RELATIVISTIC EFFECTS IN ELECTRON BERNSTEIN WAVE HEATING AND CURRENT DRIVE

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BRIEF SYNOPSIS

- Theoretical calculations using non-relativistic dielectric tensor show that mode converted (from X or O modes) electron Bernstein waves could be used for heating electrons and for current generation in high-β plasmas in spherical tori like NSTX.

- Experimental observations in NSTX and CDX-U have validated the mode conversion process.

- Recent developments:

  - a code R2D2 has been developed for studying wave propagation and evaluating the quasilinear diffusion coefficient using a fully relativistic dielectric tensor;

  - a drift kinetic Fokker-Planck code DKE with quasilinear wave diffusion has been developed for studying current drive.

- Topics discussed in this poster:

  - changes in the characteristics of electron Bernstein waves due to relativistic effects;

  - current drive by electron Bernstein waves.

RELATIVISTIC DIELECTRIC TENSOR

- From the linearized Vlasov equation, the perturbed distribution function is

$$f_1 = -\frac{1}{\Omega} \exp\left\{\frac{-i}{\Omega}\left(\lambda\phi - \frac{p_\perp k_\perp}{m\gamma}\sin\left(\phi-\psi\right)\right)\right\}\times$$

$$\int_{-\infty}^{\phi} d\phi' \exp\left\{\frac{i}{\Omega}\left(\lambda\phi' - \frac{p_\perp k_\perp}{m\gamma}\sin\left(\phi'-\psi\right)\right)\right\}\hat{P}'\; f_0\left(p_\perp, p_\parallel\right)$$

$$\frac{\hat{P}}{-q} = \frac{1}{\sqrt{2}}\left(E_l e^{-i\phi} + E_r e^{i\phi}\right)\hat{G} + E_\parallel\left(\frac{k_\perp}{\omega}\cos\left(\psi-\phi\right)\hat{H} + \frac{\partial}{\partial p_\parallel}\right)$$

$$\hat{G} = \frac{\partial}{\partial p_\perp} - \frac{k_\parallel}{\omega}\hat{H}, \qquad \hat{H} = \frac{p_\parallel}{m\gamma}\frac{\partial}{\partial p_\perp} - \frac{p_\perp}{m\gamma}\frac{\partial}{\partial p_\parallel}$$

$$\lambda = \omega - \frac{k_\parallel p_\parallel}{m\gamma}, \quad \gamma = \left(1 + \frac{p_\perp^2}{m^2c^2} + \frac{p_\parallel^2}{m^2c^2}\right)^{1/2}, \quad \Omega = \frac{qB_0}{m\gamma},$$

$$p_x = p_\perp \cos\left(\phi\right), \quad k_x = k_\perp\cos\left(\psi\right), \quad \sqrt{2}E_{l,r} = E_x \pm iE_y$$

- The plasma conductivity tensor is obtained from the current density

$$\vec{j} = q\int d^3p\,\frac{\vec{p}}{m\gamma}\,f_1 = \overline{\overline{\sigma}}\cdot\vec{E}$$

RELATIVISTIC DIELECTRIC TENSOR

FIRST APPROACH

For a relativistic Maxwellian distribution function

$$\overline{\overline{\sigma}} = \frac{1}{4\pi}\frac{\omega_p^2}{\omega_c}\frac{c^4}{v_t^4}\frac{1}{\mathrm{K}_2\left(\frac{c^2}{v_t^2}\right)}\int_0^\infty d\xi \left\{\frac{\mathrm{K}_2\left(R^{1/2}\right)}{R}\overline{\overline{T}}_1 - \frac{\mathrm{K}_3\left(R^{1/2}\right)}{R^{3/2}}\overline{\overline{T}}_2\right\}$$

where $$R = \left(\frac{c^2}{v_t^2} - i\xi\frac{\omega}{\omega_c}\right)^2 + 2\left(\frac{k_\perp c}{\omega_c}\right)^2(1-\cos\xi) + \frac{k_\parallel^2 c^2 \xi^2}{{\omega_c}^2}$$

$$\overline{\overline{T}}_1 = \begin{pmatrix} \cos\xi & -\sin\xi & 0 \\ \sin\xi & \cos\xi & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\overline{\overline{T}}_2 = \frac{c^2}{\omega_c^2}\begin{pmatrix} k_\perp^2\sin^2\xi & -k_\perp^2\sin\xi\,(1-\cos\xi) & k_\perp k_\parallel \xi\sin\xi \\ k_\perp^2\sin\xi\,(1-\cos\xi) & -k_\perp^2(1-\cos\xi)^2 & k_\perp k_\parallel\xi\,(1-\cos\xi) \\ k_\perp k_\parallel\xi\sin\xi & -k_\perp k_\parallel\xi\,(1-\cos\xi) & k_\parallel^2\xi^2 \end{pmatrix}$$

SECOND APPROACH

For any equilibrium distribution function $f_0(p_\perp, p_\parallel)$:

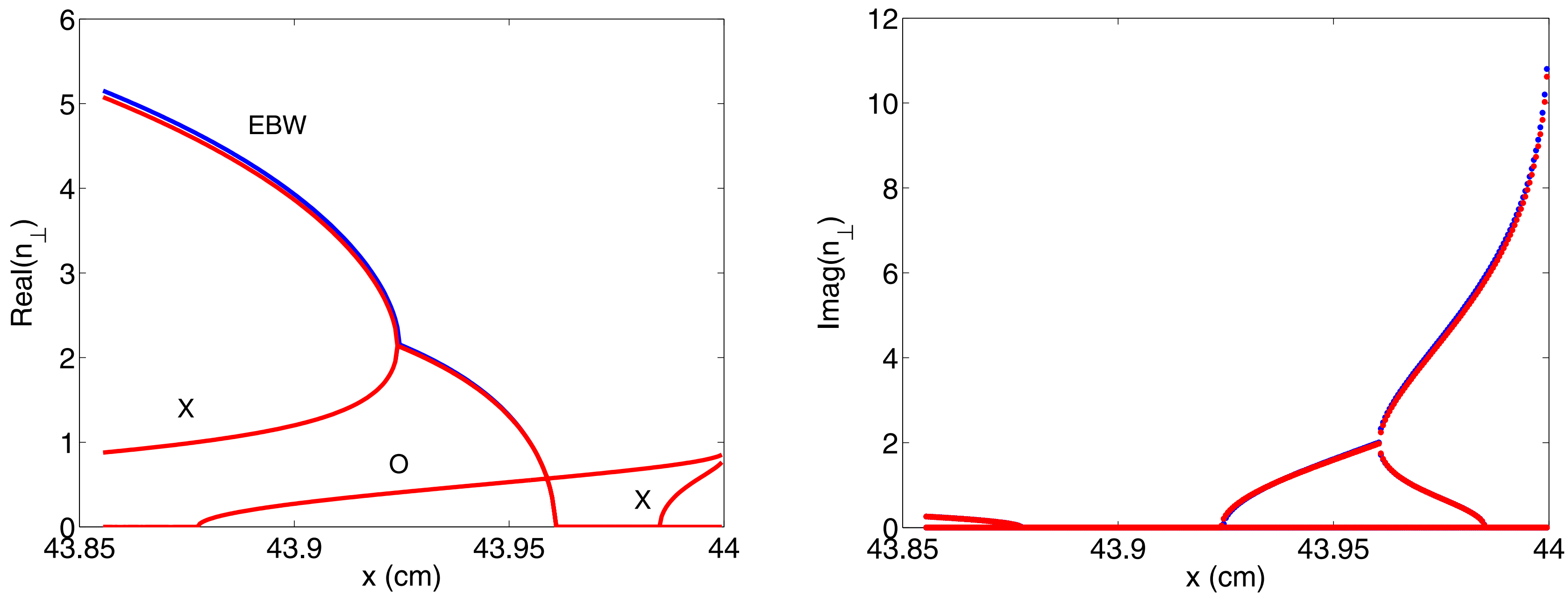
$$\overline{\overline{\sigma}} = -\frac{i}{2}\,\frac{\omega_p^2}{\omega_c}\left\langle \sum_{n=-\infty}^{\infty} \frac{1}{n-\overline{\omega}}\left(\frac{1}{\kappa T}\,\frac{p_\perp}{m\gamma}\right)\overline{\overline{\sigma}}_N\; f_0\left(p_\perp, p_\parallel\right)\right\rangle$$

where $$\overline{\overline{\sigma}}_N = \begin{pmatrix} \dfrac{n^2}{\zeta^2} p_\perp \mathrm{J}_n^2 & -i\dfrac{n}{\zeta} p_\perp \mathrm{J}_n \mathrm{J}_n' & \dfrac{n}{\zeta} p_\parallel \mathrm{J}_n^2 \\ i\dfrac{n}{\zeta} p_\perp \mathrm{J}_n \mathrm{J}_n' & p_\perp \mathrm{J}_n'^2 & i p_\parallel \mathrm{J}_n \mathrm{J}_n' \\ \dfrac{n}{\zeta} p_\parallel \mathrm{J}_n^2 & -i p_\parallel \mathrm{J}_n \mathrm{J}_n' & \dfrac{p_\parallel^2}{p_\perp}\mathrm{J}_n^2 \end{pmatrix}$$

$$\zeta = \frac{k_\perp p_\perp}{m\omega_c}, \qquad \overline{\omega} = \frac{1}{\omega_c}\left(\omega\gamma - k_\parallel \frac{p_\parallel}{m}\right),$$

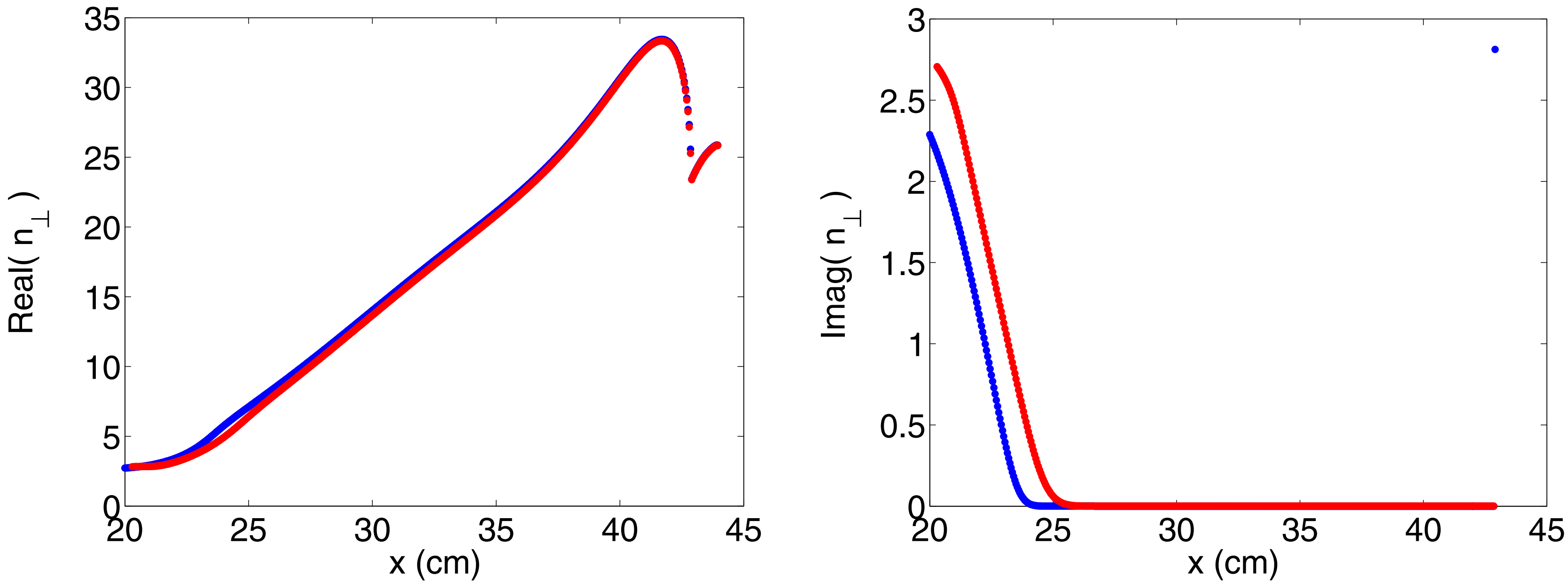
$$\omega_c = \frac{eB_0}{m}, \qquad \langle .....\rangle = \int_0^\infty dp_\perp p_\perp \int_{-\infty}^{\infty} dp_\parallel$$

COMPARISON BETWEEN RELATIVISTIC AND NON-RELATIVISTIC MODES IN THE MODE CONVERSION REGION



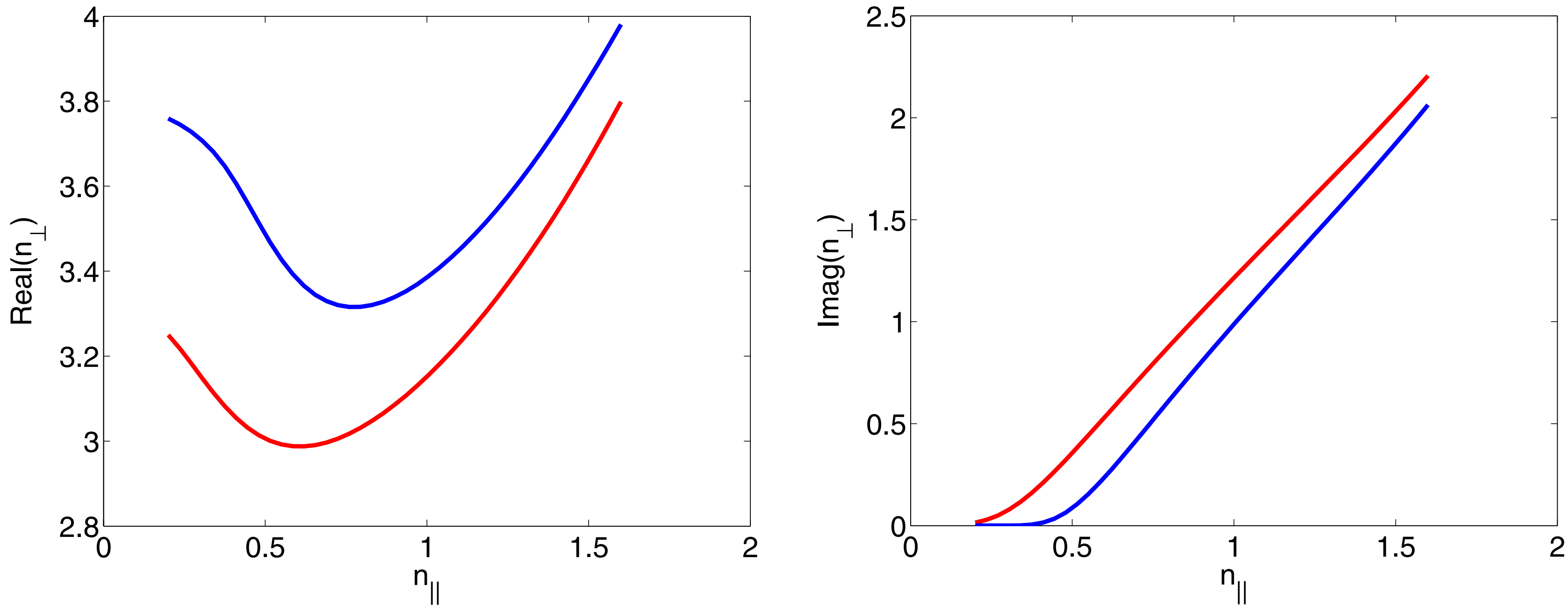
NSTX parameters, $a = 44$ cm., $f = 15$ GHz, $n_{\|} = 0.1$.

COMPARISON BETWEEN RELATIVISTIC AND NON-RELATIVISTIC EBWs AWAY FROM THE MODE CONVERSION REGION



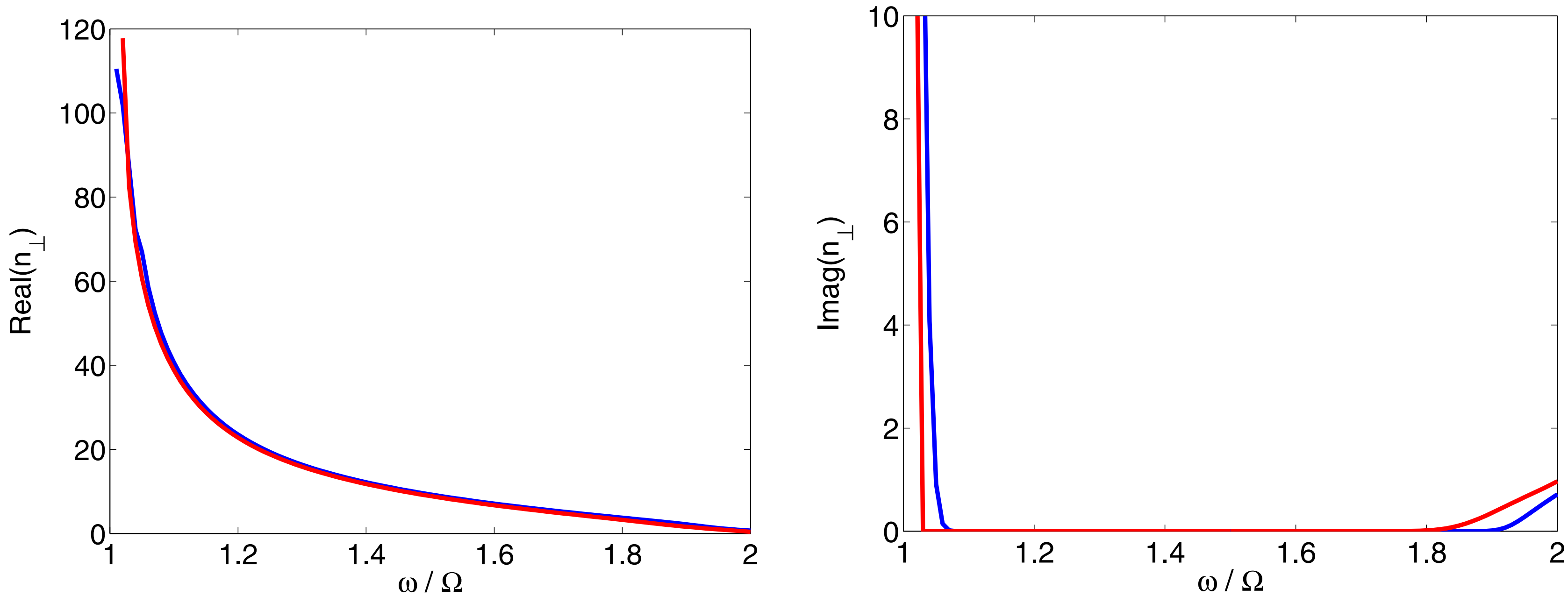
NSTX parameters, $a = 44$ cm., $f = 28$ GHz, $n_{\|} = 0.2$.

COMPARISON BETWEEN RELATIVISTIC AND NON-RELATIVISTIC EBWs



$$\omega_p/\omega_c = 6, \;\; \omega/\omega_c = 1.8, \quad T_e = 3 \text{ keV}$$

COMPARISON BETWEEN RELATIVISTIC AND NON-RELATIVISTIC EBWs



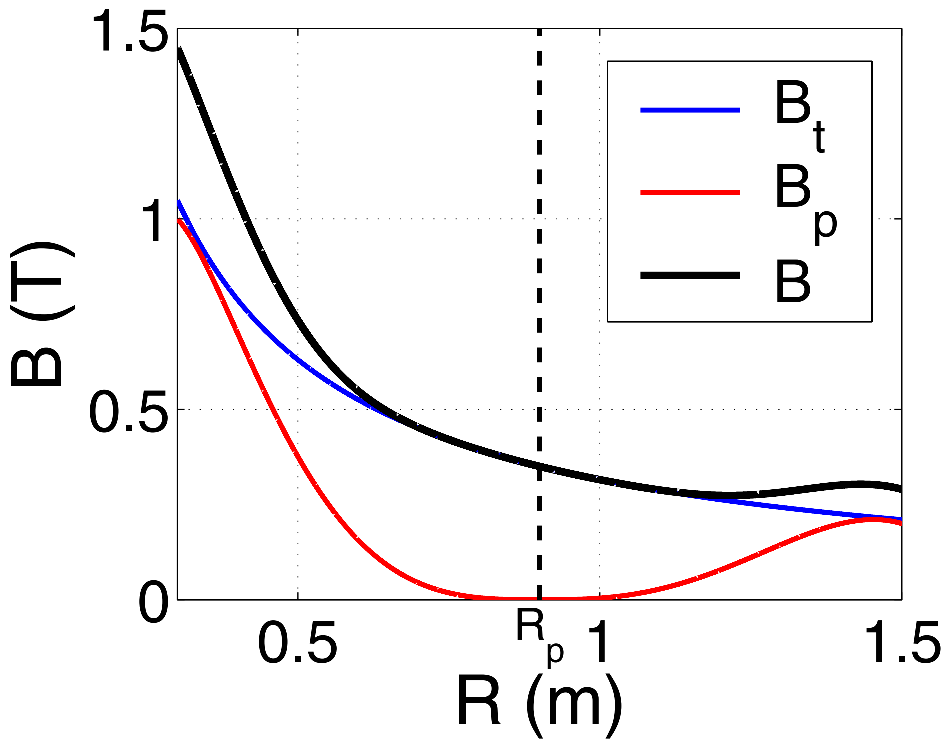
$$\omega_p/\omega_c = 6, \;\; n_\| = 0.2, \quad T_e = 3 \text{ keV}$$

FOKKER-PLANCK DESCRIPTION OF THE ELECTRON DISTRIBUTION FUNCTION

[See poster PP1.084 (Thursday afternoon) by J. Decker]

- DKE is used to solve $\{C(f)\}+\{Q(f)\} = 0$ for the electron distribution function
  - $C(f)$ is the collision operator,
  - $Q(f)$ is the quasilinear RF diffusion operator.
- There are two viable schemes for current drive by electron Bernstein waves:
  - OHKAWA: asymmetric EBW induced banana trapping of electrons $\Rightarrow$ symmetric collisional de-trapping.
  - FISCH-BOOZER: asymmetric EBW induced resisitivity.

NSTX-TYPE PARAMETERS AND PROFILES



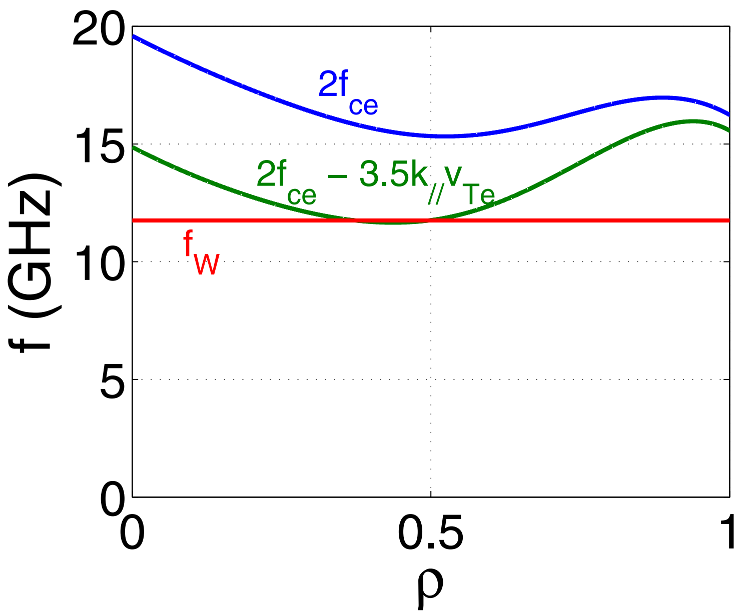
$$R = 0.9 \text{ m}, \quad a = 0.6 \text{ m}, \quad n_0 = 3 \times 10^{19} \text{ m}^{-3}, \quad T_0 = 3 \text{ keV}$$

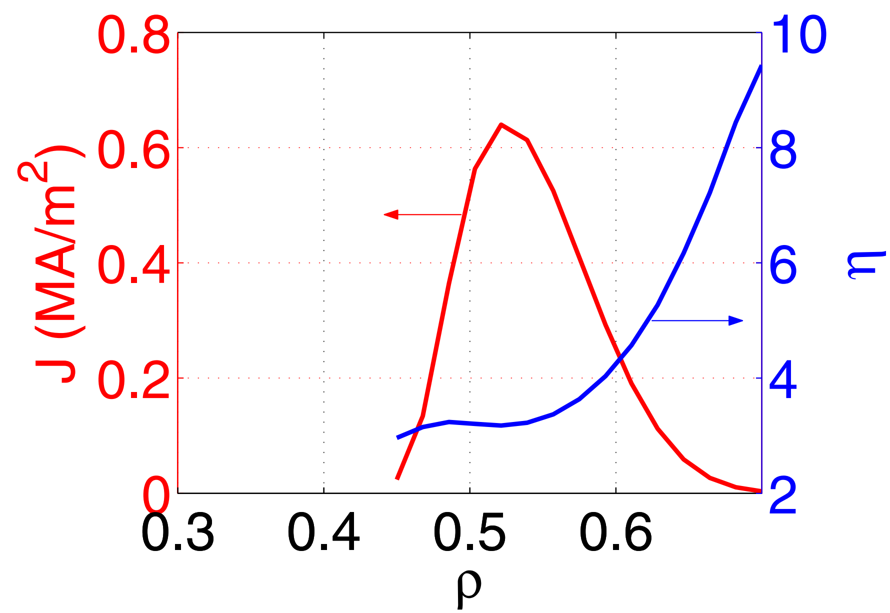
$$n = n_E + (n_0 - n_E)\left(1 - r^2/a^2\right)^{1/2}$$

$$T = T_E + (T_0 - T_E)\left(1 - r^2/a^2\right)^2$$

$$n_E/n_0 = 0.02, \quad T_E/T_0 = 0.02$$

OHKAWA CURRENT DRIVE





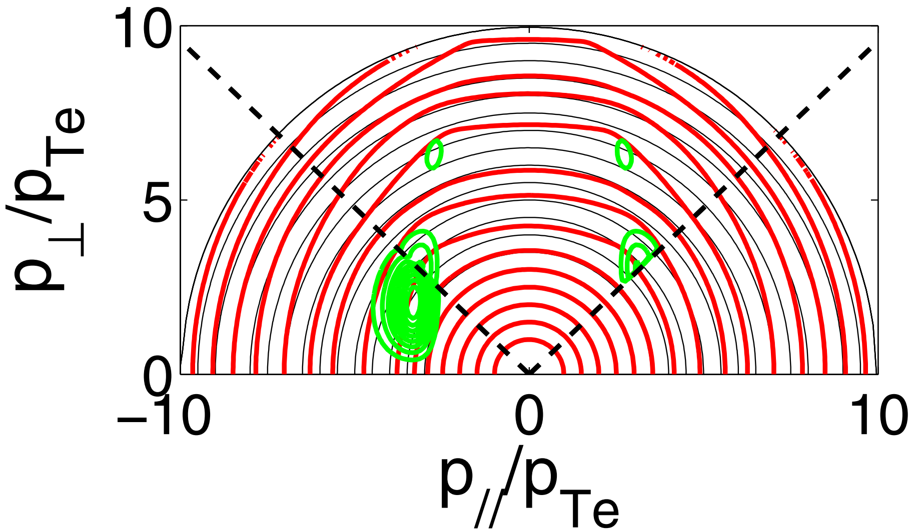
$$f = 11.8\ \text{GHz},\ n_{\|} = 1.5$$

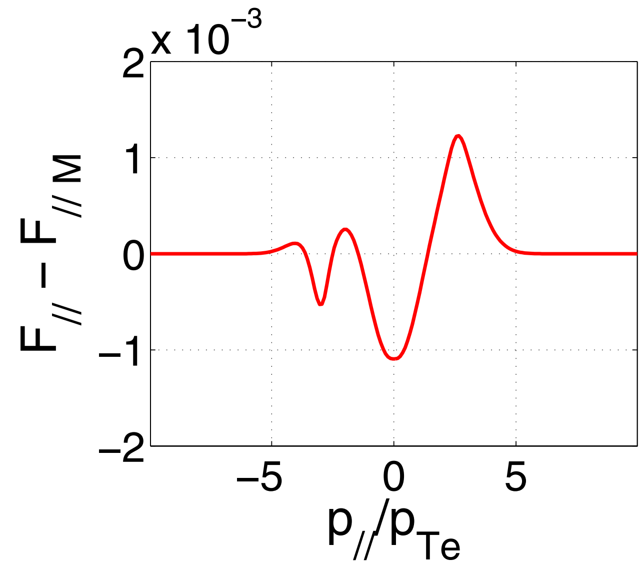
$$J_{peak} \approx 0.64\ \text{MA m}^{-2},\ P_{peak} \approx 1.4\ \text{MW m}^{-3},\ \eta'_{peak} \approx 0.47\ \text{A.m/W}$$

$$\eta = \frac{J/en_e v_{te}}{P/\nu_e n_e m_e v_{te}^2} \approx 3.2$$

OHKAWA CURRENT DRIVE

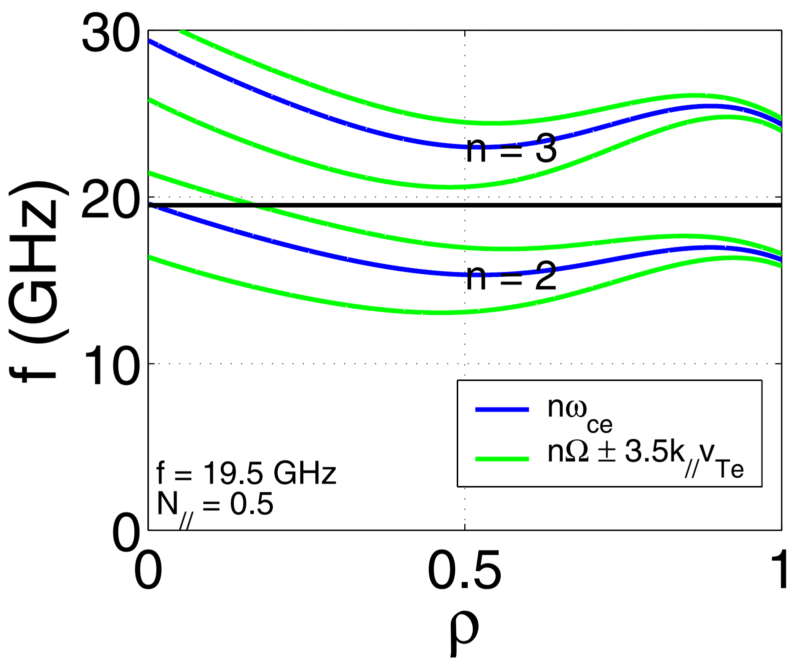
DISTRIBUTION AT PEAK CURRENT

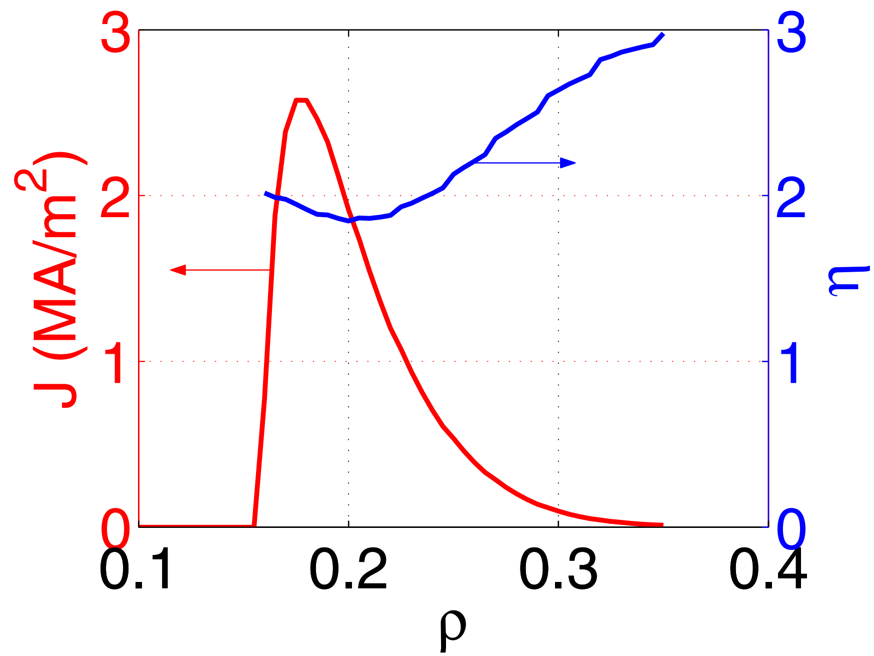




$f = 11.8$ GHz, $n_{\parallel} = 1.5$

FISCH-BOOZER CURRENT DRIVE





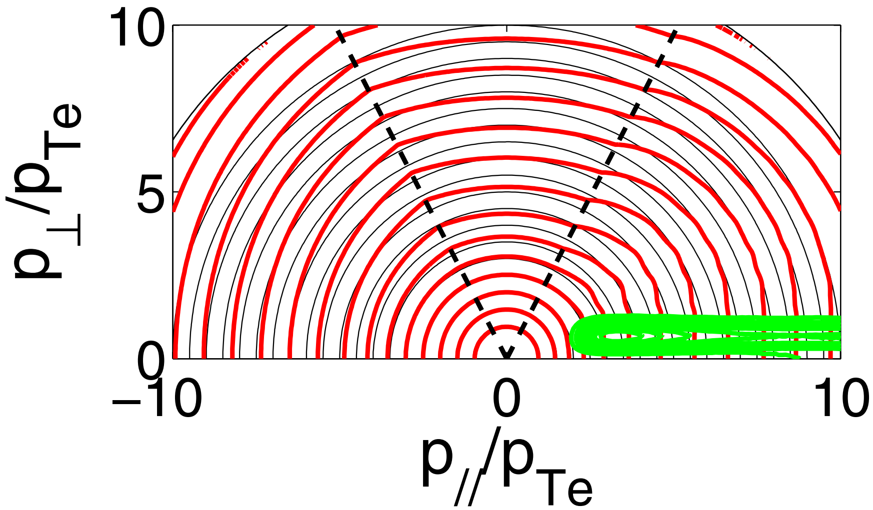
$$f = 19.5\ \mathrm{GHz},\ n_{\parallel} = 0.5$$

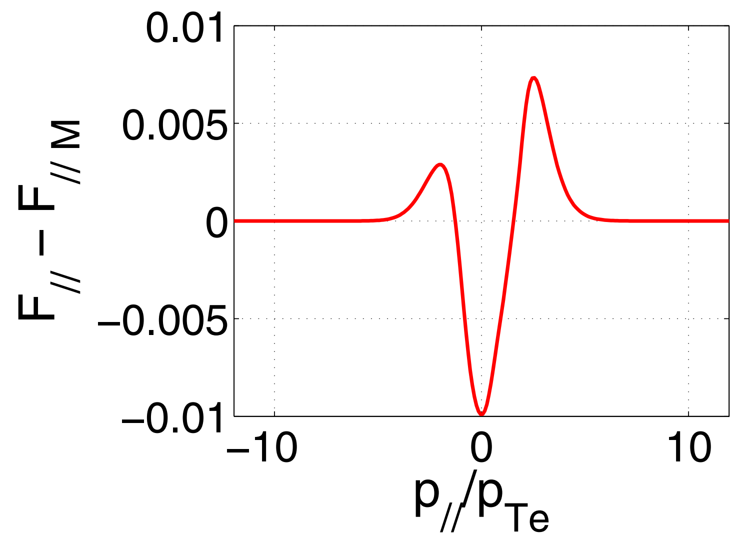
$$J_{peak} \approx 2.6\ \mathrm{MA\ m^{-2}},\ P_{peak} \approx 6.1\ \mathrm{MW\ m^{-3}},\ \eta'_{peak} \approx 0.42\ \mathrm{A.m/W}$$

$$\eta = \frac{J/en_e v_{te}}{P/\nu_e n_e m_e v_{te}^2} \approx 1.9$$

FISCH-BOOZER CURRENT DRIVE

DISTRIBUTION AT PEAK CURRENT





$f = 19.5$ GHz, $n_\parallel = 0.5$

CONCLUSIONS

- Numerical results show that relativistic effects lead to changes in the dispersion properties of the electron Bernstein wave when compared to the non-relativistically derived properties
  - the difference in the real part of the wave vector can modify the propagation characteristics of the EBWs;
  - the difference in the imaginary part of the wave vector can modify the region where the EBWs damp on electrons and drive plasma currents.

- Electron Bernstein waves offer a wide and rich range of phase space conditions for current drive in spherical tori plasmas. It may be possible to
  - spatially control the localized current drive;
  - interact with a specific part of the electron distribution function;
  - drive Ohkawa current efficiently away from the core of the plasma (current profile control);
  - drive Fisch-Boozer current efficiently in the core of the plasma.

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