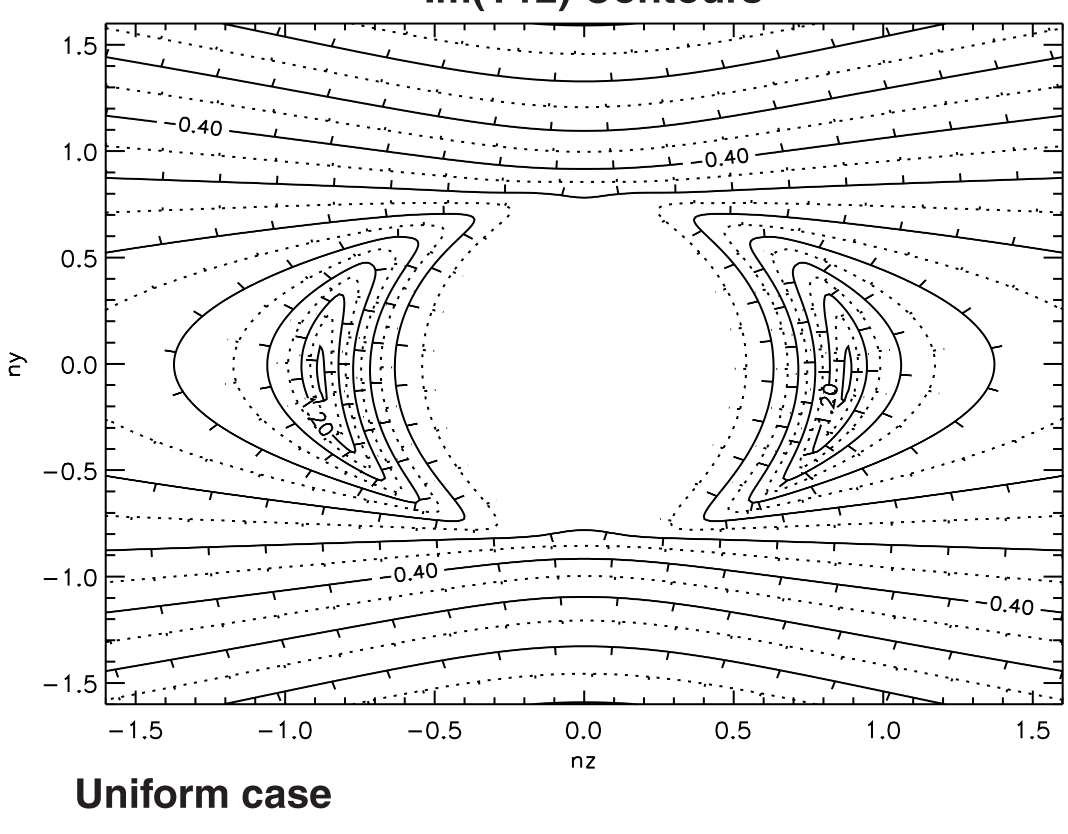


Standard case



Im(Y12) for half space of uniform, collisional plasma

Im(Y12) Contours



Uniform case